UNIVERSITAT POLITÈCNICA DE VALÈNCIA

Tesis Doctoral

ANÁLISIS Y MEJORA DEL SISTEMA INTEGRAL DE GESTIÓN DE RESIDUOS SÓLIDOS URBANOS EN LA CIUDAD DE CASTELLÓ DE LA PLANA RESPONDIENDO A DEMANDAS DE SOSTENIBILIDAD Y CIRCULARIDAD

Programa de Doctorado en Diseño, Fabricación y Gestión de Proyectos Industriales

Doctorando: Héctor Moreno Solaz

Directores: Víctor Andrés Cloquell Ballester
Miguel Ángel Artacho Ramírez

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A Román y Julia, con todo mi cariño.

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RESUMEN.

La estrategia de la Unión Europea para la gestión de residuos se articula a través de una serie de directivas que toman como punto de partida la Directiva 2008/98/CE. En ella, se establece un marco jurídico para el tratamiento de los residuos diseñado para preservar el medio ambiente, poniendo el foco en la importancia del empleo de las mejores técnicas disponibles para la gestión, recuperación y reciclado de residuos, reduciendo así el uso de los recursos naturales. Ello ha derivado en diferentes normativas que obligan a las economías a ser más sostenibles, priorizando la minimización de residuos y, cuando no sea posible, favoreciendo su reutilización y reciclado. En España, todo ello ha sido traspuesto al ordenamiento jurídico a través de la reciente Ley 7 /2022, de 8 de abril, de residuos y suelos contaminados para una economía circular, en la que el papel protagonista recae en los municipios.

La ciudad de Castelló de la Plana es una ciudad mediterránea de tamaño medio que dispone de un sistema completo de gestión de residuos sólidos urbanos y que, como todo sistema, presenta oportunidades de mejora. El objetivo fundamental de esta Tesis Doctoral es, por tanto, la mejora del sistema de gestión de residuos actual partiendo de un análisis detallado de sus principales dimensiones.

Concretamente, se ha analizado la evolución histórica de las principales fracciones de residuos de la ciudad observando cómo los factores externos pueden afectar a su tendencia; se ha estudiado la composición de los biorresiduos recogidos selectivamente para ayudar al dimensionamiento de los servicios de recogida y de nuevas instalaciones de valorización provinciales; se ha propuesto la mejor tecnología de motorización disponible para la renovación de la flota de vehículos recolectores y se ha desarrollado una metodología para priorizar los planes de acción incluidos en el Plan Local de Residuos de la ciudad, a través de un análisis de sus principales indicadores. Estas propuestas de mejora están encaminadas al cumplimiento de los Objetivos de Desarrollo Sostenible fijados para el año 2030 y atienden, por tanto, a demandas de sostenibilidad y circularidad.

En cuanto a la forma de presentación de este trabajo, debe reseñarse que ha sido elaborado mediante el compendio de publicaciones en las que se han evaluado las cuatro dimensiones del sistema citadas anteriormente. Para ello, se han analizado investigaciones anteriores y, utilizando los datos propios del municipio, se han realizado análisis estadísticos y de decisión multicriterio para obtener resultados que facilitan los procesos de toma de decisiones estratégicas, tácticas y operativas que mejorarán la gestión de los residuos sólidos urbanos. De estos análisis, se han extraído importantes

conclusiones que permitirán manejar mejor futuras situaciones extraordinarias (como la reciente crisis sanitaria), realizar acciones encaminadas a la mejora en la separación en origen, mejorar las flotas de vehículos de recogida de residuos y optimizar los recursos municipales mediante la priorización de planes de acción.

Estos resultados pueden suponer una aportación muy útil para los responsables municipales en gestión de residuos ya que, mediante el uso de los métodos aquí definidos, se proporcionan aportaciones teóricas y prácticas para la toma de decisiones, así como para el desarrollo de futuros trabajos de investigación.

RESUM.

L'estratègia de la Unió Europea per a la gestió de residus s'articula a través d'una sèrie de directives que prenen com a punt de partida la Directiva 2008/98/CE. En ella, s'estableix un marc jurídic per al tractament dels residus dissenyat per a preservar el medi ambient, posant el focus en la importància de l'ús de les millors tècniques disponibles per a la gestió, recuperació i reciclatge de residus, reduint així l'ús dels recursos naturals. Això ha derivat en diferents normatives que obliguen les economies a ser més sostenibles, prioritzant la minimització de residus i, quan no siga possible, afavorint la seua reutilització i reciclatge. A Espanya, tot això ha sigut transposat a l'ordenament jurídic a través de la recent Llei 7 /2022, de 8 d'abril, de residus i sòls contaminats per a una economia circular, en la qual el paper protagonista recau en els municipis.

La ciutat de Castelló de la Plana és una ciutat mediterrània de grandària mitjana que disposa d'un sistema complet de gestió de residus sòlids urbans i que, com tot sistema, presenta oportunitats de millora. L'objectiu fonamental d'aquesta Tesi Doctoral és, per tant, la millora del sistema de gestió de residus actual partint d'una anàlisi detallada de les seues principals dimensions.

Concretament, s'ha analitzat l'evolució històrica de les principals fraccions de residus de la ciutat observant com els factors externs poden afectar la seua tendència; s'ha estudiat la composició dels bioresidus recollits selectivament per a ajudar al dimensionament dels serveis de recollida i de noves instal·lacions de valorització provincials; s'ha proposat la millor tecnologia de motorització disponible per a la renovació de la flota de vehicles recol·lectors i s'ha desenvolupat una metodologia per a prioritzar els plans d'acció inclosos en el Pla Local de Residus de la ciutat, a través d'una anàlisi dels seus principals indicadors. Aquestes propostes de millora estan encaminades al compliment dels Objectius de Desenvolupament Sostenible fixats per a l'any 2030 i atenen, per tant, a demandes de sostenibilitat i circularitat.

Quant a la forma de presentació d'aquest treball, ha de ressenyar-se que ha sigut elaborat mitjançant el compendi de publicacions en les quals s'han avaluat les quatre dimensions del sistema citades anteriorment. Per a això, s'han analitzat investigacions anteriors i, utilitzant les dades pròpies del municipi, s'han realitzat anàlisis estadístiques i de decisió multicriteri per a obtindre resultats que faciliten els processos de presa de decisions estratègiques, tàctiques i operatives que milloraran la gestió dels residus sòlids urbans. D'aquestes anàlisis, s'han extret importants conclusions que permetran manejar millor futures situacions extraordinàries (com la recent crisi sanitària), realitzar

accions encaminades a la millora en la separació en origen, millorar les flotes de vehicles de recollida de residus i optimitzar els recursos municipals mitjançant la priorització de plans d'acció.

Aquests resultats poden suposar una aportació molt útil per als responsables municipals en gestió de residus ja que, mitjançant l'ús dels mètodes ací definits, es proporcionen aportacions teòriques i pràctiques per a la presa de decisions, així com per al desenvolupament de futurs treballs de recerca.

ABSTRACT.

The European Union's strategy for waste management is articulated through a series of directives that take Directive 2008/98/EC as a starting point. It establishes a legal framework for waste treatment designed to preserve the environment, focusing on the importance of using the best available techniques for waste management, recovery and recycling, thus reducing the use of natural resources. This has led to different regulations that oblige economies to be more sustainable, prioritizing waste minimization and, when this is not possible, favouring its reuse and recycling. In Spain, all this has been transposed into the legal system through the recent Law 7 /2022, of April 8, on waste and contaminated soils for a circular economy, in which the leading role falls to the municipalities.

The city of Castelló de la Plana is a medium-sized Mediterranean city that has a complete system of solid urban waste management and that, like any system, presents opportunities for improvement. The main objective of this Doctoral Thesis is, therefore, the improvement of the current waste management system based on a detailed analysis of its main dimensions.

Specifically, the historical evolution of the main waste fractions of the city has been analysed, observing how external factors can affect their trend; the composition of bio-waste collected selectively has been studied to help the sizing of collection services and new provincial recovery facilities; the best available motorization technology has been proposed for the renewal of the fleet of collection vehicles and a methodology has been developed to prioritize the action plans included in the Local Waste Plan of the city, through an analysis of its main indicators. These improvement proposals are aimed at meeting the Sustainable Development Goals set for the year 2030 and therefore address sustainability and circularity demands.

With regard to the presentation of this work, it should be noted that it has been prepared by means of a compendium of publications in which the four dimensions of the system mentioned above have been evaluated. For this purpose, previous research has been analysed and, using the municipality's own data, statistical and multi-criteria decision analyses have been carried out to obtain results that facilitate the strategic, tactical and operational decision-making processes that will improve the management of urban solid waste. From these analyses, important conclusions have been drawn that will make it possible to better manage future extraordinary situations (such as the recent health crisis), carry out actions aimed at improving separation at source, improve waste collection vehicle fleets and optimize municipal resources by prioritizing action plans.

These results can be a very useful contribution for municipal waste management managers since, by using the methods defined here, theoretical and practical contributions are provided for decision making, as well as for the development of future research work.

Lista de publicaciones correspondientes a la presente Tesis Doctoral.

I. *Statistical Analysis of the Long-Term Influence of COVID-19 on Waste Generation—A Case Study of Castellón in Spain*.
International Jounal of Enviromental Research and Public Health (MDPI). JCR-Q1 (2021), factor de impacto 2021: 4.614.
https://doi.org/10.3390/ijerph19106071

II. *Caracterización y análisis de la FORSU: Lecciones aprendidas tras un año de implantación de recogida selectiva (Castellón de la Plana).*
26th International Congress on Project Management and Engineering (ICPME 2022). http://dspace.aeipro.com/xmlui/handle/123456789/3227

III. *Sustainable selection of waste collection trucks considering feasible future scenarios by applying the stratified best and worst method*.
Heliyon JCR-Q2 (2021), factor de impacto 2021: 3.776.
https://doi.org/10.1016/j.heliyon.2023.e15481

IV. *Prioritizing action plans to save resources and better achieve municipal solid waste management KPIs: an urban case study*.
Journal of the Air & Waste Management Association. JCR- Q3 (2021), factor de impacto 2021: 2.636.
https://doi.org/10.1080/10962247.2023.2244461

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1. INTRODUCCIÓN.

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1.1. Antecedentes.

En el mundo se generan anualmente más de 2010 millones de toneladas de residuos sólidos urbanos (RSU), de los cuales aproximadamente el 33% no se gestiona de forma adecuada (Kaza et al., 2018). Además, el crecimiento de la población a nivel global, así como los hábitos de consumo, hacen que la generación de residuos continúe en aumento (Sadeghian Sharif et al., 2018). En este sentido, según los datos más recientes, se espera que la generación mundial de residuos alcance los 2.590 millones de toneladas en 2030 y aproximadamente 3.400 millones de toneladas anuales en 2050 (Wang et al., 2020). Este incremento es debido principalmente a la mayor concentración de la población en las áreas urbanas, al desarrollo de la economía y, como se ha mencionado, a las previsiones de aumento de la población mundial. Y es que, pese al principio globalmente aceptado de jerarquía de residuos, donde la prevención de residuos se sitúa en el primer nivel (Cole et al., 2019; Pires & Martinho, 2019), en las ciudades cada vez se ofrecen una mayor cantidad de servicios que conllevan un incremento de los RSU.

Para realizar la comparativa entre continentes, países o regiones, es importante usar un indicador que sea representativo. Para ello suele usarse la generación de RSU que produce una persona cada día, de media, en una determinada área de estudio. Así se puede observar la vinculación entre generación de RSU y las perspectivas económicas, que históricamente guardan una relación directa. Y es que en la actualidad se pueden encontrar claras diferencias entre continentes como, por ejemplo, Norte América (2,22 kg/persona/día), Europa (1,24 kg/persona/día) o África Subsahariana (0,47 kg/persona/día) (Worldbank, 2022). En ese mismo informe, se observa que los países con rentas per cápita más altas producen el 34% del total mundial de residuos, mientras que tan sólo representan el 16% de la población mundial.

Acercando el foco, en España los últimos datos que se pueden obtener del Instituto Nacional de Estadística (INE, 2021) son los correspondientes al año 2020, dónde la generación total de RSU superó los 22,4 millones de toneladas (1,33 kg/persona/día), de las cuales algo más de 2,4 millones se generaron en la Comunidad Valenciana (1,34 kg/persona/día), como se observa en la Tabla 1.1.

Tabla 1.1. Cantidad y tipología de residuos urbanos recogidos en 2020.

Tipo de residuo	España (t)	C. Valenciana (t)
Residuos domésticos y similares (domésticos y vías públicas)	16.452.778	1.949.731
Residuos domésticos voluminosos mezclados (enseres)	874.794	70.056
Residuos metálicos	46.296	3.778
Residuos de vidrio	828.865	83.548
Residuos de papel y cartón	1.340.017	80.324
Residuos de plásticos	14.254	555
Residuos de madera	149.713	16.319
Residuos textiles	39.972	5.903
RAEE´s	99.486	1.793
Residuos de pilas y acumuladores	2.197	68
Residuos animales y vegetales	1.253.212	129.776
Envases mixtos y embalajes mezclados	887.731	70.535
Residuos minerales (incluye RCD´s)	420.979	22.142
Otros	1.350	49
Total residuos mezclados	17.327.572	2.019.787
Total Residuos recogida separada	5.084.072	414.790
Total	22.411.644	2.434.577

A nivel local, en la ciudad de Castelló de la Plana, se generan anualmente en torno a 79.000 toneladas de RSU (1,25 kg/persona/día), de los cuales el 27,15% son recogidas de manera selectiva (Ajuntament de Castelló, 2022); siendo, por tanto, los residuos mezclados aún mayoritarios, pese a los esfuerzos realizados en los últimos años por parte de las administraciones públicas.

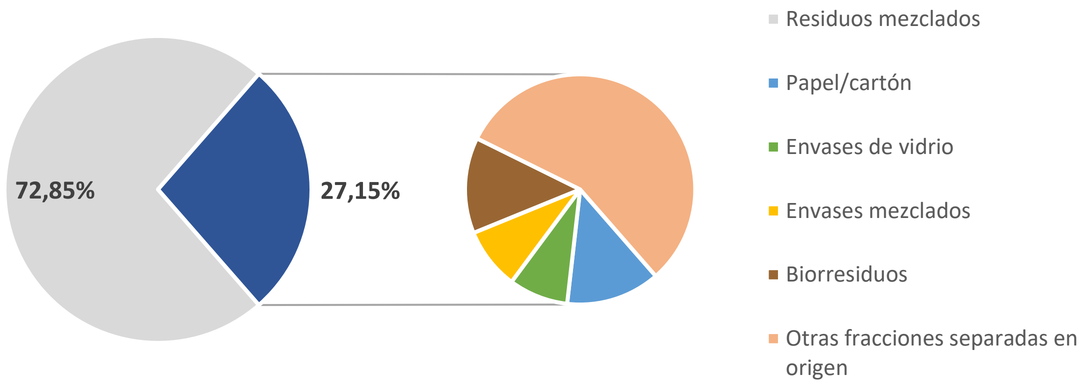

Figura 1.1. Porcentaje de separación en origen en Castelló en el año 2022 (total residuos municipales).

En cuanto a su evolución, en la Tabla 1.2 se muestran los datos históricos recogidos desde el año 2017 hasta la actualidad.

Tabla 1.2. Evolución de la generación de RSU en Castelló de la Plana.

Año	Generación RSU (t)
2017	73.040
2018	76.810
2019	78.226
2020	72.940
2021	78.773
2022	78.430

Como se puede observar, se aprecia una tendencia al alza de la cantidad de residuos generados hasta el año 2019. La crisis sanitaria acaecida en el año 2020 fue, sin duda, determinante en el cambio de tendencia (Cai et al., 2021). Ante la rápida expansión del virus SARS-CoV-2, el 14 de marzo el Gobierno de España decretó el estado de alarma en todo el territorio nacional. Esto supuso limitaciones en la libre circulación de los ciudadanos, que tuvieron su mayor exponente a partir del 28 de marzo, cuando se suspendió toda actividad laboral presencial no esencial.

Así pues, durante el periodo de confinamiento estuvieron clausurados todos los establecimientos no esenciales, como bares y cafeterías, restaurantes, hoteles, negocios comerciales y minoristas, pero siguió funcionando el comercio on-line y servicios a domicilio de hostelería y restauración. A partir de abril comenzó el plan de desescalada asimétrica por provincias, durante el cual se permitió la apertura gradual de establecimientos con limitaciones en los aforos. En junio expiró el estado de alarma y España entró en la conocida como “nueva normalidad”, en la que se mantuvo con carácter general el aforo del 75% en todos los espacios tanto al aire libre como cerrados. Tras un nuevo repunte en los casos, en octubre el Gobierno de España decretó el segundo estado de alarma que estableció un toque de queda entre las 24h00 y las 6h00, la prohibición de salir de la comunidad autónoma de residencia y la limitación de los grupos en lugares de uso público a seis personas no convivientes.

Como consecuencia de ello, en el año 2020 se produce una disminución del total de residuos de la ciudad de Castelló de la Plana. Una vez las restricciones se fueron relajando y la economía y el libre movimiento de la población se recuperó, en el año 2021 se obtuvo una cantidad de residuos muy similar a la recogida en 2019. En 2022, último año en el que hay datos de recogida de RSU completos, se ha generado una cantidad total similar al año anterior. Estos datos motivaron un análisis más exhaustivo de lo ocurrido a través de los pesajes diarios disponibles de cada fracción.

Como se ha mencionado con anterioridad, según la jerarquía de residuos, justo después de las estrategias para minimizar la generación de residuos, están las que tienen que ver con la reutilización y preparación para el reciclado. De este modo, en los últimos años se está poniendo el foco en mejorar los sistemas de recuperación y reciclaje de los RSU para su uso como materias primas en diferentes procesos, contribuyendo así al desarrollo de la economía circular (Das et al., 2021) y al cumplimiento de los Objetivos de Desarrollo Sostenible (ODS), en particular al número 12 (Producción y Consumo responsables) que tiene entre sus metas *"reducir la generación de RM mediante prevención, reducción, reciclado y reutilización".* No obstante, la jerarquía de residuos debe entenderse como una estrategia transversal para abordar varios ODS y fomentar un desarrollo más sostenible.

En esta línea, la separación en origen resulta fundamental para alcanzar los objetivos fijados por la Unión Europea, y que han sido traspuestos al ordenamiento jurídico español a través de la reciente Ley 7/2022, de 8 de abril, de residuos y suelos contaminados para una economía circular. En ella, se establece como meta para el año 2025 que un mínimo del 55% en peso de los RSU se debe destinar a la preparación para la reutilización o al reciclado, mediante la implantación de servicios de recogida separada de residuos de, al menos, las fracciones de papel, metales, plástico, vidrio, biorresiduos, textiles, aceites de cocina, residuos domésticos peligrosos y voluminosos.

Anteriormente, en la Comunidad Valenciana, el Decreto 81/2013, de 21 de junio, del Consell, de aprobación definitiva del Plan Integral de Residuos de la Comunitat Valenciana (PIRCV) estableció las líneas maestras en la gestión de residuos a nivel autonómico. Además, a través de los Planes Zonales se adaptaron sus contenidos a cada zona concreta, garantizando una adecuada dirección de la gestión de residuos en toda la Comunidad Valenciana.

Así, el Plan Zonal de Residuos de las Zonas II, IV y V aprobado mediante la Orden de 2 de diciembre de 2004, estableció que los municipios pertenecientes a dicho Plan Zonal (entre ellos Castelló de la Plana) debían integrarse en una entidad supramunicipal (Consorcio o Mancomunidad) que asumiera la responsabilidad de la valorización y eliminación de todos los residuos urbanos o municipales aportados por los municipios integrantes. Por ello, en diciembre de 2005 se constituyó el Consorcio de Residuos C2 que encomendó la gestión de las previsiones del Plan Zonal a la mercantil Reciclados de Residuos La Plana S.A, quedando, por tanto, como competencia exclusiva de los Ayuntamientos la recogida y transporte de residuos hasta sus instalaciones y en consecuencia, siendo responsables de una adecuada separación en origen.

En la ciudad de Castelló de la Plana, en cuanto a la recogida domiciliaria de RSU, la fracción resto es la mayoritaria, con un 72,85% en peso del total municipal. Esta fracción dispone de un servicio de recogida en carga trasera y carga lateral estructurado en 14 rutas de frecuencia diaria. Pero, además, actualmente la ciudad de Castelló de la Plana cuenta con servicios de recogida domiciliaria separada para todas las fracciones citadas anteriormente, exceptuando los residuos peligrosos, que se gestionan a través de los puntos limpios. La gestión de estas fracciones en la ciudad de Castelló de la Plana se resume como sigue:

- Vidrio. Es la primera fracción a la que se dotó de contenedor específico y actualmente su gestión está financiada por los envasadores a través del SCRAP Ecovidrio. La recogida, dependiendo de la opción elegida por el municipio, puede realizarse a través de Ecovidrio o mediante gestión directa municipal, recibiendo las compensaciones por tonelada establecidas en los convenios sectoriales. Los contenedores presentan un bajo porcentaje de impropios, lo que permite que prácticamente su 100% se utilice para fabricar de nuevo vidrio, con un rendimiento cercano al 97%. Actualmente este servicio se presta de forma directa por parte de Ecovidrio en la ciudad de Castelló de la Plana con una frecuencia de recogida quincenal.
- Envases ligeros (metales, plásticos, etc.) y papel/cartón. Igual que ocurre con el vidrio, su recogida selectiva está financiada en parte por los envasadores a través del SCRAP Ecoembes. La gestión suele ser directa por parte del municipio, recibiendo compensaciones del SCRAP por tonelada recogida y por contenedor instalado. Son fracciones que están en constante aumento, especialmente los envases ligeros, y que están obligando a los municipios a reforzar sus frecuencias de recogida. Para la recogida selectiva de papel y cartón, que representa el 3,59% en peso del total, el servicio cuenta con tres equipos de recogida de carga superior y uno de carga lateral, como sucede con la recogida selectiva de envases ligeros, que aporta el 2,36% en peso de residuos del total municipal. Ambas fracciones se entregan para su posterior tratamiento a gestores que realizan una clasificación previa del material para su posterior valorización.
- Textil y calzado. Desde hace más de diez años, en Castelló de la Plana existen contenedores específicos en vía pública que son recogidos por entidades con algún fin social, con una frecuencia de recogida semanal. Estos servicios no generan costes al Ayuntamiento, siendo el residuo la única contraprestación que percibe el adjudicatario. Según la Ley 7/2022, de 8 de abril, de residuos y suelos

contaminados para una economía circular, junto con el aceite vegetal, todos municipios deben realizar obligatoriamente la recogida separada de esta fracción antes del 31 de diciembre de 2024.

- Aceite vegetal usado. En la ciudad existen contenedores específicos en vía pública para su recogida (un total de 24 unidades), pero este residuo también puede ser depositado en los puntos limpios fijos o móviles con los que cuenta el servicio. Es una fracción en auge debido, por un lado, a su poder contaminante cuando llega a cursos de agua, pero también a los problemas de obstrucción de desagües que genera en los domicilios.
- Residuos domésticos peligrosos. Estos residuos se gestionan a través de los puntos limpios de la ciudad. Actualmente el servicio dispone de tres puntos limpios móviles y uno fijo para la recogida de residuos peligrosos, voluminosos, residuos de aparatos eléctricos y electrónicos (RAEE´s) o residuos de la construcción y demolición (RCD´s). Mención especial, merece la gestión de las pilas y baterías debido a la alta capacidad contaminante que poseen por la presencia de metales pesados. Dichos metales, a su vez, hacen que sea económicamente rentable su reciclado, por lo que pueden encontrarse puntos para recoger este tipo de residuo en el mobiliario urbano, supermercados, edificios públicos, etc.
- Enseres voluminosos. Estos residuos deben depositarse en el punto limpio fijo, pero debido a que no todos los ciudadanos pueden realizar este desplazamiento, la mayoría de los Ayuntamientos ofrecen un servicio puerta a puerta de recogida con preaviso. A pesar de ello, con frecuencia se suele observar el abandono de este tipo de residuos generalmente junto a los contenedores de residuos mezclados, sin notificación previa. Estas actitudes provocan que sea necesario reforzar los servicios encareciendo la gestión integral de RSU.
- Biorresiduos. Ha sido la última fracción implantada en la ciudad de Castelló de la Plana. Actualmente, la recogida de biorresiduos se realiza mediante tres camiones recolectores de carga lateral que realizan seis rutas de recogida con frecuencia alterna. Para ello, se han instalado en la vía pública 1.098 contenedores de color marrón de 2.000 litros de capacidad (12,72 l/hab). Los contenedores recogen los residuos domiciliarios, pero también los de los establecimientos de hostelería como hoteles, restaurantes, comercios, además de colegios o establecimientos de comida para llevar. Actualmente, esta fracción aporta el 3,66% del peso total municipal.

Aunque la composición de los residuos varía mucho dependiendo de la localidad (Nanda & Berruti, 2021), está globalmente aceptado que los biorresiduos son el principal componente de los RSU con cerca de un 40% en peso (Chen et al., 2020). Por ello, en la Unión Europea la normativa sobre el tratamiento de biorresiduos obliga a realizar un esfuerzo a las entidades locales para la recogida, separación y posterior tratamiento, generalmente compostaje (Slavík et al., 2019), ya que cuando estos residuos se compostan, la composición de las materias primas iniciales es fundamental para obtener un compost de calidad (Huerta-Pujol et al., 2011; Moretti et al., 2020).

Por ello, la presencia de residuos impropios mezclados con los biorresiduos recogidos dificulta su utilización posterior como fertilizante (Malamis et al., 2017; Sharifi & Renella, 2015). Este hecho motivó que durante el primer año de su implantación se incidiera en conocer la composición de los biorresiduos recogidos selectivamente, a través de caracterizaciones macroscópicas que fueron objeto de un posterior análisis.

La recogida de esta materia orgánica tradicionalmente se ha realizado por parte de algunos agricultores para aprovechar el residuo como fertilizante. Poco a poco, la complejidad y cantidad de los residuos provocó una evolución hacía vehículos motorizados dotados de cajas cerradas para maximizar la carga y evitar las perdidas, reduciendo también la presencia de olores.

El crecimiento demográfico en las ciudades ha ido provocando un rápido aumento en la generación de residuos, por lo que las administraciones públicas tuvieron que desarrollar sistemas más complejos de recogida y tratamiento de los RSU. Además, el desarrollo de los productos alimentarios ha llevado asociado un mayor uso de materiales plásticos, metálicos y de vidrio lo que ha generado que la composición de la “bolsa de basura tipo” cambiara, pasando de un elevado porcentaje de materiales compostables, o fácilmente biodegradables, a unos porcentajes cada vez más importantes de restos inorgánicos. Debido a que estos últimos necesitan muchos años para su completa degradación, así como a las dificultades para su segregación en las plantas de tratamiento, se observó la importancia de separarlos en origen.

En España la primera fracción que se recogió de forma selectiva fue el vidrio en 1982, mientras la recogida selectiva de los materiales plásticos, metálicos y bricks, además del papel/cartón tuvo que esperar a finales del siglo XX. De esta forma, gradualmente, las ciudades se han ido aprovisionando de flotas de vehículos recolectores destinados a la recogida de cada una de las fracciones contenerizadas de los RSU. Para aumentar su capacidad de carga se les dota de un sistema de compactación que permite maximizar la carga hasta las plantas de transferencia o tratamiento. El resultado, son vehículos de grandes dimensiones con un consumo de combustible muy elevado debido a los ciclos cortos de paro/arranque, así como a la utilización de sus prensas hidráulicas para la compactación.

Respecto a la forma de recogida, existen diferentes sistemas siendo los más utilizados los siguientes:

- Carga superior: Es el sistema más empleado para la recogida de vidrio. Se trata de camiones dotados con una pluma en los que, de forma general, mediante un sistema de doble gancho, uno permite la elevación del contenedor con la grúa y el otro acciona su mecanismo de apertura. El tamaño estándar de estos contenedores es de 3 m^3.
- Carga trasera: Son los más utilizados, especialmente en zonas de accesibilidad reducida. Constan de un conductor y dos operarios que se encargan de llevar el contenedor hasta la parte trasera del vehículo. Los contenedores disponen de ruedas y suelen tener un volumen reducido (en torno a 1 m^3) para facilitar su manejo.
- Carga lateral: Se trata de camiones robotizados que ofrecen la ventaja de ser más eficientes, al necesitar tan solo un operario que se encarga de conducir el camión y de manejar el robot que vacía los contenedores. Con este sistema, los contenedores pueden tener un volumen mayor que generalmente oscila entre los 2 y los 3,5 m^3.

En cuanto a la motorización de estos vehículos, tradicionalmente se han empleado vehículos diésel ya que presentaban un menor consumo. Pero las últimas innovaciones tienden a sistemas más respetuosos con el medio ambiente y que a su vez sean más silenciosos, como el gas natural comprimido (GNC) (Hagos & Ahlgren, 2018), los motores híbridos, o los eléctricos. Según las guías de gestión de residuos de alguna comunidad autónoma (ARC, 2023), el tipo de motorización de los vehículos de recogida de residuos tiene una gran influencia en las emisiones de gases de efecto invernadero que se emiten en las ciudades. A continuación, en la Tabla 1.3 se muestra la estimación realizada por la Agencia Catalana de Residuos de los factores de emisión de cada vehículo empleado para la recogida de RSU, según su tipología.

Tabla 1.3. Factores de emisión vehículos recolectores RSU. Fuente: Agencia Catalana de residuos.

Combustible	Unidades	Factor de emisión (kg CO_2 eq/unidad)
Diésel	litros	2,503
Gasolina 95	litros	2,196
Gasolina 98	litros	2,196
Híbrido diésel	litros	2,503
Híbrido gasolina	litros	2,196
Biodiésel	litros	2,616
Bioetanol	litros	2,295
Gas natural comprimido (GNC)	kg	2,67
Gas licuado del petróleo (GLP)	litros	1,52
Energía eléctrica convencional	kWh	0,308
Energía eléctrica origen 100% renovable	kWh	0

Además, aunque el sistema de recogida más extendido para la recogida de residuos en las ciudades es el contenedor en la vía pública, en el ámbito autonómico, el PIRCV en su actualización aprobada por el Decreto 55/2019, de 5 de abril, establece la obligación de que los municipios con más de 50.000 habitantes censados dispongan de una recogida puerta a puerta o equivalente, de al menos las fracciones de biorresiduos y envases ligeros. Sin embargo, la Ley 5/2022, de 29 de noviembre, de la Generalitat Valenciana, modifica los criterios de esta exigencia, que pasa a ser obligatoria para todos aquellos municipios que presenten una recogida separada de las fracciones papel, metales, plástico, vidrio y biorresiduos inferior en un 90% a la media de separación en origen de los municipios de la Comunidad Valenciana de su misma tipología.

Así, las ratios actuales de la ciudad de Castelló de la Plana obligan a considerar la implantación de este sistema de recogida, en el que las experiencias desarrolladas en otras ciudades cuantifican la separación en origen entre el 60% y el 80% (Ragazzi et al., 2017). En la práctica, con este sistema cada vivienda dispondrá de los materiales necesarios para separar los residuos en su hogar, además de cubos para sacarlos a la puerta del domicilio conforme a un calendario establecido. De esta forma, cada día se recogerían una o dos fracciones, intercalando las recogidas para dar servicio a lo largo de toda la semana. En estos sistemas también suele existir medios de identificación del productor, ya sea con códigos, pegatinas, RFID, etc. Las ventajas residen en que, al existir una identificación del usuario, se produce una mayor implicación, ya que si se aporta un residuo fuera del calendario establecido, no es recogido y genera una incidencia. Gracias a esto, los porcentajes de separación de residuos están por encima de los que se pueden obtener con otros sistemas de recogida. Otra de sus ventajas reside en la eliminación casi total de los contenedores en la vía pública y, como consecuencia de ello, la disminución de la cantidad de enseres voluminosos que suele aparecer junto a ellos. Por el contrario, es un sistema donde los costes son mayores debido a la mano de obra necesaria y al elevado número de vehículos que se precisan para completar las rutas.

En cualquiera de las modalidades expuestas anteriormente (recogida contenerizada o puerta a puerta), es evidente que el aumento de las rutas va a ser una constante en los próximos años, por ello la elección de los vehículos a emplear es fundamental ya que sus elevados costes de adquisición junto con sus características, determinarán el éxito del servicio de recogida de RSU (Erdem, 2022).

En el caso del Ayuntamiento de Castelló de la Plana a lo largo del año 2022 se destinó a la recogida, gestión y tratamiento de residuos de la ciudad un total de 16.827.585,06€, lo que supone aproximadamente un 9% del presupuesto municipal, siendo como en otras ciudades la mayor partida presupuestaria (Sanjeevi & Shahabudeen, 2016). De esta manera, el gasto por habitante para el 2022 se sitúa cerca de los cien euros.

En esta línea, Ley 7/2022, de 8 de abril, de residuos y suelos contaminados para una economía circular, obliga a que todos estos gastos se sufraguen a través de una tasa que refleje los costes reales del servicio de recogida, transporte y tratamiento de los RSU. Muchos de los municipios ya disponen de una tasa o impuesto por la gestión de los RSU, y la única forma de que la ciudadanía no vea aumentado este impuesto es minimizar las cantidades que acaban siendo depositadas en vertedero. El motivo es que, esta Ley obliga a un nuevo impuesto de 30 euros por cada tonelada de residuos que acaben en vertedero (Spain, 2022). Si se tiene en cuenta, que el rechazo actual de las instalaciones del Consorcio C2, ronda el 75% (Reciplasa, 2023) se puede estimar que el incremento de costes para el Ayuntamiento de Castelló de la Plana rondará los 1,2 millones de euros al año.

Todo ello obliga a las administraciones locales a ser más eficientes en el manejo de sus recursos con el objetivo de gestionar de la mejor forma posible sus sistemas de gestión de residuos y, en consecuencia, dotarse de una planificación estratégica. La necesidad de desarrollar Planes Locales de Residuos (PLR) tiene su origen en la Directiva 2008/98/CE del Parlamento Europeo y del Consejo de 19 de noviembre de 2008 sobre los residuos. En dicha Directiva se establece que los Estados Miembros desarrollarán uno o varios planes de gestión de residuos que cubran todo su territorio geográfico y que representen un análisis detallado y actualizado de la situación de la gestión de residuos, así como de las medidas que se adoptarán con el fin de incrementar la preparación para la reutilización, el reciclado, la valorización y la eliminación de los residuos de forma respetuosa con el medio ambiente.

A nivel nacional y atendiendo a las disposiciones que aparecen en la Directiva, se aprobó la antigua Ley 22/2011, de 28 de julio, de residuos y suelos contaminados en la que en su artículo 14 establece la creación de un Plan Estatal Marco pero que, a su vez, las Comunidades Autónomas y las Entidades Locales deberán redactar programas de gestión de residuos en el ámbito de sus competencias. Este hecho se ratifica en la nueva Ley 7/2022, de 8 de abril, de residuos y suelos contaminados para una economía circular, para que las Comunidades Autónomas y Entidades Locales puedan proseguir con la elaboración de Planes y Programas de residuos.

En la Comunidad Valenciana, la revisión del PIRCV obliga a todos los municipios a disponer de Planes Locales de Residuos (PLR), de una u otra forma dependiendo de su tamaño. Estos planes, a su vez, deben establecer un sistema de indicadores cuantitativos y cualitativos que permitan evaluar el grado de desarrollo del Plan Local y el cumplimiento de los objetivos (De Pascale et al., 2021).

En este sentido, el Plan Local de Residuos de la ciudad de Castelló de la Plana (PLR) se aprobó por el Excmo. Ayuntamiento en pleno en sesión ordinaria el 31 de marzo de 2022, según la Ley 7/1985, de 2 de abril, Reguladora de las Bases de Régimen Local.

El PLR de Castelló de la Plana tiene por objeto establecer las disposiciones pertinentes y proponer la ordenación material y territorial de la gestión de residuos de competencia municipal para dar cumplimiento a las previsiones contenidas en el vigente PIRCV y en el Plan Estatal Marco de Gestión de Residuos. No debe olvidarse que las competencias municipales se refieren exclusivamente a la recogida y transporte de residuos y no al tratamiento, valorización y eliminación; operaciones que son asumidas en el ámbito de la Comunidad Valenciana por un órgano supramunicipal, en este caso el Consorcio de Residuos C2.

En el PLR se establecen una serie de objetivos y de planes de acción que se agrupan en cuatro ejes estratégicos. Sin embargo, el desarrollo de estos planes no ha seguido una metodología que priorice por dónde empezar a acometerlos, y se limita a un reparto económico más o menos proporcional entre las anualidades desde 2022 hasta 2026, para facilitar su aplicabilidad con la menor afección posible a las cuentas municipales. Ello hace necesario un análisis para tratar de alcanzar los objetivos del PLR de una manera más eficiente.

En resumen, como se ha evidenciado a lo largo del presente apartado, existen diferentes dimensiones dentro de los sistemas de gestión de residuos que deben ser analizadas para mejorar su eficiencia desde un punto de vista sostenible y circular. Asimismo, se ha puesto de manifiesto que, dentro de la gestión local de los RSU, las competencias directas no incluyen el tratamiento y la eliminación, por lo que los esfuerzos deben centrarse en la recogida y transporte.

1.2. Marco normativo.

En el campo de la gestión de RSU la normativa comunitaria, estatal y autonómica es muy extensa. A modo de resumen, a continuación, se presenta un listado con la normativa más relevante de los últimos años en esta materia, según su origen:

Normativa Europea.

- Directiva 94/62/CE, del Parlamento Europeo y del Consejo, de 20 de diciembre de 1994, relativa a los envases y residuos de envases. Revisión vigente desde 4 de Julio de 2018.
- Directiva 99/31/CE del Consejo, de 26 de abril de 1999, relativa al vertido de residuos sólidos urbanos. Revisión vigente desde 4 de Julio de 2018.
- Directiva 2004/12/CE del Parlamento Europeo y del Consejo, de 11 de febrero de 2004, por la que se modifica la Directiva 94/62/CE, del Parlamento Europeo y del Consejo, de 20 de diciembre de 1994, relativa a los envases y residuos de envases.
- Directiva 2005/20/CE del Parlamento Europeo y del Consejo de 9 de marzo de 2005, por la que se modifica la Directiva 94/62/CE, del Parlamento Europeo y del Consejo, de 20 de diciembre de 1994, relativa a los envases y residuos de envases.
- Directiva 2006/66/CE del Parlamento Europeo y del Consejo de 6 de septiembre de 2006, relativa a las pilas y acumuladores y a los residuos de pilas y acumuladores y por la que se deroga la Directiva 91/157/CEE. Revisión vigente desde 4 de Julio de 2018.
- Directiva 2008/12/CE del Parlamento Europeo y del Consejo de 11 de marzo de 2008, por la que se modifica la Directiva 2006/66/CE del Parlamento Europeo y del Consejo de 6 de septiembre de 2006, relativa a las pilas y acumuladores y a los residuos de pilas y acumuladores.
- Directiva 2008/35/CE del Parlamento Europeo y del Consejo de 11 de marzo de 2008, por la que se modifica la Directiva 2002/95/CE sobre restricciones a la

utilización de determinadas sustancias peligrosas en aparatos eléctricos y electrónicos.

- Directiva 2008/98/CE del Parlamento Europeo y del Consejo, de 19 de noviembre de 2008, sobre los residuos y por la que se derogan determinadas directivas.
- Directiva 2008/103/CE del Parlamento Europeo y del Consejo, de 19 de noviembre de 2008, por la que se modifica la Directiva 2006/66/CE del Parlamento Europeo y del Consejo de 6 de septiembre de 2006, relativa a las pilas y acumuladores y a los residuos de pilas y acumuladores.
- Directiva 2009/1/CE, de la Comisión del 7 de enero de 2009, por la que se modifica para su adaptación al progreso técnico la Directiva 2005/64/CE del Parlamento Europeo y del Consejo, relativa a la homologación de tipo de los vehículos de motor en lo que concierne a su aptitud para la reutilización, el reciclado y la valoración.
- Directiva 2010/75/UE del Parlamento Europeo y del Consejo, de 24 de noviembre de 2010, sobre las emisiones industriales (prevención y control integrados de la contaminación).
- Directiva 2011/65/UE del Parlamento Europeo y del Consejo, de 8 de junio de 2011, sobre restricciones a la utilización de determinadas sustancias peligrosas en aparatos eléctricos y electrónicos.
- Directiva 2012/19/UE del Parlamento y del Consejo de 4 de julio de 2012, sobre residuos de aparatos eléctricos y electrónicos. Revisión vigente desde 4/7/2018.
- Directiva 2013/2/UE de la Comisión de 7 de febrero de 2013, por la que se modifica el Anexo I de la Directiva 94/62/CE del Parlamento Europeo y del Consejo relativa a los envases y residuos de envases.
- Directiva 2013/56/UE del Parlamento y del Consejo de 20 de noviembre de 2013, por la que se modifica la Directiva 2006/66/CE del Parlamento Europeo y del Consejo de 6 de septiembre de 2006, relativa a las pilas y acumuladores y a los residuos de pilas y acumuladores.
- Directiva 2018/849/UE del Parlamento Europeo y del Consejo de 30 de mayo de 2018 por la que se modifica la Directiva 2000/53/CE, la Directiva 2006/66/CE y la Directiva 2012/19/UE.
- Directiva 2018/850/UE del Parlamento Europeo y del Consejo de 30 de mayo de 2018, por la que se modifica la Directiva 1999/31/CE relativa al vertido de residuos.

- Directiva 2018/851/UE del Parlamento Europeo y del Consejo de 30 de mayo de 2018, por la que se modifica la Directiva 2008/98/CE sobre residuos.
- Directiva 2018/852/UE del Parlamento Europeo y del Consejo de 30 de mayo de 2018, por la que se modifica la Directiva 94/92/CE relativa a los envases y residuos de envases.
- Reglamento (UE) n° 849/2010 de la Comisión, de 27 de septiembre de 2010, por el que se modifica el Reglamento (CE) n° 2150/2002 del Parlamento Europeo y del Consejo, relativo a las estadísticas sobre residuos.
- Reglamento (UE) Nº 493/2012 de la comisión de 11 de junio de 2012 por el que se establecen, de conformidad con la Directiva 2006/66/CE del Parlamento Europeo y del Consejo, normas detalladas para el cálculo de los niveles de eficiencia de los procesos de reciclado de los residuos de pilas y acumuladores.
- Decisión 2001/118/CE de la Comisión de 16 de enero de 2001, por la que se modifica la Decisión 2000/532/CE en lo que se refiere a la lista de residuos.
- Decisión 2001/119/CE de la Comisión de 22 de enero de 2001, que modifica la Decisión 2000/532/CEE.
- Decisión 2003/33/CE del Consejo de 19 de diciembre de 2002, por el que se establecen los criterios y procedimiento de admisión de residuos en los vertederos de acuerdo con el artículo 16 y el Anexo II de la Directiva 1999/31/CEE.
- Decisión 2014/955/UE de la Comisión de 18 de diciembre de 2014, por el que se modifica la Decisión 2000/532/CEE, sobre la lista de residuos, de conformidad con la Directiva 2008/98/CE.

Legislación española.

- Ley 11/2012, de 19 de diciembre, de medidas urgentes en materia de medio ambiente.
- Ley 5/2013, de 11 de junio, por la que se modifican la Ley 16/2002 de 1 de julio, de prevención y control integrados de la contaminación, y la Ley 22/2011, de 28 de julio, de residuos y suelos contaminados.
- Ley 7/2022, de 8 de abril, de residuos y suelos contaminados para una economía circular.
- Real Decreto 1619/2005, de 30 de diciembre, sobre la gestión de neumáticos fuera de uso.
- Real Decreto 252/2006, de 3 de marzo, por el que se revisan los objetivos de reciclado y valorización establecidos en la Ley 11/1997, de 24 de abril, de

Envases y Residuos de Envases y por el que se modifica el Reglamento para su ejecución aprobado por Real Decreto 782/1998, de 30 de abril.

- Real Decreto 105/2008, de 1 de febrero, por el que se regula la producción y gestión de los residuos de construcción y demolición.
- Real Decreto 106/2008, de 1 de febrero, sobre pilas y acumuladores y la gestión ambiental de sus residuos.
- Real Decreto 943/2010, de 23 de julio, por el que se modifica el Real Decreto 106/2008, de 1 de febrero, sobre pilas y acumuladores y la gestión ambiental sobre sus residuos.
- Real Decreto 1436/2010, de 5 de noviembre, por el que se modifican diversos reales decretos para su adaptación a la Directiva 2008/112/CE, del Parlamento Europeo y del Consejo, que modifica varias directivas para adaptarlas al Reglamento (CEE) n.º 1272/2008, sobre clasificación, etiquetado y envasado de sustancias y mezclas.
- Real Decreto 110/2015, de 20 de febrero, sobre residuos de aparatos eléctricos y electrónicos.
- Real Decreto 710/2015, de 24 de julio, por el que se modifica el Real Decreto 106/2008, de 1 de febrero sobre pilas y acumuladores y la gestión ambiental de sus residuos.
- Real Decreto 553/2020, de 2 de junio, por el que se regula el traslado de residuos en el interior del territorio del Estado.
- Real Decreto 646/2020, de 7 de julio, por el que se regula la eliminación de residuos en vertedero.
- Real Decreto 27/2021, de 19 de enero, por el que se modifican el Real Decreto 106/2008, de 1 de febrero, sobre pilas y acumuladores y la gestión ambiental de sus residuos, y el Real Decreto 110/2015, de 20 de febrero, sobre residuos de aparatos eléctricos y electrónicos.
- Real Decreto 1055/2022, de 27 de diciembre, de envases y residuos de envases.
- Orden AAA/1783/2013, de 1 de octubre, por la que se modifica el Anejo I del Reglamento para el desarrollo y ejecución de la Ley 11/1997, de 24 de abril de Envases y Residuos de Envases aprobado por Real Decreto 782/1998, de 30 de abril.
- Orden AAA/699/2016 de 9 de mayo por la que se modifica la operación R1 del Anexo II de la Ley 22/2011, de 28 de julio de residuos y suelos contaminados.

- RESOLUCIÓN de 20 de enero de 2009, de la Secretaría de Estado de Cambio Climático, por la que se publica el Acuerdo del Consejo de ministros por el que se aprueba el Plan Nacional Integrado de Residuos para el período 2008-2015.
- Resolución de 16 noviembre de 2015, de la Dirección General de la Calidad Ambiental y Evaluación Ambiental y Medio Natural, por la que se publica el Acuerdo del Consejo de ministros de 6 de noviembre de 2015, por el que se aprueba el Plan Estatal Marco de Gestión de Residuos (PEMAR) 2016-2022.

Normativa de la Comunidad Valenciana.

- Ley 5/2022, de 29 de noviembre, de la Generalitat, de residuos y suelos contaminados para el fomento de la economía circular en la Comunitat Valenciana
- Decreto 240/1994, de 22 de noviembre, del Gobierno Valenciano, por el que se aprueba el Reglamento Regulador de la Gestión de Residuos Sanitarios.
- Decreto 218/1996, de 26 de noviembre, del Gobierno Valenciano, por el que se designa en el ámbito de la CV el organismo competente para efectuar las funciones a que se refiere el Reglamento CEE 259/93, de 1 de febrero relativo a la vigilancia y control de los traslados de residuos en el interior, a la entrada y a la salida de la Comunidad Europea.
- Decreto 81/2013, de 21 de junio, del Consell, de aprobación definitiva del Plan Integral de Residuos de la Comunitat Valenciana. Modificado por Decreto 55/2019, de 5 de abril, del Consell, por el que se aprueba la Revisión del Plan Integral de Residuos de la Comunitat Valenciana.
- Decreto 22/2015, de 13 de febrero, del Consell, por el que se regulan las funciones y el Registro de Entidades Colaboradoras en materia de calidad ambiental de la Comunitat Valenciana.
- Decreto-Ley 4/2016, de 10 de junio, del Consell, por el que se establecen las medidas urgentes para garantizar la gestión de residuos municipales.
- Decreto 55/2019, de 5 de abril, del Consell, por el que se aprueba la Revisión del Plan Integral de Residuos de la Comunitat Valenciana.
- Decreto Ley 13/2020, de 7 de agosto, del Consell, de declaración de servicio público de titularidad autonómica de las operaciones de selección y clasificación de envases ligeros y residuos de envases recogidos selectivamente.

1.3. Cuestión a investigar.

De lo expuesto hasta aquí se evidencia que el análisis de los factores que puedan provocar una **variación en la generación** de RSU **(I)** de una población resulta fundamental para llevar a cabo una gestión adecuada de los mismos. Sin una interpretación clara de los datos de generación será más difícil establecer políticas y estrategias efectivas para su posterior gestión, pudiendo derivar en un mayor impacto medioambiental, social y económico. Además, el análisis y la difusión de los datos de generación de residuos puede ayudar a concienciar a la población sobre la importancia de adoptar hábitos más sostenibles, promoviendo la participación activa de la ciudadanía. En consecuencia, los datos sobre generación de RSU son vitales para la planificación urbana y la toma de decisiones a nivel local, ayudando al diseño de sistemas de recogida más eficientes y, por tanto, mejorando la sostenibilidad. En esta Tesis Doctoral se evaluará el impacto que, a largo plazo, más allá de los periodos de confinamiento, ha generado la pandemia generada por SARS-CoV-2 y la enfermedad denominada COVID-19 en la generación de las distintas fracciones de residuos recogidas en la ciudad de Castellón.

Respecto al estudio de la **composición** de los RSU **(II)**, dicha información proporciona una visión detallada sobre el buen uso de los sistemas elegidos, así como para el dimensionamiento de futuros servicios. La información sobre la composición de los RSU permite además diseñar planes y programas de gestión que se ajusten a las necesidades específicas de la ciudad y evaluar si la separación en origen se está realizando adecuadamente. Así, conociendo las características y el volumen generado, se pueden establecer objetivos y enfocar los esfuerzos hacia aquellas tareas que requieran una mayor atención. Además, la composición de los residuos influirá directamente en la selección de tecnologías y métodos de tratamiento que, sin ser aspectos de competencia directa municipal, acaban sufragándose con las tasas e impuestos establecidos por los ayuntamientos. Por tanto, mediante la caracterización de biorresiduos se podrán conocer sus principales componentes, ayudando a la planificación de los recursos económicos municipales para su gestión, así como al diseño de los procesos de tratamiento más eficientes y sostenibles. De esta forma, en la presente Tesis Doctoral se analizará la composición de los biorresiduos recogidos selectivamente durante el primer año de implantación de dicha fracción en la ciudad con el objetivo de evaluar el sistema adoptado.

En referencia a la recogida de RSU, el transporte sostenible es cada vez más importante en la movilidad urbana, debido a los desafíos ambientales y sociales a los que deben enfrentarse las ciudades. Por ello, los **vehículos para la recogida** de RSU **(III)** deben ir modernizándose y adaptándose a estas nuevas demandas para reducir las emisiones de gases de efecto invernadero derivados de la gestión de RSU. Este aspecto, además de mejorar la calidad del aire de las ciudades y contribuir a la reducción del calentamiento global, minora la dependencia del petróleo y fomenta el uso racional de los recursos naturales. Pero, además, debe destacarse la exigencia cada vez mayor de la ciudadanía hacía sus administraciones, demandado unos servicios públicos de calidad que, en materia de gestión de residuos, significan rapidez, frecuencia, bajos niveles de ruido, limpieza y sostenibilidad. La inversión necesaria es elevada y la incertidumbre actual sobre la mejor tecnología de propulsión requieren un estudio detallado de cara a optimizar recursos y reducir las externalidades negativas asociadas al servido de recogida de RSU. Así, en esta investigación se analizarán las principales tecnologías disponibles para los vehículos recolectores y se propondrá la alternativa más idónea de cara a una posible futura renovación de la flota.

El análisis de los factores expuestos con anterioridad requiere una planificación estratégica de acciones que respondan a las necesidades detectadas, ofreciendo así un servicio eficiente y sostenible para la gestión de los RSU. Así, se pretende describir el documento estratégico para la planificación municipal de la gestión de residuos del Ayuntamiento de Castelló de la Plana (PLR) para establecer una **priorización de las acciones estratégicas (IV)** que en él se recogen. Ello contribuirá al uso eficiente de los recursos humanos, materiales y financieros de la administración, primando las actividades que tienen un mayor impacto en el logro de los resultados deseados. Este hecho evitará la dispersión de esfuerzos en actividades que a la larga resulten menos importantes, o que no contribuyan directamente a los objetivos estratégicos; ayudando a mantener el enfoque en lo más relevante y midiendo el progreso hacia esos objetivos. Todo ello es fundamental para una gestión eficiente y una toma de decisiones más objetiva.

Con todo, y con el objetivo de mejorar la gestión de RSU de la ciudad, se han analizado factores relacionados con: **I.** los cambios en la generación de RSU, **II.** su composición, **III.** los sistemas de recogida para abordar con garantías **IV.** la planificación estratégica (PLR) desde una perspectiva de sostenibilidad.

1.4. Objetivos de la investigación.

Partiendo del compromiso medioambiental que deben tener los municipios para minimizar la cantidad de RSU que terminan en vertedero, las administraciones deben hacer un esfuerzo por mejorar el rendimiento total del sistema, desde la concienciación ciudadana hasta las mejoras en los procesos que conforman la gestión integral de RSU.

Así, a partir de lo expuesto anteriormente, el objetivo principal de la Tesis Doctoral ha sido analizar diferentes dimensiones del sistema de gestión de RSU de la ciudad de Castelló de la Plana, especialmente las que son de plena competencia municipal, para mejorar su gestión desde modelos que aseguren un crecimiento sostenible en el tiempo.

Para su cumplimiento se han definido los siguientes objetivos específicos:

- Analizar la evolución histórica de las principales fracciones de residuos de la ciudad de Castelló de la Plana, tanto las que se recogen en contenedor como las depositadas en los puntos limpios, observando cómo factores externos, como la reciente pandemia por COVID-19, pueden afectar a sus tendencias y en consecuencia a los servicios de recogida, tratamiento y eliminación.
- Estudiar la composición de la materia orgánica en la ciudad, que es el componente principal de los RSU y, por tanto, la fracción mayoritaria que depositar en las plantas de tratamiento y compostaje; ayudando al dimensionamiento de los servicios de recogida y de las nuevas instalaciones de valorización que se deben implementar en la provincia.
- Evaluar las diferentes alternativas que ofrece el mercado para la renovación de la flota de vehículos recolectores, y proponer la mejor tecnología disponible para la ciudad de Castelló de la Plana, ya que su compra comprometerá el servicio durante al menos diez años. Para ello, deberán tenerse en cuenta diferentes escenarios futuros que pueden afectar a esta elección.
- Desarrollar una metodología para priorizar los planes de acción incluidos en el PLR de la ciudad de Castelló de la Plana, a través de un análisis histórico de sus principales indicadores (KPIs). Con ella se establecerá una herramienta objetiva que favorezca las sinergias entre los diferentes planes, mejorando la eficiencia del sistema y permitiendo ahorros económicos importantes.

1.5. Hipótesis iniciales.

Para el desarrollo de la investigación, así como poder para evaluar los resultados obtenidos de manera objetiva, se han tenido en cuenta las siguientes hipótesis iniciales que ayudarán a la comprensión del problema específico:

- Respecto a la generación de residuos, la hipótesis de partida es la existencia de diferencias estadísticamente significativas en las cantidades de RSU generados entre los años previos a la pandemia por COVID-19 y las recogidas a lo largo de 2020, año de su aparición. Además, se supone que estas diferencias diferirán entre las distintas fracciones analizadas y podrán ser identificadas a largo plazo, considerando periodos superiores al de los confinamientos.
- Para el análisis de los biorresiduos recogidos de forma selectiva, la hipótesis inicial reside en que las aportaciones se aproximarán a los porcentajes de materia orgánica globalmente aceptados en la composición de los RSU (entorno al 40% de materia orgánica) y en que, además, los residuos impropios que se puedan encontrar estarán próximos a los límites establecidos en la Ley 7/2022 de residuos y suelos contaminados para una economía circular (inferiores al 20% para el año 2022 y al 15% para el año 2027).
- En lo que se refiere a la renovación de la flota de vehículos, la hipótesis inicial se fundamenta en que el empleo de criterios de sostenibilidad y la definición y consideración de escenarios futuros en la toma de decisión proporcionará a los decisores resultados completos, concluyentes y fiables que además diferirán de los que se obtendrían sin considerar la incertidumbre asociada a escenarios difícilmente predecibles.
- Por último, respecto al análisis y mejora del Plan Local de Residuos de la ciudad, la hipótesis de partida reside en que el estudio y análisis estadístico de los datos históricos de sus KPIs ayudará a adoptar un orden de prioridad en las acciones contenidas en el documento estratégico de la ciudad, mejorando de esta forma el rendimiento global del sistema.

Una vez definidos los objetivos e hipótesis iniciales, en el siguiente apartado se describe la estructura adoptada en la redacción de la presente Tesis Doctoral.

1.6. Estructura y contenido de la Tesis Doctoral.

La presente Tesis Doctoral se estructura en ocho capítulos. A continuación, se procede a resumir cada uno de ellos, sin tener en cuenta este primero que ha servido como introducción:

- Capítulo 2: Este capítulo se corresponde con la primera publicación y trata sobre la influencia de la pandemia por COVID-19 en la generación de residuos de la ciudad de Castelló de la Plana. En este sentido, algunas investigaciones previas ya reconocían el impacto del COVID-19 en la generación de RSU, sin embargo, la mayoría de estudios abordaban una fase temprana de la pandemia y se centraron en la evolución total de los residuos mediante análisis descriptivos que carecían de apoyo estadístico. En este capítulo se proporciona un análisis fiable sobre las diferencias de generación de las diferentes fracciones de RSU de la ciudad. Se realiza un análisis ANOVA de medidas repetidas para todas las fracciones desde 2017 hasta 2020 a partir de sus pesajes diarios. Adicionalmente, se utilizó el test de Bonferroni para asegurar el nivel de confianza e identificar en qué años aparecían diferencias. El estudio longitudinal identifica las tendencias de cada fracción de residuos antes de la pandemia y muestra cómo cambiaron con la llegada de la crisis sanitaria.
- Capítulo 3: Este capítulo se corresponde con la segunda publicación y versa a cerca de la composición de los biorresiduos recogidos separadamente durante el primer año de implantación de la recogida selectiva de esta fracción en la ciudad. Durante ese primer año, se realizaron caracterizaciones macroscópicas mediante el muestreo aleatorio de un contenedor por distrito en cada uno de los doce meses que ha durado la experiencia. En el capítulo se comparan los resultados obtenidos en los seis distritos de la ciudad, con los de experiencias piloto previas, así como con los datos de otras ciudades. Para ello se ha tenido en cuenta la evolución de los pesajes mensuales, la tasa de recogida por habitante y la composición de los residuos depositados.
- Capítulo 4: Este capítulo se basa en la tercera publicación, que investiga la importancia del transporte en la recogida de residuos de la ciudad. Así, en este capítulo se ha elegido la mejor motorización disponible para los vehículos recolectores compactadores de RSU de la ciudad de Castelló de la Plana, utilizando una técnica de decisión multicriterio. Estos métodos se utilizan con asiduidad en la gestión de RSU, sin embargo, a pesar del papel fundamental que desempeña el transporte en la sostenibilidad de las ciudades, pocas veces se han empleado para evaluar alternativas de transporte sostenible en el ámbito de

la gestión de RSU. En este capítulo se evalúan diferentes tecnologías de motorización para camiones recolectores (diésel, gas natural comprimido (GNC), híbrido GNC-eléctrico, eléctrico e hidrógeno) bajo criterios de sostenibilidad aplicando la técnica llamada Stratified Best and Worst Method que permite considerar posibles escenarios futuros.

- Capítulo 5: Este capítulo se corresponde con la última de las publicaciones. En él, se pone el foco en el análisis del PLR de la ciudad de Castelló de la Plana, empleando una metodología que sirve para priorizar de forma objetiva los planes de acción incluidos en el sistema de gestión de rendimiento de la ciudad (dónde se han definido objetivos estratégicos, indicadores y planes de acción). Así, en este capítulo se identifican una serie de relaciones entre los indicadores, partiendo de sus datos históricos aplicando la técnica de análisis de componentes principales (PCA) y, mediante estas relaciones identificadas, se han podido priorizar aquellos planes de acción que deberían activarse previamente para gestionar el servicio de una forma más eficiente.
- Capítulo 6: En este capítulo se presentan y se discuten los principales resultados obtenidos en cada uno de los capítulos anteriores en un texto refundido. Debe reseñarse que, los datos obtenidos ya han sido comparados con los de la literatura previa en cada una de las publicaciones. Es pues éste, un capítulo de síntesis en el que se describe el significado de los hallazgos obtenidos, y se explica en qué medida se han logrado cumplir con los objetivos de la investigación.
- Capítulo 7: En este capítulo se presentan las principales conclusiones de la Tesis Doctoral y se proponen varias líneas de investigación para futuros desarrollos, así como posibles oportunidades de mejora.

En el último apartado de la Tesis Doctoral se incluye la bibliografía general. No se ha incluido la bibliografía correspondiente a las publicaciones, ya que ésta forma parte de los capítulos mencionados anteriormente. Por último, se ha incluido un Anexo (Anexo 1) con la versión editorial de los artículos publicados correspondientes a los capítulos citados anteriormente.

A modo de síntesis, la Figura 1.2 presenta un esquema donde se resume el alcance de cada artículo y su contribución a esta Tesis Doctoral.

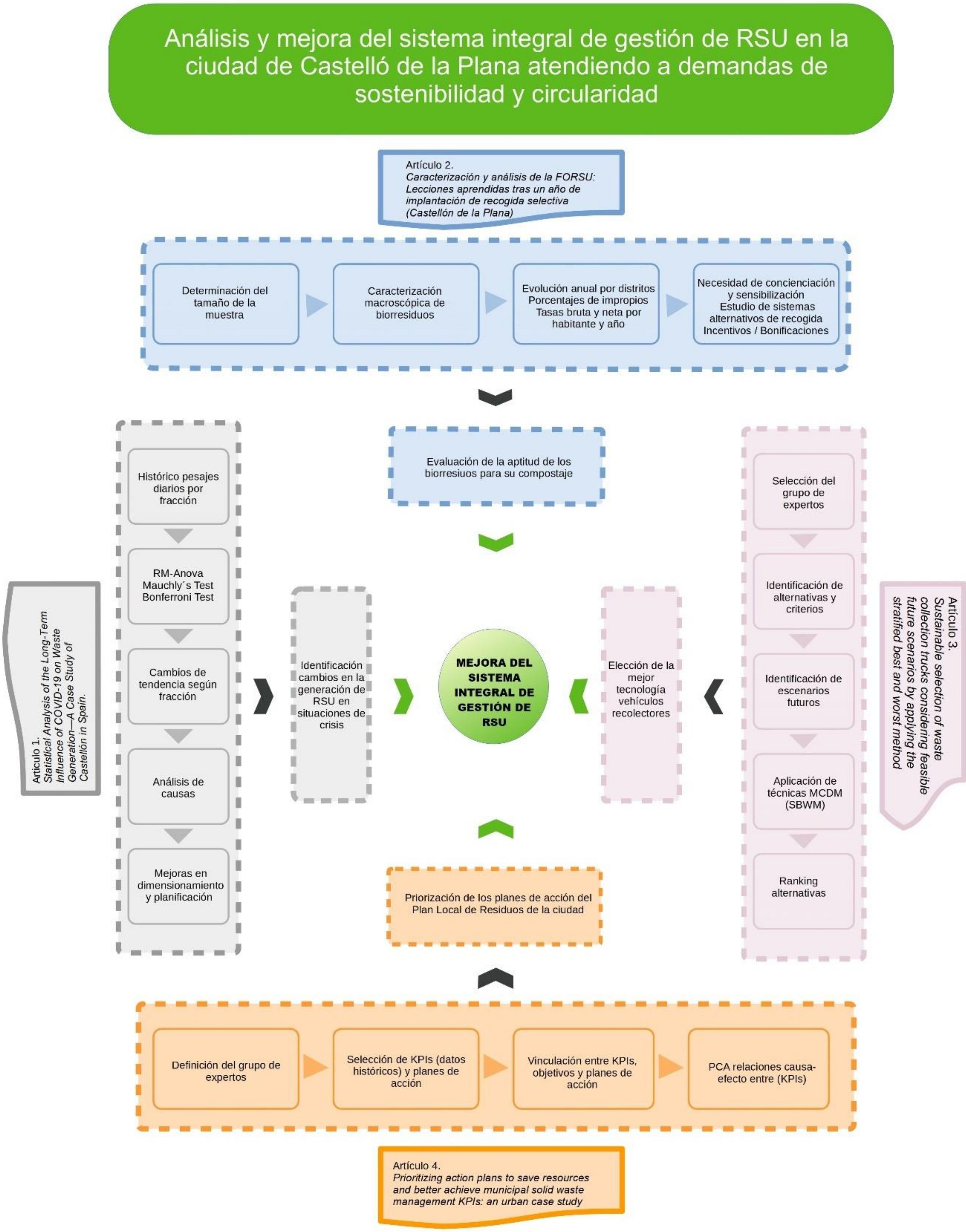

Figura 1.2. Esquema de análisis y mejora del sistema de gestión de RSU.

2. Statistical analysis of the long-term influence of COVID-19 on waste generation – A case study of Castellón in Spain.

2. STATISTICAL ANALYSIS OF THE LONG-TERM INFLUENCE OF COVID-19 ON WASTE GENERATION – A CASE STUDY OF CASTELLÓN IN SPAIN.

Miguel-Ángel Artacho-Ramírez [1], Héctor Moreno-Solaz [2,] *, Vanesa G. Lo-Iacono-Ferreira [1] and Víctor-Andrés Cloquell-Ballester [1]

[1]Project Management, Innovation and Sustainability Research Center (PRINS), Universitat Politècnica de València, 46022 Valencia, Spain; miarra@dpi.upv.es (M.-Á.A.-R.); valoia@upv.es (V.G.L.-I.-F.); vacloque@dpi.upv.es (V.-A.C.-B.)

[2]Ayuntamiento de Castelló de la Plana, 12001 Castelló de la Plana, Spain

*Correspondence: hcmoso@gmail.com

Abstract.

Existing research recognizes the COVID-19 impact on waste generation. However, the preliminary studies were made at an early pandemic stage, focused on the household waste fraction, and employed descriptive statistics that lacked statistical support. This study tries to fill this gap by providing a reliable statistical analysis setting inferential confidence in the waste generation differences found in Castellón. Repeated measures ANOVA were carried out for all the waste fractions collected and recorded in the city landfill database from 2017 to 2020. Additionally, Bonferroni's multiple comparison test ($p < 0.05$) was used to assure confidence level correction and identify which pairs of years' differences appeared. The longitudinal study identified trends for each waste fraction before the pandemic and showed how they changed with the advent of the crisis. Compared to 2019, waste collection in 2020 significantly grew for glass and packaging; remained unchanged for beaches, paper and cardboard, and dropped substantially for households, streets, markets, bulky waste, hospitals, and recycling centres. Total waste showed no differences between 2017 and 2019 but dropped significantly in 2020. These findings may help us better understand the long-term implications of COVID-19 and improve municipal solid waste management in a similar crisis.

Keywords.

COVID-19; waste generation; inferential analysis; long term effects.

2.1. Introduction.

The management of municipal solid waste (MSW) has become an increasing global concern as urban populations continue to grow and consumption patterns change. MSW is one of the essential human activities with social and environmental effects [1]. For that reason, the health and environmental implications associated with MSW management are being increasingly analysed and studied [2].

Once the World Health Organization (WHO) declared the coronavirus disease of 2019 (COVID-19) a global pandemic on 11 March 2020, governments worldwide implemented measures to control the spread of the virus [3,4]. From nationwide lockdowns to access limitations or travel restrictions, various disruptive measures seriously affected global supply chains, industries, services, and financial markets—and there was an unprecedented impact on the economy, environment, and people's lives [5,6]. People had to change the way they worked, studied, and interacted, abruptly modifying habits and the methods in which they consumed products and services [7–9].

The COVID-19 crisis was expected to influence waste generation, given the relationship that MSW has with socioeconomic changes, behaviour, and lifestyle [10–13]. A considerable amount of literature has been published recently analysing COVID-19's impact on waste generation in several cities and countries. However, most of these preliminary studies were made at an early stage of the pandemic when the situation was still developing, leading to controversial results in the amount of waste generated compared with a pre-pandemic scenario. For example, Charlebois et al. [14] and Zand and Heir [15] found an increase in food waste in Canada and Tehran, respectively, and Principato et al. [16] and Fan et al. [17] found the opposite in Italy and Shanghai, respectively. These pioneering studies, with some exceptions [3,18], gathered data during the lockdown for short periods (a few months) and were focused on the household fraction [19–22].

Moreover, these studies employed interviews, focus groups [23], secondary data [24], and surveys without reaching representative sample sizes and non-probabilistic sampling methods, thus affecting the representativeness of the findings. Additionally, up to date studies, with some exceptions [3], are focused on measuring the amount of waste [25] without considering changes in waste fractions and composition, which is crucial for analysing the influence of COVID-19 on waste management [17]. Thus, despite the fact that these pioneering works provided a preliminary and valuable understanding of the potential impacts of COVID-19 on waste collection and disposal behaviour, many were descriptive in nature and lacked statistical support. Therefore, the generalisability of their findings is limited. Table 2.1 provides a summary of these preliminary works, showing the mentioned limitations, e.g., their focus on short periods (lockdowns), their reliance on self-reported and indirect data, the prevalence of the analysis of the household waste fraction, and the derivation of results and conclusions from descriptive data analyses. It is worth noting that information about statistical analyses in Table 2.1 only refers to the methods used in previous works to analyse differences in the waste generation between the pre-COVID-19 and COVID-19 scenarios.

Table 2.1. Summary of preliminary works on waste generation differences found between pre-COVID-19 and COVID-19 scenarios.

Work	Country	Period Analysed	Methodology	Waste Fractions	Statistical Analysis
Amicarelli & Bux [21]	Italy	March to May, 2020	Food diaries	Household	Descriptive (sum of reported data)
Charlebois et al. [14]	Canada	August, 2020	Survey	Household	Descriptive (percentages)
NZWC & LFHW [26]	Canada	June, 2020	Survey	Household	Descriptive (percentages)
Principato et al. [16]	Italy	March to April, 2020	Survey	Household	Descriptive (percentages)
Bogevska et al. [27]	North Macedonia	May to June, 2020	Survey	Household	Descriptive (percentages)
Aldaco et al. [24]	Spain	March to April, 2020	Secondary data	Household	Descriptive (Difference)
Jribi et al. [19]	Tunisia	March to April, 2020	Survey	Household	Descriptive (percentages)
Ben Hassen et al. [28]	Qatar	May to June, 2020	Survey	Household	Descriptive (means, variation ratio, frequencies, and percentages)
Ismail et al. [20]	Malaysia	March to April, 2020	Secondary data	Household	Descriptive and One-way ANOVA
Brizi & Biraglia [22]	India & USA	Lockdowns	Survey	Household	Descriptive and Sequential Mediation Model
Richter et al. [8]	Canada	March to September, 2020	Landfill database	Household/Total Waste	Descriptive (measures of central tendency)
Ikiz et al. [23]	Canada	May, 2020	Interviews & focus group	Household	Qualitative analysis
Zand & Heir [15]	Iran	Not reported	Estimation	Total Waste/Medical Waste	Descriptive
Fan et al. [17]	China, Singapore, Czech Republic	March to May, 2020	Survey and Secondary Data	Plastic/Household	Descriptive
Cai et al. [18]	USA, Brazil, Canada, UK, France, and Italy	2019, 2020, 2021	Secondary data	Total Waste	Descriptive (variation ratio)
Richter et al. [3]	Canada	January 2018 to September 2020	Landfill database	Solid/ Mixed Solid/ Construction/Grit/ Mixes Asphalt Shingles/ Biomedical	Descriptive (boxplots)

Filho et al. [29]	41 countries	Lockdowns	Survey	Plastic	Descriptive
Olatayo et al. [30]	South Africa	2019 to 2020	Estimations from secondary data	Plastic (PPE)	Descriptive (Material Flow Analysis)
Babbitt et al. [31]	USA	March to July 2020	Survey	Household	Descriptive
Urban & Nakada [32]	Brazil	2010 to 2020	Secondary data	Household/ Recyclables/ Streets	Descriptive (means)
Vittuary et al. [33]	Italy	May 2020	Survey	Household (food)	Descriptive (percentages)
Strotman et al. [34]	Germany	October 2020	Survey	Household (Food)	Descriptive (percentages)
Kasim et al. [35]	Guyana and Nigeria	Lockdowns	Survey/Interviews	Household (Food)	Descriptive
Laila et al. [36]	Canada	February to August 2020	Survey/Interviews/Audits	Household (Food)	Descriptive/Non-parametric test (Wilcoxon)

The present work tries to fill this gap by providing a reliable statistical analysis setting inferential confidence in the waste generation differences found in Castellón, a medium-sized city in the Valencia region of Spain. Specifically, the authors compared waste generation in the city from 2017 to 2020, considering all waste fractions as recorded in municipal landfill data. Thus, the starting hypothesis is statistically significant differences in the waste generation between pre-COVID-19 and COVID-19 scenarios in the long term. These differences will depend on the analysed fractions.

The remainder of this paper is structured as follows: Section 2 is concerned with the case study description and the used methods for data analysis in this study, Section 3 presents and discusses the obtained results for each one of the waste fractions analysed, and finally, Section 4 provides the conclusions drawn from findings, the impact they may have on MSW management, the limitations of the study and further work to be carried out.

2.2. Materials and Methods.

2.2.1. Case Study.

The research was undertaken in Castellón. The city's population increased 2.7% between 2017 and 2020 and reached 174,262 inhabitants [37]. Castellón is not a tourist town. It has a negative floating population of about 15,000 inhabitants who move to other tourist destinations during July and August. In the distribution of companies according to activity, the services sector, in which the HORECA (hotel, restaurant, and catering) channel predominates, is the most important (68%), followed by construction (21%) and, finally, industry (11%) [37].

The city was in lockdown along with all of Spain from 15 March until 21 June of 2020. All non-essential establishments were closed, such as cafes, restaurants, hotels, and commercial and retail businesses, but internet commerce and catering services continued to operate. Food stores and supermarkets, considered essential establishments, were open while open-air markets were closed. Regarding health centres and hospitals, consultations were made by telephone, with visits to health centres only allowed when hospitalisation was necessary or in other exceptional cases [38,39].

On 28 April 2020, a national plan for asymmetric de-escalation began. Some establishments (such as hospitals, restaurants, and coffee shops) opened with some commercial shops with a restricted capacity [40]. On 21 June 2020, the state of alarm ended, and Spain entered a situation called the "new normal". A capacity limit of 75% was generally enforced in all spaces, both outdoors and indoors, including markets, beaches, and pools [41]. The Spanish government decreed the second state of alarm on 25 October 2020, established a curfew between 12:00 a.m. and 6:00 a.m., and announced restrictions on travel between regions [42]. Measures changed during this period. From 21 December 2020, establishments were allowed to accommodate larger groups of people and stay open until 11:00 p.m. The second state of alarm ended on 9 May 2021 [43].

Figure 2.1 shows the six districts of Castellón. Between the port district and the main nucleus of Castellón, there is the Marjalería area with dispersed single-family houses.

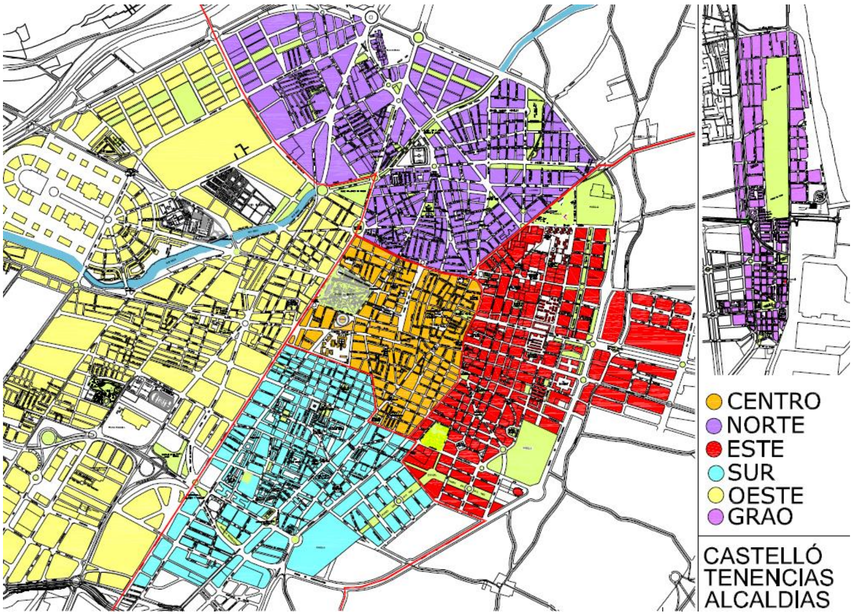

Figure 2.1. Castellón map with districts (39°59.1402′ N, 0°2.961′W). Adapted with permission from Ayuntamiento de Castelló de la Plana [44].

A similar urban composition can be found around the periphery. The industrial sector is concentrated around the urban nucleus, except for the service sector that is within. From a waste manager's point of view, the service is highly heterogeneous and must cover nearly four kilometres of beach managed by the municipality.

Waste managed by Castellón falls into two categories: Containerized, which includes waste deposited in containers on public roads or in public places, e.g., markets, hospitals, etc., and non-containerized which is waste from cleaning services or special wastes, e.g., beach cleaning, street cleaning, bulky waste, etc. This fraction is commonly called "Other MSW".

All waste is categorised as MSW, including all origins (HORECA channel establishments, markets, hospitals, and industry), providing it meets the definition set by the Spanish Act 22/2011 [45].

Containerized waste is categorised as recyclable or non-recyclable (mixed). Recyclable waste refers to waste separated from the waste stream and set aside for purposes of recovery, reuse, or recycling. Mixed MSW includes urban garbage (domestic and HORECA), itinerant markets, the hospital fraction that can be assimilated to urban waste, and daily collections from grey containers. This waste is destined for a two-phase treatment plant with a semi-automatic mechanical separation and a composting tunnel [46]. The recyclable fraction is divided into four categories by colour and delivered to each corresponding treatment plant for management. Table 2.2 shows the frequency and characteristics of the analysed waste fractions in this study. It should be noted that bio-waste was implemented in September 2020, so it is not included in this analysis.

Table 2.2. Waste fraction characteristics of Castellón.

Waste Fraction	Category (Bin Colour)	Collection Frequency	Nº Containers in Street	Waste Volume Capacity (l)	Description of Waste Fraction
Packaging	Recyclable, containerized (yellow)	Two to three times a week, depending on location	713	2,139,000	Plastic bottles and bags, metal cans, mixed packaging (e.g., aluminium and paperboard)
Glass	Recyclable, containerized (green)	Every 14 days	718	2,154,000	Bottles, tins, jars, etc. glass items.
Paper and cardboard	Recyclable, containerized (blue)	Two to three times a week, depending on location	560	1,680,000	Cardboard, paper, newspapers, labels, etc.
Household	Mixed MSW, containerized (grey)	Every day	3,379	3,379,000	Traditional waste system 'All in one'. According to law, it should only contain waste that is non-admissible in other fractions

Hospitals	Mixed MSW, containerized (grey)	Every day	140	140,000	Domestic assimilable hospital waste (paper, food, textile, etc.)
Markets	Mixed MSW, containerized (grey)	Every day	80	80,000	Domestic assimilable market waste (paperboard, food, etc.)
Streets	Non-containerized	Every day	-	-	Waste collected from ground and street litter bins
Beaches	Non-containerized	Monday to Saturday	-	-	Waste collected from sand and beach litter bins
Recycling centre bulky	Non-containerized	On demand	-	277,000	Bulky waste (furniture, home appliances, wood, etc.) deposited in recycling centre
Recycling centre pruning	Non-containerized	On demand	-	40,000	Pruning (branches, trunks, leaves) disposed in recycling centre
Bulky waste	Non-containerized	Monday to Saturday	-	-	Bulky waste disposed in streets with (or without) previous order

In addition to these fractions, other types of waste such as batteries, asbestos, tires, or construction and demolition waste are collected by special collection services.

2.2.2. Data Collection and Statistical Analysis.

Information was gathered from a system connected to the scales used by the collector trucks for each fraction. The total waste per year was calculated as the sum of all the waste fractions analysed. The period under analysis is from 1 January 2017 to 31 December 2020 for all six city districts. Waste collected in 2021 was excluded because bio-waste was included as a new waste fraction in the city, thus altering the amount of waste collected in other waste fractions and avoiding comparability with previous years.

A repeated-measures analysis of variance (RM ANOVA) with the waste fractions as dependent variables was conducted to analyse if statistically significant differences in the mean for waste appeared over the years. RM ANOVA can be used for investigating changes in mean scores over three or more time points [47]. Thus, the collection of all waste fractions for 2017, 2018, 2019 and 2020 were compared with significant levels of differences set at $p < 0.05$. Data were explored to identify and exclude outliers. To test if data are normally distributed, the Kolmogorov-Smirnov test and the Shapiro-Wilk test were used for waste fractions recorded daily (> 50 cases) and for waste fractions recorded every month (<50 cases), respectively [48]. Mauchly's criterion test was used to assess if the covariance structure satisfies the sphericity condition [47]. If the sphericity assumption was violated, a Greenhouse-Geisser correction was used. Bonferroni's multiple comparison test ($p < 0.05$) was used to assure confidence level correction and identify between the pair of years in which the differences appeared. The Eta squared value (η^2) was calculated to measure the effect size, setting the size of the differences found ($\eta^2 = SS_{effect}/SS_{total}$, where: SS_{effect} is the sum of squares for the effect that is being studied, and SS_{total} is the total sum of squares for all effects, errors, and interactions in the RM ANOVA study).

All data analyses were performed using the SPSS 16 statistical application for Windows.

2.3. Results and Discussion.

Outliers appeared in all the waste fractions recorded daily for at least one year (households, hospitals, markets, and streets). After excluding those outliers, all the waste fractions analysed were normally distributed ($p > 0.05$ in all the normality tests performed). RM ANOVAs carried out for all the waste fractions show significant differences between years. The significance of Mauchly's test, F values, significance, and η^2 values are shown in Table 2.3. Mauchly's test of sphericity for hospital, beach, and glass waste indicated that the assumption of sphericity had been violated (Mauchly's test (sig.) < 0.05) and, therefore, a Greenhouse-Geisser correction was used.

Table 2.3. RM ANOVA.

	Mauchly Test (sig.)	F	Sig.	η^2
Household	0.087	74.626	0.000	0.908
Hospitals	0.029 *	3,489,815 *	0.000 *	0.923
Markets	0.092	3230.795	0.000	0.784
Streets	0.199	12.072	0.000	0.421
Beaches	0.000*	31,600 *	0.000 *	0.276
Recycling centre bulky	0.189	1426.977	0.000	0.939
Recycling centre pruning	0.090	217.996	0.000	0.889
Bulky	0.201	201.264	0.000	0.970
Packaging	0.692	154.700	0.000	0.991
Paper and cardboard	0.828	53.844	0.000	0.947
Glass	0.027 *	37.150 *	0.000 *	0.772
Total waste	0.150	8616.609	0.000	0.961

* Greenhouse-Geisser correction.

Waste fractions were classified into three groups according to the number of statistically significant differences found in their means among the years. Group 1 is defined by fractions of waste in which statistically significant differences appeared for all pairwise comparisons (see Figure 2.2, and Table 2.4). In Group 1, a statistically significant increasing trend is observed for packaging collection from 2017 to 2020. In the case of markets and bulky waste, the increasing trend stops with a significant decrease in the amount of waste collected in 2020. In the case of the recycling centre bulky waste, the increasing trend stopped in 2018 with a significant decrease in the amount of waste collected in 2019 and in 2020. Implementing the scheduled "door-to-door" collection service for the bulky waste in 2019 could explain both the increase in bulky waste and the significant decrease in the bulky waste from recycling centres.

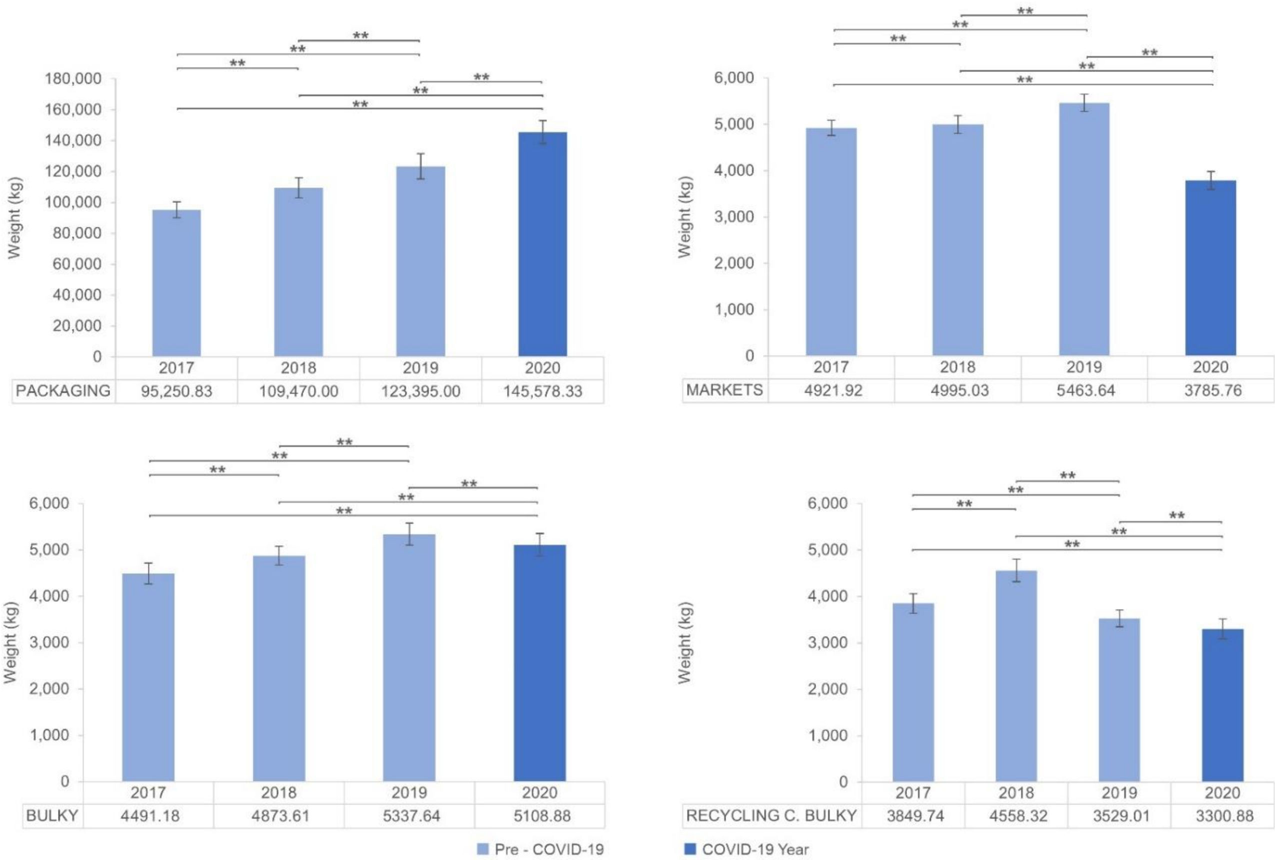

Figure 2.2. Mean and 95% CI for each year in waste fractions of Group 1: packaging, markets, bulky and recycling centre bulky waste collection. (**) for $p < 0.01$.

Table 2.4. Significant differences in packaging, markets, bulky and recycling centre bulky waste collection from Bonferroni's comparison test.

		Packaging	Markets	Bulky	Recycling C. Bulky
Years		Monthly Means Difference	Daily Means Difference	Daily Means Difference	Daily Means Difference
(I)	(J)	(I) - (J)	(I) - (J)	(I) - (J)	(I) - (J)
2020	2017	50,327.500 **	−1136.159 **	617.700 **	−548.864 **
	2018	36,108.333 **	−1209.272 **	235.272 **	−1257.436 **
	2019	22,183.333 **	−1677.881 **	−228.754 **	−228.132 **
2018	2019	−13,925.000 **	−648.609 **	−464.026 **	1029.304 **
2017	2018	−14,219.167 **	−73.113 **	−382.428 **	−708.571 **
	2019	−28,144.167 **	−541.722 **	−846.454 **	320.733 **

** $p < 0.01$.

The environmental awareness campaigns conducted by administrations and non-governmental organisations in the years preceding the COVID-19 pandemic have led to a steadily growing collection of recyclable waste fractions (packaging, glass, and paper). However, the results in the packaging fraction in 2020 should be explained by the plastic waste boom during the pandemic. Many factors contributed to this increase in plastic waste. The pandemic induced impulsive and irrational stockpiling of groceries and essential plastic packaged products [49]. A loss of faith in unpackaged products in a new hyper hygienic approach significantly increased the use of single-use plastic (SUP) [50]. The temporary relaxation of bans on SUP bags in supermarkets also contributed to this trend [51,52]. Moreover, lockdowns and quarantines increased online food delivery and e-shopping, increasing the use of plastic-based packing materials [53,54]. Finally, the remarkable increase in the use of masks, gloves, protective suits, hand sanitizer bottles, and all kinds of personal protection equipment (PPE), along with the increase in pharmaceutical packaging waste, led to more plastic packaging waste [55–57]. This increase in plastic pollution poses new challenges for effective plastic waste management that need to be addressed with new strategies and directives [50,58].

In the specific route of the municipal markets, the trend for waste had been upward in recent years, except for 2020, with a significant drop in the average daily collection. This is partly due to the decline in economic and commercial activity and the protocols established by the health authorities regarding the disinfection of posts and other measures that were difficult to comply with and that led to the temporary closure of many market stalls. The drop in collection could also be related to the increase in the packaging waste fraction. The loss of faith in unpackaged products could partly explain this, along with the increased buying of less-perishable products [49,59], the closure of restaurants, and the increase in online food delivery forced by lockdowns. The wish to avoid densely populated places led people to buy food and groceries from smaller nearby outlets, limiting the purchase time spent, and fewer family members were involved in offline grocery shopping [60], which may have played a role in reducing activity in municipal markets.

Bulky waste collection in 2020 may be related to lockdowns and a drop in domestic refurbishments and economic activity. Lockdowns and mobility restrictions can also be responsible for the decrease in bulky waste taken to recycling centres by the public.

Group 2 contains fractions of waste in which no differences were found for a few years (Figure 2.3, Table 2.5). The glass fraction of waste showed no differences between 2017 and 2018 but grew significantly in 2019 and 2020. For household, hospitals, and recycling centre pruning, waste grew and showed statistically significant differences between 2017 and 2018. Such a difference disappeared between 2018 and 2019.

Finally, waste decreased significantly in 2020. Finally, both paper and cardboard and beaches showed no differences in mean waste between 2019 and 2020, respectively, putting an end to a steadily growing and steadily decreasing trend in previous years.

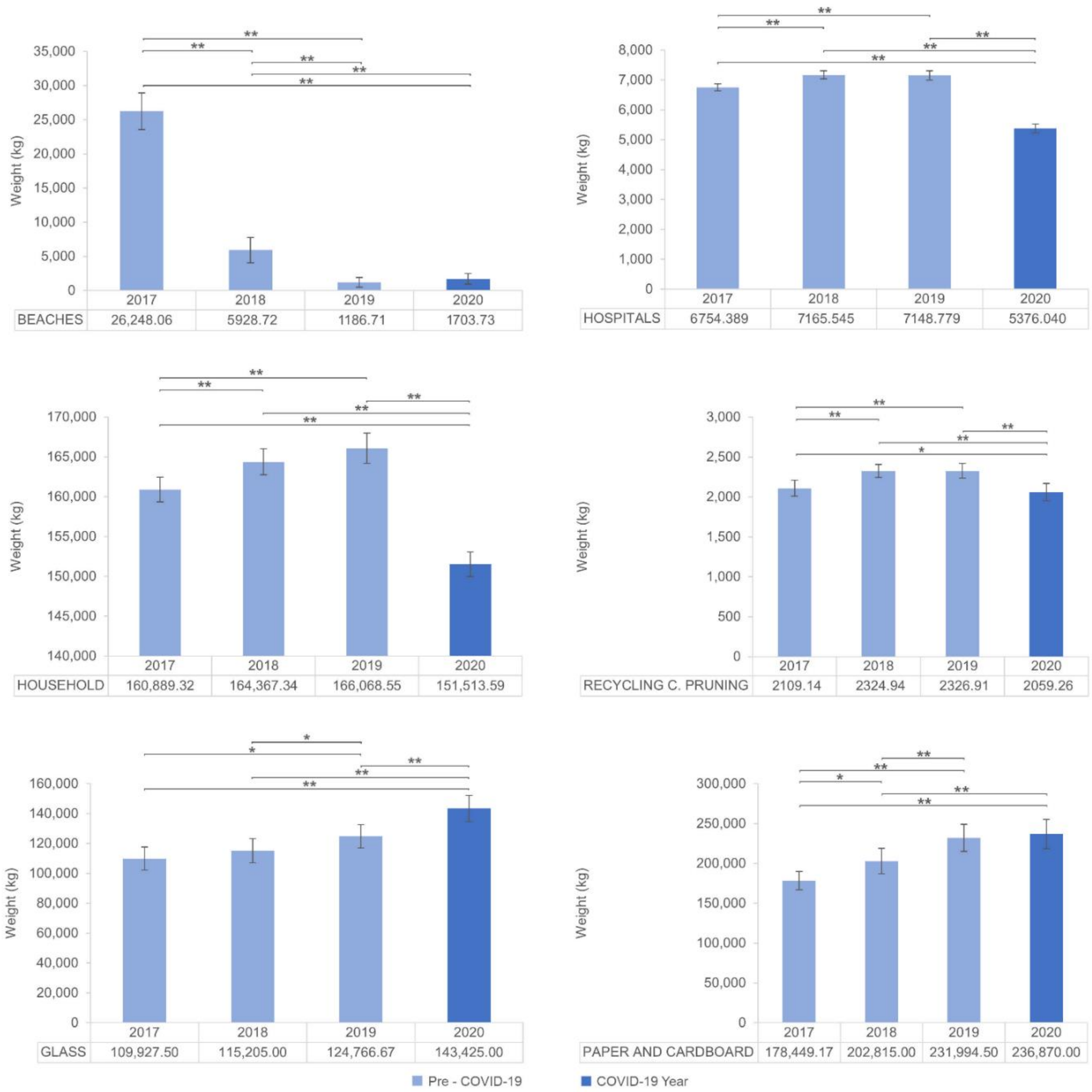

Figure 2.3. Mean and 95% CI for each year in waste fractions of Group 2: glass, household, hospitals, recycling centre pruning, paper and cardboard and beaches waste collection. (*) is used for $p < 0.05$ and (**) for $p < 0.01$.

Table 2.5. Significant differences for glass, household, hospitals, recycling centre pruning, paper and cardboard and beach waste from Bonferroni's comparison test.

		Glass	Household	Hospitals	Recycling C. Pruning	Paper and Cardboard	Beaches
Years		Monthly Mean Differences	Daily Mean Differences	Daily Mean Differences	Daily Mean Differences	Monthly Mean Differences	Daily Mean Differences
(I)	(J)	(I) - (J)	(I) - (J)	(I) - (J)	(I) - (J)	(I) - (J)	(I) - (J)
2020	2017	33,497.500 **	−9375.726 **	−1378.350 **	−49.877 *	58,420.833 **	−24,544.327 **
	2018	28,220.000 **	−12,853.753 **	−1789.505 **	−265.654 **	34,055.000 **	−4224.993 **
2018	2019	18,658.333 **	−14,554.959 **	−1772.739 **	−267.654 **	−29,179.500 **	4742.011 **
2017	2018	−9561.667 *	−3478.027 **	−411.155 **	−215.802 **	−24,365.833 *	20,319.335 **
	2019	−14,839.167 *	−5179.233 **	−394.389 **	−217.778 **	−53,545.333 **	25,061.345 **

** $p < 0.01$. * $p < 0.05$.

The remarkable increase of glass collected in 2020 is in line with the findings of Filho et al. [29]. This increase could partly be explained by the decline in activity in hotels and restaurants. Lockdowns and reduced activity due to indoor capacity restrictions meant glass consumed at restaurants and hotels that used to be repackaged and sent back to beverage companies was consumed at home and placed in glass waste containers. Moreover, according to Tchetchik et al. [9], the COVID-19 crisis made people more prone to increase recycling and further reduce consumption. The authors found that the perceived link between exposure to the pandemic threat and climate change and economic vulnerability increased pro-environmental behaviour. An increase in recycling at home could also explain the increased volumes of paper and cardboard, although with no significant differences compared to 2019. The slowdown in economic activity for the leading paper and cardboard producers like shops, the hospitality industry, and industrial sectors [61] could explain the reduced volume of paper and cardboard waste in 2020.

The household fraction shows a statistically significant decrease in 2020. As said in the introduction, previous studies analysing the influence of pandemics on household waste led to controversial results. The descriptive nature of these studies mainly focused on lockdown periods, which made it difficult to evaluate such an influence in the long term. This work enables us to state that household waste volume in a pandemic was significantly lower than in pre-pandemic years. These results could be related to a generalised decrease in family consumption from the economic contraction provoked by the pandemic. Moreover, several authors found that changes to family routines (e.g., working from home, better time management, more organised purchase and cooking habits, greater use of 'smart food delivery') due to the pandemic may have also played a role in the observed reduction in household waste [21,36,62].

The hospital fraction also showed a statistically significant decrease in 2020, which is in line with the observed household trend. This parallel trend could be because the waste from hospitals managed by city councils can be assimilated into urban waste and does not pose any special management requirements since it was only used by non-infectious patients. It should be noted that hospital waste that is not assimilable to domestic waste (hazardous waste) which used to represent 15% of waste in healthcare facilities [63] is not collected through municipal services and has a specific channel for its management. Hazardous waste in Castellón probably grew exponentially, as happened in other cities such as Wuhan (0.6 kg/patient to 2.5 kg/patient) [64] or countries like Jordan (3.95 kg/patient to 14.16 kg/patient) [65], and this should be analysed in future studies because the pandemic has created a huge burden of healthcare systems that must also treat and properly dispose of all the waste that could further spread the SARS-CoV-2 virus [66].

Regarding recycling centre pruning waste, the reduction in 2020 could be again related to mobility restrictions which may have hampered disposals at recycling facilities. In the case of beach waste, the collection includes vegetable matter washed ashore and the elimination of algae in the sand, which has been growing in recent years due to an increase in sea temperatures. A new collection procedure set in 2018 led to a remarkable decrease in waste. Since then, the beach material removed is accumulated in points far from the shore, where it is allowed to dry to reduce the moisture content, leading to a weight reduction in the waste to be managed. Once the material has dried, it is transported to a screening plant to recover the maximum amount of sand for spreading again on the beach, thereby significantly reducing the amount of final waste. Finally, following the Ministry of Ecological Transition recommendations to enhance the circular economy, part of the algae is buried in the beach dunes to reinforce and regenerate them. These algae serve as an organic substrate that contributes to their recovery. No significant differences appeared between 2019 and 2020 despite cleaner beaches being reported as one of the positive side effects of COVID-19 on the environment [67].

Finally, Group 3 contains fractions of waste whose collection values showed no significant differences in mean values over four years. These waste fractions were streets and total waste, in which no differences appeared between 2017 and 2019, whereas the mean value significantly dropped in 2020 (see Figure 2.4 and Table 2.6).

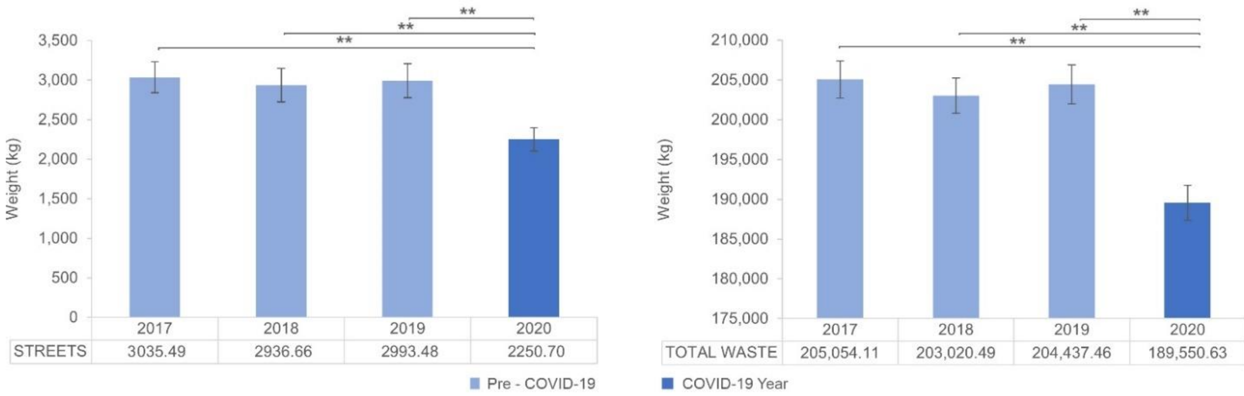

Figure 2.4. Mean and 95% CI for each year in waste fractions of Group 3: streets and total waste collection. (**) for p < 0.01.

Table 2.6. Significant differences in streets and total waste collection from Bonferroni's comparison test.

		Streets	Total Waste
Years		Daily Means Difference	Daily Means Difference
(I)	(J)	(I) - (J)	(I) - (J)
2020	2017	−784.791 **	−15,503.484 **
	2018	−685.961 **	−13,469.868 **
	2019	−742.789 **	−14,886.838 **

** $p < 0.01$.

The significant drop in street waste collected from public roads could be related to the lockdowns, mobility restrictions, and the closure of the hotel, restaurant, and nightlife industries. Total waste shows the same trend as streets. Some preliminary studies predicted an increase in MSW due to the COVID-19 pandemic, and may be influenced by the initial panic buying experienced worldwide [68,69]. However, the results obtained considering one year for the city of Castellón (with statistical support) show the opposite. These results are in line with Cai et al. [18]. These authors found that compared to normal periods in 2019, significant decreases in total waste were observed in most of the months in 2020 in Montreal (e.g., by 9.5% in May 2020) and Trento (e.g., by 13.7%, 25.3%, 14.7% from March to May 2020 and 16.5% in January 2021). Thus, it could be said that the shutdown of most of the productive and commercial activities due to the COVID-19 crisis resulted in significant economic losses which, in turn, led to a waste decrease in the long term.

Considering only 2019 and 2020, waste collection for 2020 significantly grew for glass and packaging; it remained unchanged for beaches and paper and cardboard, and significantly decreased for households, streets, markets, hospitals, recycling centre pruning, recycling centre bulky waste, and total waste.

2.4. Conclusions.

This study sheds further light on the influence of the COVID-19 crisis on the generation of MSW. It complements the abundant previous descriptive studies in the literature with a longitudinal study based on the statistical inference that enables the quantitative establishment of the long-term impact of the pandemic on the generation of the waste fractions collected by the municipality of Castellón.

The comparison performed on waste fractions from 2017 to 2020 using RM ANOVA enables establishing waste trends and how these vary because of the effect of the pandemic. The results show that waste collection patterns significantly changed in Castellón city in 2020 because of the impact of COVID-19. Thus, the starting hypothesis has been confirmed, as statistically significant changes in waste generation appeared, and the analysed waste fractions were affected in different ways. Considering only 2019 and 2020, waste in 2020 significantly grew for glass and packaging; remained unchanged for beaches and paper and cardboard; and significantly dropped for households, streets, markets, hospitals, recycling centre pruning, and recycling centre bulky. Finally, total waste showed no differences from 2017 to 2019 but significantly dropped in 2020.

The start of the COVID-19 pandemic provoked changes in the waste amount, composition and distribution, safety and infection risk, and disposal rate, increasing the complexity of waste management worldwide. Changes in waste generation resulted in storage, transportation, disposal, and treatment challenges. The response of public authorities and municipal waste operators in Castellón was to quickly adapt their waste management systems and procedures to the new scenario. Ensuring the safety of the staff was a priority, followed by guaranteeing collection services with the same frequency as usual, including on-demand collection. Municipal waste collection staff were provided with additional personal protective equipment (PPE) and trained about safety measures and new protocols for disinfection equipment and vehicles. Differences in waste generation among fractions forced MSW managers to reorganise resources and adapt routes. For example, the increase in packaging and glass fractions in Castellón led to increasing collection frequencies to avoid container overflow. Given the reduction of the street waste fraction, the scheduled operations in streets were reduced and reorganized to improve wet cleaning services, such as sweeping and disinfection in markets, hospitals, and public roads, cleaning litter bins, and washing containers. The pandemic crisis mainly affected collection systems, but it progressively reached other players such as recyclers in the long term. Sorting and treatment systems also experienced some disruptions because new restrictions appeared for manual sorting and recycling due to safety precautions. Daily waste operations were also affected by increased monitoring to avoid illegal dumping, shortages of personnel, and increased communication to inform citizens about adequately managing their waste. As can be seen, despite the fact that the total waste dropped, the issues to be considered by MSW managers significantly increased in number and difficulty. Despite the agile adaptation of the administration and MSW managers, all the changes were made reactively. If they had had the objective and reliable data about changes in material flows obtained in this study, they could have planned their actions better, reorganizing resources more efficiently. Additionally, the present paper’s findings might better help understand the long-term implications of COVID-19 and prepare planners and policymakers for changes in the waste stream due to pandemics or other unprecedented emergencies.

However, a note of caution is due here since previous studies showed that waste generation and composition might vary depending on the location [70], socioeconomic factors, or climatic factors [10,12,71,72]. Thus, further studies should be carried out in cities of different sizes and with different economic activities. Such studies should include the analysis of hazardous medical waste not analysed in the present study. Moreover, the pandemic persists, so further studies should analyse whether the results remain visible, return to the previous trend, or whether there is a rebound effect after returning to normality. Thus, long-term analyses of the total impact of COVID-19 on resources and waste management and the dynamics of material flow seem necessary. Finally, waste management and planning practices applied after the advent of the pandemic should be evaluated with the goal of identifying managerial improvements.

Author Contributions.

Conceptualization, M.-Á.A.-R. and H.M.-S.; methodology, M.-Á.A.-R.; software, M.-Á.A.-R.; validation, V.G.L.-I.-F. and V.-A.C.-B.; formal analysis, V.-A.C.-B.; investigation, H.M.-S.; resources, H.M.-S.; data curation, V.G.L.-I.-F.; writing—original draft preparation M.-Á.A.-R.; writing—review and editing, M.-Á.A.-R. and H.M.-S.; visualization, V.G.L.-I.-F.; supervision, M.-Á.A.-R.; project administration, V.-A.C.-B. All authors have read and agreed to the published version of the manuscript.

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Conflicts of Interest.

The authors declare that they have no conflicts of interest.

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3. CARACTERIZACIÓN Y ANÁLISIS DE LA FORSU: LECCIONES APRENDIDAS TRAS UN AÑO DE IMPLANTACIÓN DE RECOGIDA SELECTIVA (CASTELLÓN DE LA PLANA).

3. CARACTERIZACIÓN Y ANÁLISIS DE LA FORSU: LECCIONES APRENDIDAS TRAS UN AÑO DE IMPLANTACIÓN DE RECOGIDA SELECTIVA (CASTELLÓN DE LA PLANA).

Héctor Moreno Solaz [1, *]; Víctor Andrés Cloquell-Ballester [2]; Natalia Edo Alcón [3]; Cristóbal Badenes Catalán [1]; Miguel-Ángel Artacho-Ramírez [2].

[1]Dirección de Servicios Urbanos, Infraestructuras y Medio Ambiente. Ayuntamiento Castellón de la Plana
[2]Centro de Investigación en Dirección de Proyectos, Innovación y Sostenibilidad de la Universitat Politècnica de València; [3]Eurofins Iproma

*Correspondence: hcmoso@gmail.com

Abstract.

Los biorresiduos son el componente mayoritario de las distintas fracciones de residuos domésticos ya que suponen aproximadamente un 40 % en peso con respecto al total (PEMAR, 2016). En el contexto de la Unión Europea, la Directiva 2008/98/CE incluye en el Artículo 22 la recogida separada de biorresiduos para su correcto tratamiento y valorización. El siguiente artículo tiene como objeto el análisis de los resultados obtenidos durante el primer año de implantación del servicio de recogida selectiva de fracción orgánica de los residuos sólidos urbanos (FORSU) en la ciudad de Castelló de la Plana. Se han tenido en cuenta la evolución de los pesajes mensuales obtenidos, la tasa de recogida por habitante y la composición de los residuos depositados. Para ello se ha realizado una caracterización mensual, mediante el muestreo aleatorio de un contenedor por distrito en cada uno de los doce meses que duró la experiencia. Los resultados revelan una generación de biorresiduos recogidos de manera selectiva de 0,045 kilogramos por habitante y día, y una tasa media de impropios del 39,86%. Estos resultados se han comparado con los obtenidos en experiencias piloto previas a la implantación definitiva que tuvo lugar a finales del año 2020.

Keywords.

Residuo sólido urbano; fracción orgánica; biorresiduos; caracterización; FORSU.

3.1. Introducción.

La cantidad de residuos generados en las ciudades está en constante aumento y éstos son cada vez más diversos y peligrosos. La calidad en la gestión de residuos, por lo tanto, se ha vuelto más importante debido a su impacto directo en el medio ambiente y la salud humana. (Fasihi & Parizadi, 2021).

En este sentido, la Directiva 2008/98/CE Marco de Residuos, del Parlamento Europeo y del Consejo de 19 de noviembre, dispone que los Estados miembros deberán adoptar las medidas necesarias para aumentar un 50% en peso la preparación para la reutilización y reciclado de residuos domésticos a corto plazo. Así, la Unión Europa está fomentando los tratamientos biológicos de los residuos orgánicos como alternativa a los vertederos y también a mejorar el reciclaje de la materia orgánica. La composición de estos residuos es muy importante para obtener un compostaje de buena calidad (Huerta-Pujol et al., 2011).

El Plan Estatal Marco de Gestión de Residuos (PEMAR, 2016), en la búsqueda de una economía circular, apuesta por la reincorporación a los procesos productivos los materiales contenidos en los residuos, fomentando acciones para mejorar la gestión de la fracción orgánica de los residuos municipales.

En el ámbito de la Comunidad Valenciana, Plan Integral de Residuos (Comunidad Valenciana, 2019), establece el objetivo de que antes del 2020 todos los municipios y entidades locales responsables de los servicios de recogida de residuos, deben tener implantada una recogida de biorresiduos, con el fin de reducir la emisión de gases de efecto invernadero originados por la eliminación de residuos en vertederos, así como la recogida separada y el tratamiento adecuado de los biorresiduos, para producir compost seguro para el medio ambiente y otros materiales producidos a partir de los biorresiduos.

Castelló de la Plana es una ciudad mediterránea, capital de la provincia de Castellón, ubicada al norte de la Comunidad Valencia con una población de 172.589 habitantes en 2021 (INE, 2021). En el siguiente artículo se analiza la evolución de la generación de bioresiduos en la ciudad de Castelló de la Plana, tras un año desde su implantación. Para ello, se han utilizado dos variables fundamentales, la tasa bruta de recogida por habitante y día (TRD-B), y tras caracterizar una muestra mensual de dichos biorresiduos se ha podido determinar también la tasa neta de recogida por habitante y día (TRD-N). Los resultados, en cuanto a cantidad y calidad, se han comparado con tres experiencias piloto anteriores que se habían desarrollado en la ciudad en los años 2017, 2018 y 2019, respectivamente donde se obtuvo de media una TRD-N de 0,03 kg/hab.día. (Gallardo et al. 2017, 2019, 2021) como se desarrolla en la Tabla 3.1.

Tabla 3.1. Resumen experiencias piloto previas.

Zona	Centro	Norte	Oeste	Grao	Este	Colegios
Población	3.956	1.451	2.244	843	1.820	14.084
Duración	179	179	179	182	182	91
Contenerización (l)	9.600	11.000	14.400	11.000	14.400	96.000
Cont/habitante (l)	2,43	7,58	6,42	13,05	7,91	6,82
Generación bruta (kg)	5.180	12.080	9.200	13.421	14.280	28.526
Generación neta (kg)	4.184	10.051	7.491	12.223	13.969	23.893
% impropios	19 %	17 %	19 %	9 %	2 %	16 %
TRD_B (kg/hab.día)	0,007	0,047	0,023	0,087	0,043	0,022
TRD_N (kg/hab.día)	0,006	0,039	0,019	0,080	0,042	0,019
Resumen		Experiencia 1		Experiencia 2		Experiencia 3*
Población		7.651		2.663		14.084
Lcont/hab		4,57		9,54		6,82
% impropios		18 %		5 %		16 %
TRD_B (kg/hab.día)		0,019		0,057		0,022
TRD_N (kg/hab.día)		0,016		0,054		0,019

*Nota: La columna únicamente incluye los datos correspondientes a la experiencia en los colegios.

3.2. Metodología.

3.2.1. La implantación en la ciudad.

La implantación progresiva del sistema de recogida de la fracción orgánica en la ciudad de Castelló de la Plana comenzó en septiembre de 2020. Tras los primeros meses de implantación, en diciembre de ese mismo año se comenzó a caracterizar durante un año los biorresiduos depositados en contenedor específico mediante muestras mensuales.

La implantación de este nuevo servicio incrementó los costes de la recogida de residuos de la ciudad en casi un 9% (Ayuntamiento Castelló, 2020) y se puede resumir de la siguiente manera:

- Suministro instalación y mantenimiento de 1.098 contenedores de 2.000 litros de capacidad y carga lateral automática (12,72 litros/habitante).
- Pre-recogida diaria de forma manual de los restos depositados fuera de los contenedores, mediante dos camiones volquete baúl, de 4,5 m³.
- Recogida mecanizada diaria, con frecuencia alterna, mediante tres camiones robotizados recolectores de 19 m³ de carga lateral.
- Limpieza de contenedores con una frecuencia mensual, con vehículo robotizado lava contenedores de carga lateral.
- Reducción del servicio de recogida de la fracción resto (o todo en uno), mediante retirada de 400 contenedores de 1100 litros dicha fracción.

3.2.2. Caracterización de la fracción orgánica.

El objetivo principal de las caracterizaciones fue llevar a cabo un seguimiento de la implantación de la recogida selectiva de la FORSU en la ciudad durante un año, lo que permitiría detectar las fortalezas, debilidades y necesidades del sistema, así como orientar las tareas de educación ambiental a poner en marcha con la ciudadanía. Los impropios por definición, son residuos que no deberían estar en el contenedor objeto de estudio, en este caso serán plásticos, vidrio, cartón, textil, etc.

En la actualidad no existe ninguna metodología estandarizada para calcular el número mínimo de muestras en la caracterización de residuos sólidos urbanos, sino que se han desarrollado una gran variedad de métodos distintos que se aplican en función de las condiciones de cada caso y la información que se quiere obtener. De todas ellas, se ha utilizado la metodología desarrollada por la Comisión Europea (2004) para el análisis de residuos sólidos (SWA-Tool). En ella se establecen una serie de recomendaciones y mínimo estándares para correcta caracterización de RSU.

Esta metodología utiliza datos sobre la composición de los residuos (medias y desviaciones estándar) procedentes de estudios piloto o de estudios que se hayan realizado con anterioridad, según la siguiente fórmula:

$$n = \left(\frac{t_{\alpha;n-1} \cdot CV}{\varepsilon}\right)^2 \qquad (1)$$

Donde:

n: Número mínimo de muestras

$t_{\alpha;n-1}$: Desviación del valor medio que se acepta para lograr el nivel de confianza deseado $(1-\alpha)$. *Viene expresado por el coeficiente de confianza de la distribución "t" para un nivel de significación "α" y n-1 grados de libertad. En función del nivel de confianza se usa un valor diferente que viene dado por la forma que tiene la distribución "t" cuando* $n-1=\infty$. *Los valores más frecuentes son:*

- Nivel de confianza 90% → = 1,645
- Nivel de confianza 95% → = 1,960
- Nivel de confianza 99% → = 2,576

CV: Es la varianza que esperamos encontrar en la población, expresada mediante el coeficiente de Variación (en tanto por uno):

$$CV = \frac{s}{-x}$$

Los datos de medias (x) y desviaciones estándar (s) se deben obtener de un estudio piloto previo.

ε : Margen de error máximo que se admite (en tanto por uno).

A la hora de calcular el número mínimo de muestras para determinar la composición de la FORSU recogida selectivamente en Castellón, se ha escogido un nivel de confianza del 95% según lo indicado por la herramienta y un error del 10%. Respecto al error elegido, Pehlken, et al. (2000) consideran adecuado tomar un error del 10% en los muestreos de RSU. Las medias y desviaciones estándar necesarias del contenedor de FORSU se han obtenido de los datos del estudio piloto más reciente realizado en el año 2019 (Gallardo et al., 2021).

En la Tabla 3.2 se muestra el número mínimo de muestras obtenido y todos los datos implicados en la realización del cálculo tras la aplicación de la ecuación 1 a las fracciones consideradas.

Tabla 3.2. Cálculo del número mínimo de muestras.

FRACCIÓN	Experiencia 3 (2019)			$t_{0,05;\infty}$	ε (‰)	n
	Media (%)	Desv. St. (%)	CV (‰)			
Materia Orgánica	74,83	22,86	0,305	1,96	0,1	36

Como se observa en la Tabla 3.2, el número mínimo de muestras necesarias para obtener resultados representativos es de 36 en el caso de la materia orgánica.

Por otro lado, la SWA-Tool indica que es fundamental evaluar los factores que pueden influir en la composición de los residuos, algunos de ellos son: la estacionalidad, la estructura residencial (zona rural, suburbana, centro de ciudad, etc.), el tamaño del contenedor, el sistema de recogida, el origen de los residuos, los factores socioeconómicos o la frecuencia de recogida. Así pues, siguiendo las directrices de la metodología, para poder tener en cuenta la estacionalidad se decidió tomar muestras mensuales a lo largo de todo un año. Mientras que para poder considerar la estructura residencial y los factores socioeconómicos se decidió tomar muestras en cada uno de los 6 distritos en los que se divide la ciudad de Castellón. En total se han realizado 72 caracterizaciones (1 caracterización al mes en cada distrito), por lo que se puede decir que los resultados obtenidos de composición del contenedor de la FORSU son representativos, ya que cumplen con el número mínimo de muestras necesarias (Tabla 3.2).

Por último, una vez conocido el número de caracterizaciones realizadas, se pueden calcular el error exacto que se ha cometido despejando de la ecuación 1 el error (Ɛ). Así pues, cuando n=72, el error asumido es del 5%.

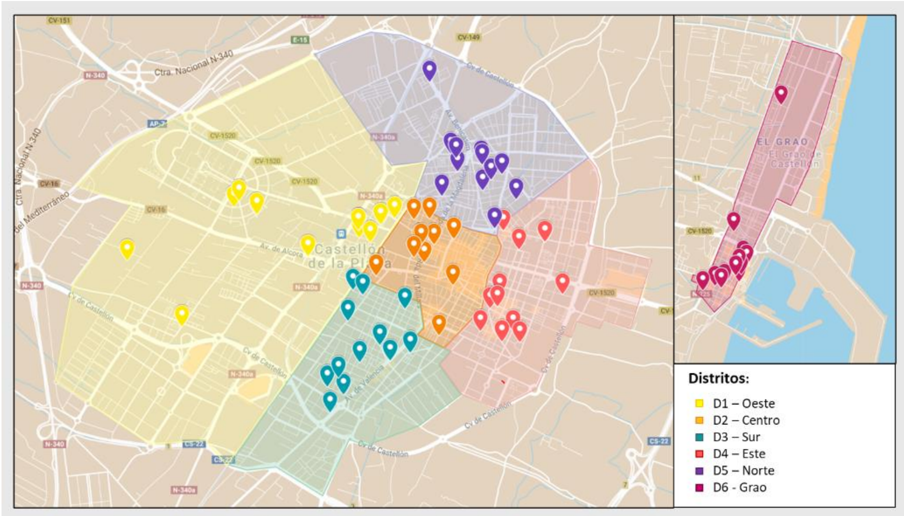

Figura 3.1. Ubicación de la muestra de contenedores elegida para su caracterización.

Por lo tanto, la muestra que se caracteriza para cada distrito corresponde a un contenedor procedente de cada uno de ellos. Además, como se ha indicado anteriormente, el tamaño de muestra es un contenedor de fracción orgánica de 2.000 litros, sin tener en cuenta la cantidad de residuos contenidos dentro del mismo. Para su caracterización, estos contenedores fueron llevados a la planta de transferencia de RSU de RECIPLASA en Almazora. El periodo de análisis fue el comprendido entre el 1 de diciembre de 2020 y el 30 de noviembre de 2021.

Figura 3.2. Contenedores FORSU preparados para su caracterización.

3.3. Resultados.

3.3.1. Análisis cuantitativo. Generación de biorresiduos en la ciudad.

En la Tabla 3.3 se muestran los pesajes y ratios obtenidos respecto a la fracción orgánica a lo largo de periodo indicado. Debe reseñarse que, dado que las rutas de recogida comprenden varios distritos, no ha sido posible obtener los pesajes de cada uno de ellos de manera diferenciada.

Tabla 3.3. Recogida selectiva de biorresiduos en contenedor marrón.

Año	Mes	FORSU (kg)	TRD-B (kg/hab-dia)
2020	Diciembre	230.720	0,045
2021	Enero	240.880	0,045
	Febrero	231.000	0,048
	Marzo	251.600	0,047
	Abril	246.420	0,048
	Mayo	251.880	0,047
	Junio	239.500	0,046
	Julio	205.800	0,038
	Agosto	196.870	0,037
	Septiembre	243.800	0,047
	Octubre	244.200	0,046
	Noviembre	230.840	0,045
TOTAL		2.813.510	-
MEDIA MENSUAL		234.456	0,045

La cantidad de FORSU bruta total recogida selectivamente en la Ciudad de Castellón, desde diciembre de 2020 hasta noviembre de 2021 ha sido 2.813.510 kg, lo que supone una media mensual de 234.456 kg. Este dato representa aproximadamente un 4% del total de los residuos generados en Castelló de la Plana mensualmente, ello que confirma que las áreas densamente pobladas tienen dificultades para lograr altas tasas de recogida selectiva de sólidos municipales (Rolewicz-Kalinska et al., 2020).

En cuanto a su evolución, destaca la tendencia ascendente en la cantidad recogida desde la implantación del contenedor marrón hasta marzo, como consecuencia de la buena acogida y de las campañas de sensibilización previas realizadas. Así, los meses donde la recogida de FORSU bruta a ha sido mayor corresponden a marzo, abril y mayo.

Su posterior estabilización y su descenso en los meses de verano son consecuencia del periodo vacacional, y es idéntico a lo que ocurre con la generación global de residuos en la ciudad (Figura 3.3) debido a la población flotante negativa que tiene la ciudad en los meses de verano. Finalmente, la cantidad de FORSU bruta recogida vuelve a valores parecidos a los de primavera a partir de septiembre.

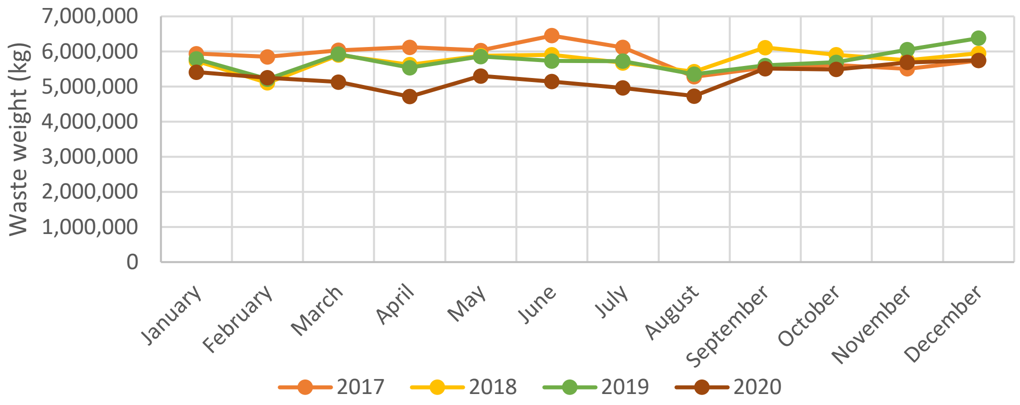

Figura 3.3. Estacionalidad en la generación total de residuos de Castelló de la Plana.

3.3.2. Análisis cualitativo. Tasas de impropios.

Tras las caracterizaciones realizadas, en la Tabla 3.4 se muestran los porcentajes de materiales impropios obtenidos en las muestras mensuales de cada uno de los seis distritos de la ciudad de Castelló de la Plana, así como los pesajes brutos y netos de la FORSU.

Tabla 3.4. Caracterización de la FORSU recogida selectivamente.

Impropios (%)	Oeste	Centro	Sur	Este	Norte	Grao	Global	Bruto (kg)	Neto (kg)	TRDn (kg/hab.-día)
Diciembre	14.95	35.94	41.41	22.35	7.89	6.80	25.80	230,720	171,203	0.033
Enero	28.82	46.38	18.57	30.48	27.29	51.05	34.47	240,880	157,855	0.030
Febrero	44.43	22.81	37.94	44.24	43.83	40.36	38.74	231,000	141,512	0.029
Marzo	42.53	43.84	58.37	22.27	46.30	32.71	43.02	251,600	143,371	0.027
Abril	32.07	39.96	45.46	46.43	71.32	29.64	41.44	246,420	144,292	0.028
Mayo	58.80	40.80	37.35	18.22	38.86	47.11	37.19	251,880	158,212	0.030
Junio	23.20	87.32	50.13	37.55	57.80	61.33	47.72	239,580	125,200	0.024
Julio	36.97	44.56	58.22	39.47	58.69	0.00	38.35	205,800	126,879	0.024
Agosto	32.22	45.05	46.53	40.20	42.09	56.31	42.78	196,860	112,657	0.021
Septiembre	45.33	52.05	52.46	40.85	27.68	72.50	46.86	243,800	129,545	0.025
Octubre	12.05	48.66	29.99	60.58	56.23	56.28	36.99	244,220	153,877	0.029
Noviembre	32.92	47.52	68.77	53.60	30.43	54.80	45.28	230,840	126,327	0.024
Media	31.02	43.68	43.53	36.28	43.76	43.55	39.86	234,467	140,911	0.027

En cuanto a la FORSU neta recogida, se han recogido 1.690.930 kg de materia orgánica compostables que incluye: restos de comida, restos vegetales y otros materiales aptos para su compostaje. Esto supone una recogida media mensual de 140.911 kg de materia orgánica (Tabla 3.4). Respecto a su evolución, se observa un descenso desde diciembre hasta febrero, estabilizándose y volviendo a aumentar en mayo. La menor cantidad de

FORSU neta recogida se da en el periodo de junio a noviembre, salvo por un pequeño ascenso puntual en octubre.

En comparación con los estudios anteriores, las caracterizaciones realizadas en las experiencias piloto mostraban un porcentaje de impropios muy inferior al detectado durante el primer año de implantación global en la ciudad. Así en los distritos Centro, Norte y Oeste que eran los que peores resultados mostraban en las experiencias piloto (20% de impropios) en esta ocasión se encuentran por encima del 34% y en dos de ellos se supera el 40% de impropios. Por su parte, los distritos Este y Grao que mostraban porcentajes de impropios inferiores al 10% en las pruebas realizadas, revelan que durante el primer año de implantación dichos impropios también están en sintonía con el resto de la ciudad rondando el 40%. A destacar el incremento de impropios hallado en el distrito Este, que de un 2% en su experiencia piloto, pasa a un 38% de residuos impropios.

En comparación con otras ciudades de tamaño similar y también con recogida contenerizada en carga lateral, como el núcleo urbano de Terrasa (10,69% impropios), Santa Coloma de Gramanet (7,56% de impropios) u Hospitalet del Llobregat (5,39% de impropios) (SDR, 2021), los porcentajes de impropios de Castelló de la Plana son más elevados.

De media, el distrito donde la FORSU recogida selectivamente tiene mayor calidad para su compostaje es el distrito Oeste, puesto que el contenido en materia orgánica se encuentra cercano al 70%. En el resto de los distritos, se ha obtenido una calidad muy baja (alrededor del 56% de materia orgánica) con un contenido en impropios muy elevado, superior al 40%.

Si se observan los datos mensuales, es durante el mes de diciembre dónde mejores porcentajes de impropios se han obtenido. Ello debe llevar a una reflexión profunda sobre la influencia de la pandemia declarada en marzo de 2020, por COVID-19 y en particular la tercera ola que fue la que golpeó con fuerza en el país. Tal vez, la ergonomía de este nuevo contenedor (pedal, palanca, etc.) haya motivado que a él se deriven residuos que deben ir en el contenedor resto, siendo éste en la ciudad de Castelló de la Plana de apertura manual con tapa de 1x1 metros, aproximadamente. Este hecho podría ser objeto de análisis en futuros estudios.

En cuanto a los pesajes netos (FORSU neta), diciembre, enero, mayo y octubre se corresponden con los meses donde la cantidad de materia orgánica compostable recogida ha sido más alta; por el contrario, en agosto esta recogida ha sido la menor.

Respecto a la evolución, se observa un descenso en la cantidad de materia orgánica neta recogida desde diciembre hasta febrero lo que indica que la calidad de la FORSU va disminuyendo desde el inicio del estudio. Entre los meses de febrero a abril se produce una estabilización de la cantidad recogida, ascendiendo de nuevo en mayo. A continuación, en el periodo estival que va desde junio hasta septiembre, la FORSU neta cae por debajo de la media, recogiéndose para esos meses la menor cantidad de materia orgánica compostable y por ende la mayor cantidad de impropios. Finalmente, entre agosto y octubre vuelve a aumentar, para descender de nuevo en el mes de noviembre.

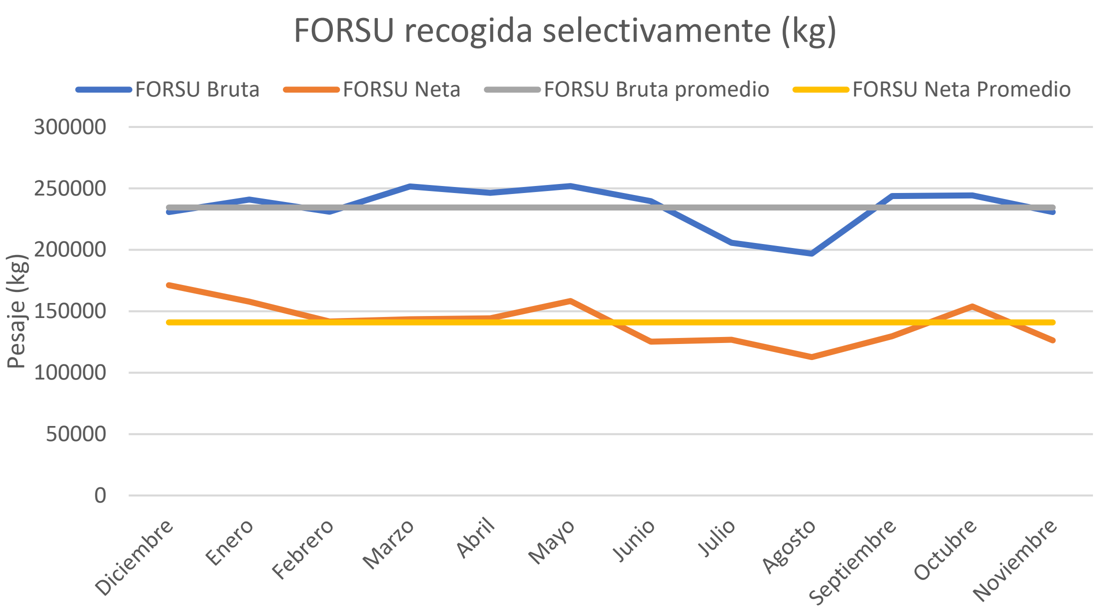

Figura 3.4. Evolución de la FORSU recogida selectivamente en Castellón de diciembre 2020 a noviembre 2021.

3.3.3. Evolución de las TRD.

Respecto a la tasa bruta, como se muestra en la Figura 3.5, para el periodo de diciembre 2020 a noviembre 2021, la TRD-B media ha sido de 0,045 kg/hab-día. Los meses donde esta tasa ha sido mayor corresponden a febrero, marzo, abril, mayo y septiembre de 2021 con tasas del 0,047 – 0,048 kg/hab-día; mientras que en septiembre y octubre de 2020 y julio y agosto del 2021 se obtuvieron los valores más bajos, por debajo de 0,040 kg/hab-día. Si se atiende a su evolución, se observa un claro ascenso en la TRD-B hasta febrero, el cual corresponde al periodo de adaptación de los ciudadanos a este nuevo tipo de recogida y al aumento paulatino de su colaboración. Como ocurre con la cantidad bruta recogida, la tasa se estabiliza entre los meses de febrero a junio, desciende durante los meses estivales (julio y agosto) y aumenta de nuevo tras el verano. Cabe señalar que en los meses de octubre y noviembre de 2021 se aprecia de nuevo un leve descenso.

De manera global, la TRD-B obtenida es ligeramente inferior a los valores obtenidos en la prueba piloto del año 2018 donde se obtenía una tasa bruta de recogida diaria por habitante y día de 0,054. No obstante, se han superado ampliamente los valores de las experiencias 1 y 3, que no alcanzaban los 0,02 kg/hab-día (Tabla 3.1).

En comparación con las ratios de otras ciudades en las que el contenedor marrón se implantó hace más de cinco años, como Barcelona (ARC, 2021) o Madrid (Madrid, 2021), los datos de Castelló de la Plana todavía se encuentran lejos de alcanzar sus TRD-B (0,17 kg/hab-día y 0,15 Kg/hab-día, respectivamente). No obstante, si se comparan los datos con ciudades donde la implantación ha sido más reciente, como Valencia con 0,07 kg/hab-día (Valencia, 2021) o Bilbao con 0,02 kg/hab-día (Bizkaia, 2021), las ratios están más próximas.

Respecto a la tasa neta de recogida por habitante y día, al no disponerse de pesajes por distritos la valoración debe realizarse en el global de la ciudad. En este sentido, la TRD-N obtenida (0,027 kg/hab-día) supera a las que se obtuvieron en los años 2017 y 2019, pero es sensiblemente inferior a prueba piloto del año 2018 realizada en los distritos Este y Grao (0,054 kg/hab-día). La TRD-N fue más alta en los meses iniciales del estudio (diciembre y enero), junto con mayo, con valores entre el 0,030 – 0,033 kg/hab-día; por el contrario, en agosto se obtuvo la más pequeña, 0,021 kg/hab-día, igual que ocurre con la TRD-B.

Respecto a la evolución (Figura 3.5), se observa un descenso en la TRD-N desde diciembre hasta marzo, lo que a su vez indica una disminución de la calidad de la FORSU recogida, ya que en ese mismo periodo la TRD-B aumenta. Entre los meses de marzo a mayo la TRD-N crece levemente, sin embargo, vuelve a descender con valores por debajo de la media desde junio hasta septiembre, alcanzando su mínimo en agosto. Finalmente, en septiembre y octubre se produce un aumento de la TRD-N, para volver a bajar en noviembre. Así pues, de forma general, el gráfico muestra una tendencia descendente de la TRD-N durante el periodo que dura el estudio.

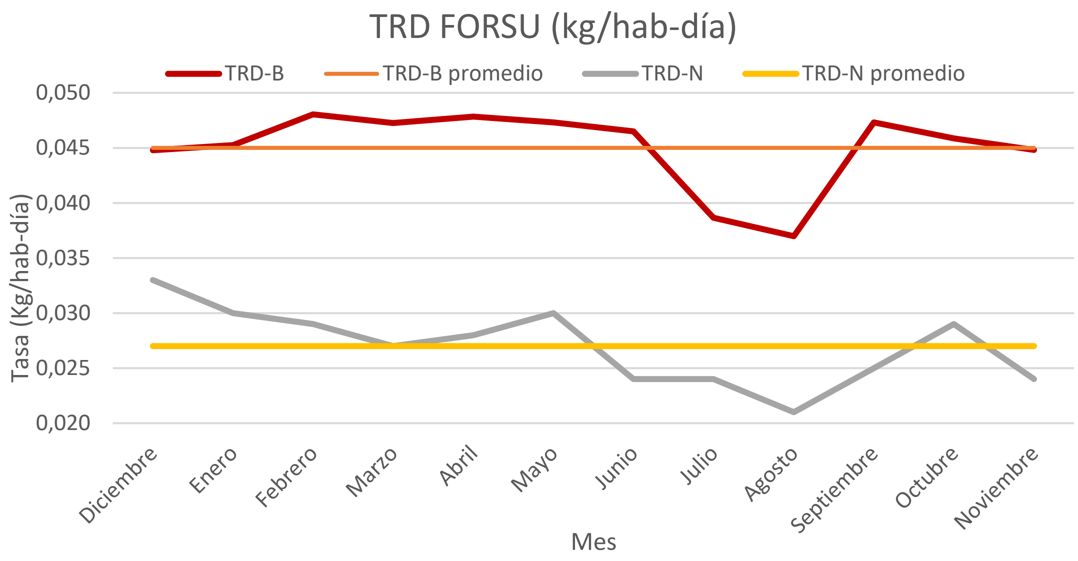

Figura 3.5. Evolución de la TRD de la FORSU de diciembre 2020 a noviembre 2021.

3.4. Conclusiones.

Las experiencias piloto llevadas a cabo en la ciudad durante los años 2017, 2018 y 2019 de entre tres y seis meses de duración, pusieron de manifiesto algunos datos a tener en cuenta de cara a la implantación definitiva del contenedor marrón en la ciudad de Castelló de la Plana. De ellas, se observó que cuanto más alta era la ratio de contenerización (litros/habitante) mejores TRD bruta y neta se obtenían. Por ello, durante la implantación de la fracción orgánica se en la ciudad se estableció una cifra final de 12,72 litros por habitante.

En cuanto a los resultados cuantitativos, durante el primer año de implantación se han recogido selectivamente 2.813.510 kg de biorresiduos, con una tasa por habitante y día (TRD-B) de 0,045 próxima a ciudades con implantación reciente del contenedor marrón.

En cuanto a la calidad de los biorresiduos, globalmente, la FORSU recogida de manera selectiva para la ciudad de Castellón de media está compuesta por un 60,14% de materia orgánica y un 39,86% de impropios, lo que supone una calidad baja o muy baja para su compostaje. De forma general, se puede decir que la calidad de la FORSU ha sido más alta en los 6 primeros meses de estudio (invierno-primavera) que en los 6 últimos (verano-otoño), es decir, con el paso del tiempo ha ido evolucionando negativamente.

Para el periodo de diciembre 2020 a noviembre 2021, la TRD-N media ha sido de 0,027 kg/hab-día. Respecto a su evolución, se observa una clara disminución hasta marzo, lo que indica una bajada de la calidad de la FORSU recogida, ya que en ese mismo periodo la TRD-B aumentó. De forma general, se pude decir que durante los 12 meses del estudio la TRD-N tiene una tendencia descendente.

De media, el distrito donde la FORSU recogida selectivamente tiene mayor calidad para su compostaje es el distrito Oeste. Este distrito es el que cuenta con una media de edad más baja en la ciudad, lo cual puede evidenciar una relación que sea objeto de análisis en posteriores estudios.

Para mejorar estos resultados, serán necesarias acciones de educación y sensibilización ambiental, enfocadas a concienciar a los ciudadanos por ejemplo en el uso de la bolsa adecuada (compostable) ya que es uno de los impropios más comunes en el contenedor de orgánica. Otras medidas de mayor envergadura consistirían en el cambio de modelo de recogida o la implantación de sistemas de identificación del productor.

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4. Sustainable selection of waste collection trucks considering feasible future scenarios by applying the Stratified Best and Worst Method.

4. SUSTAINABLE SELECTION OF WASTE COLLECTION TRUCKS CONSIDERING FEASIBLE FUTURE SCENARIOS BY APPLYING THE STRATIFIED BEST AND WORST METHOD.

Héctor Moreno Solaz[1, *], Miguel-Ángel Artacho-Ramírez[1], Pablo Aragonés-Beltrán[1] and Víctor-Andrés Cloquell-Ballester[1]

[1]Project Management, Innovation and Sustainability Research Center (PRINS), Universitat Politècnica de València, 46022 Valencia, Spain; hcmoso@gmail.com (H.M.-S); miarra@dpi.upv.es (M.-Á.A.-R.); aragones@dpi.upv.es (P. A.-B); vacloque@dpi.upv.es (V.-A.C.-B.)

*Correspondence: hcmoso@gmail.com

Abstract.

Municipal solid waste (MSW) management is vital in achieving sustainable development goals. It is a complex activity embracing collection, transport, recycling, and disposal; and whose management depends on proper strategic decision-making. The use of decision support methods such as multi-criteria decision-making (MCDM) is widespread in MSW management. However, their application mainly focuses on selecting plant locations and the best technologies for waste treatment. Despite the critical role played by transport in promoting sustainability, MCDM has seldom been applied for the selection of sustainable transport alternatives in the field of MSW management. There are a few MCDM studies about choosing waste collection vehicles, but none that include the most recent green vehicles among the options or consider feasible future scenarios. In this article, different engine technologies for collection trucks (diesel, compressed natural gas (CNG), hybrid CNG-electric, electric, and hydrogen) are evaluated under sustainability criteria in a Spanish city by applying the stratified best and worst method (SBWM). This method enables considering the uncertainty associated with future events to establish various feasible scenarios. The results show that the best-valued options are electric and diesel trucks, in that order, followed by CNG and hybrid CNG-electric, and with hydrogen-powered trucks coming last. The SBWM has proven helpful in defining a comprehensive framework for selecting the most suitable engine technology to support long-term MSW collection. Considering sustainability among the criteria and feasible future scenarios in waste management collection decision-making provides more comprehensive and conclusive results that help managers and policymakers make better informed and more reliable decisions.

Keywords.

Municipal solid waste; waste collection trucks; MCDM; stratified best and worst method; stratification; sustainable mobility.

4.1. Introduction.

All human activities should care for and preserve the environment by meeting current ecological requirements and standards. Studies and efforts to control the environmental impact of human actions have grown exponentially in recent years [1]. Hence, sustainability is gradually being consolidated as a premise in decision-making processes, especially in those expected to have a long-term impact. Municipal solid waste (MSW) management, defined as the management of domestic and commercial garbage generated under the jurisdiction of a municipal body [2] is not an exception. Waste disposal and waste handling are global problems [3] and many countries are implementing mitigation strategies in MSW to reduce greenhouse gas (GHG) emissions [4]. Additionally, MSW management is called to play a relevant role in the circular economy because landfills as end-of-life product receivers could promote remanufacturing and zero-waste implementations. As a result, sustainable waste management is crucial for reaching sustainable development goals and a more sustainable society [5]. For this reason, the collection, transfer, and transport of MSW are some of the most challenging tasks for local municipalities and represent a significant portion of municipal expenditure [6]. To pursue sustainability, MSW management must face complex mobility challenges. A well-designed transport system improves delivery operations and quality of life by reducing costs, resources, and energy consumption [7]. The collection of MSW is carried out by varyingly sized collecting vehicles working within schedules that collect waste from bins in the streets until full. The waste is then transported to treatment plants or intermediate transfer stations using powerful trucks that consume a lot of energy. This energy currently comes mainly from petroleum derivatives, specifically diesel, that produce high levels of GHG emissions and noise [8]. In addition, in recent years, European regulations on selective collection have forced municipalities to increase the number of routes and vehicles to collect five different fractions of waste (glass, paper & cardboard, packaging, biowaste, and mixed waste) [9], [10]. Additionally, door-to-door collection is becoming more frequent in many municipalities since this system achieves the best separation ratios [11]. Therefore, the optimal design of routes, the location of transfer plants, and the type of collection truck are vital to obtaining cost-effective and environmentally friendly solutions [12]. However, although current technological alternatives for transport appear to be clean and sustainable, there is much uncertainty about their global ecological fit and long-term deployment [13]. Thus, apart from the interaction of economic, institutional, social, political, and environmental factors, there is uncertainty about regulation, normalization, and deployment of existing green vehicles. These factors and uncertainties make it difficult to find the suitable alternative that best fits real-world conditions.

In this scenario, multi-criteria decision-making (MCDM) methods are appropriate for choosing the best engine technology because they can concurrently synthesize these conflicting criteria and achieve a trade-off among them [14]. MCDA concepts, methods, and applications have been widely studied in the operational research literature [15], [16]. Among the better-known models are those based on multiple attribute utility theory (MAUT) [17], analytic hierarchy process (AHP) [18] and analytic network process (ANP) [19], as well as outranking methods such as ELECTRE [20] or PROMETHEE [21] or a technique for order preference by similarity to ideal solution (TOPSIS) [22]. These methods assume that the decision-maker has a certain level of knowledge about the alternatives and the consequences of the choice. When there is vagueness or imprecision in the data or in the judgments in the context of the decision problem, fuzzy MCDM can be used [23].

MCDM has been extensively used for decades in various waste management problems and circumstances. However, its application mainly focuses on selecting suitable locations and waste treatment, disposal, and recycling technologies [24]. To the authors' knowledge, the selection of truck engine technologies, including the most recent green vehicles, has not yet been addressed. Moreover, the most applied MCDM methods in waste management have been AHP (47%), followed by ANP (9%), and VIKOR (7%) [24]. Studies including uncertainty management are less frequent (37%), and only one percent deal with the probability of different scenarios occurring [24]. After making a decision, the decision-maker frequently becomes hesitant about whether the proper weightings were assigned to the criteria, given that various possibilities may occur in the near future [25]. Thus, as a complex system operating in volatile, uncertain, complex, and ambiguous (VUCA) environments, waste management should develop plans to manage uncertainty considering feasible future scenarios.

This paper aims to select the best engine technology for waste collection trucks in the city of Castellon, considering sustainability and feasible future events that could in the long term affect the decision to be made at present. The paper applies a recent MCDM method, the stratified MCDM (SMCDM) [25], which is based on the best and worst method (BWM) [26] and enables computing weightings for criteria for feasible future scenarios. The starting hypothesis is that considering sustainability among criteria and feasible future scenarios in waste management collection decision-making will provide more comprehensive and conclusive results to help managers and policymakers make more informed and reliable decisions.

The remainder of this paper is structured as follows. Section 2 provides a background of previous academic works on MCDM methodologies in the context of waste collection and the research gap of the paper. In Section 3, the methodology of this research is presented, and Section 4 contains the main results of the application of this methodology in the city of Castellon (Spain) for selecting among vehicle motor options. A discussion of the results is then presented in Section 5. Finally, Section 6 provides the conclusions, the limitations of the study, and suggests research work.

4.2. Background.

Multi-criteria decision-making (MCDM) involves a broad range of methods to support decision-making to reach a compromise when there are multiple criteria. The most used methodologies are the analytic hierarchy process (AHP), outranking procedures, and a technique for ordering preferences by similarity to an ideal solution (TOPSIS) [27].

Several studies use MCDM techniques to deal with waste management problems. Many of these studies focus on either locating waste treatment plants [28]–[31] or on technological decisions within the broad field of waste treatment [14], [32]–[34]. However, most only describe one scenario without considering the impact of future situations and the probabilities of occurrence.

A feasible future scenario is a possible or trending situation that can be imagined or achieved by applying different variables (including political, economic, social, and cultural). In this sense, SMCDM was created to consider feasible future scenarios in the decision-making process.

SMCDM is based on the concept of stratification (CST) introduced by Zadeh [35]. The author considered a series of stratum or multiple levels through which the system transits from the input to a given target state or desired level. The concept has proven helpful in logistic informatics [36], artificial intelligence, natural language processing, big data, and robotics [37]. Asadabadi [25] was the first author to apply the CST in MCDM, and first coined the term SMCDM in the literature by considering future events that might influence decision-making. Single and integrated uses of SMCDM can be found in the literature. It has been applied for humanitarian aid distribution center selection in a post-disaster planning phase [38], for long-term planning in flood risk management [39], for implementation of Industry 4.0 in the mobility sector [40], and for selecting sustainable circular suppliers [41].

Because of its newness, little research on applying SMCDM can be found for waste management. As stated by Torkayesh et al. [24], only one percent of the existing studies with uncertainty-based MCDM methods in this field use the concept of stratification. As remarkable exceptions, we can find the work of Torkayesh et al. [42], applying SMCDM for waste disposal technology selection, Torkayesh & Simic [43], using the method for recycling facility location and the work of Tirkolaee et al. [44], employing SMCDM for sustainable healthcare landfill location selection. However, a developing trend of using uncertainty-based MCDM methods has arisen [24] because their greater reliability and accuracy ensure more scientifically robust and informed decision-making processes. Specifically, SMCDM enables decision-makers to develop plans considering different scenarios, and uncertainty can be managed to select the option that best fits real-world conditions.

Regarding the choice of vehicles, several MCDM studies compare options for motorizing people transport [45], [46]; or more recently, mobility sharing systems [47]. Furthermore, in the last few years, some authors have focused on aspects related to electric vehicles, such as multiple fuel supply systems [48], smart charging scheduling at workplaces [49], or the management of lithium-ion batteries at the end of their lives [50]. However, there is little academic literature on analyzing available technologies for waste collection truck motors using MCDM, and none that considers feasible future scenarios simultaneously.

Table 4.1 summarizes the literature review on the application of MCDM techniques for the collection and transport of waste. A survey has been carried out on the literature using the following keywords: MCDM; multi-criteria; waste collection; MSW; vehicles; trucks; technologies; fuel; electric; and transport.

Table 4.1. Application of MCDM techniques in waste collection and transportation.

Work	Country	Problem description	Simple MCDM	Hybrid MCDM	Assessed Alternatives	Considering future scenarios
[51]	USA	Rank fuel alternatives for waste collection vehicles	-	TOPSIS, SAW	Waste collection trucks	No
[52]	Turkey	Rank waste collection systems in a smart city	TOPSIS	-	Technologies for smart collection	No
[53]	Tunisia	Route planning with GIS tools	ELECTRE III	-	Route optimization	No

[54]	Serbia	Rank fuels for waste collection	WASPAS	-	Waste collection trucks	No
[55]	Egypt	Optimizing construction and demolition waste transportation	COPRAS OCRA	-	Number and volume of vehicles	No
[56]	India	Evaluate different collection alternatives	Linear optimization model	-	Cost-benefit vs home segregation degree	Yes
[57]	Saudi Arabia	Choose recycling collection method for recovered fiber	-	BWM, TOPSIS	MCDM results comparation	No
[58]	Pakistan	Provide a facilitating framework incorporating circular economy principles	-	SWARA, VIKOR	Critical facilitators for the adoption of smart waste management	No
[59]	Saudi Arabia	Complete solid waste collection system selection	T-SHFS	-	Smart technologies for waste collection	No
[60]	Turkey	Select most appropriate policy for small household appliance collection methods		-	Small household appliance collection systems	No
[61]	Spain	Design methodology to evaluate circularity alternatives for construct and demolition waste	VIKOR	-	Types of recycled concrete, influenced by transport distances	No
[62]	Canada	Design waste collection program	CBA	-	Levels of satisfaction	No
[63]	Bosnia and Herzegovina	Selecting the best municipal solid waste collection scenario	-	AHP, VIKOR	Degrees of waste separation	No
[64]	Iran	Assess environmental problems derived from petroleum products in transportation	PROMETHEE	-	Fuels for light-duty vehicles	Yes
[65]	China	Locate a recyclable waste transportation vehicle parking center	-	DEMATEL, EW, WASPAS	Facility location	No

[66]	Poland	Planning of waste management systems in urban areas	-	Selection compromise programming	Waste management systems and waste fractions	Yes
[67]	Turkey	Analysis of location selection Problem for underground waste containers	-	MAIRCA, MABAC	Waste container location	No
[68]	Iran	Design transportation system in industrial waste management	-	BWM, PROMETHEE	Routes and fleet optimization	No
[69]	Iran	Define new model for urban waste collection and energy generation	-	NSGA-II, MOPSO	Integrated waste management models	No
[70]	Iran	Minimize the transportation cost and maximize the suitability	-	DELPHI, TOPSIS, E-CONSTRAINT	Holistic decision support tool	No
[71]	Malaysia	Define a Route optimization method combinate with GIS	AHP	-	Route optimization	No
[72]	Turkey	Evaluate smart waste collection systems based on internet of things	-	CODAS and IVq-ROFSs	Smart waste collection alternatives	No
[73]	Italy	Minimize operational costs and environmental impact of MSW management (heuristic approaches)	BWM	-	Algorithms for routes optimization	No
[74]	India	Mitigate the interacting barriers to online e-waste collection platforms	DEMATEL	-	Strategies for mitigating existing barriers	No
[75]	Italy	Evaluate smart reverse logistics development scenarios	-	Fuzzy DANP and fuzzy COBRA	Scenarios integrating Industry 4.0 technologies	No
[76]	India	Evaluate different collection alternatives	AHP	-	MSW collection and transportation methods and vehicles	No

As can be seen in Table 4.1, none of these academic works apply techniques that consider the occurrence of feasible future scenarios using the stratified BWM (SBWM). It is possible using CST to assess each criterion under each foreseen scenario [25]. This approach provides this research with considerable potential because it enables important decisions to be made, such as selecting waste collection trucks by considering feasible future events that will probably affect the final suitability of choice.

4.2.1. Research gap and contributions.

The inclusion of uncertainty management in MCDM applied to waste management is still far from frequent – but the number of examples continue to grow given its reliable results. Using the concept of stratification (CST) and considering future scenarios in the decision-making process is even less frequent and practically residual in MSW [24]. To the authors' knowledge, no MCDM study has included the most recent green vehicles as alternatives for selecting truck engine technologies in MSW management. Thus, the present work tries to fill these gaps in the literature by applying the SMCDM to choose the most suitable engine technology for MSW collection trucks in the city of Castellon. Moreover, with the inclusion of sustainability criteria in the decision-making process, the paper defines a comprehensive framework to select the most suitable engine technology for long-term MSW collection.

4.3. Methodology.

The objective is to select the best engine technology for waste collection trucks considering feasible future events. A MCDM known as the stratified best and worst method (SBWM) has been chosen [42] as it considers feasible future scenarios when prioritizing available alternatives. The SBWM is an extension of the best and worst method (BWM), which is used to assess and compare the criteria chosen in each possible scenario.

4.3.1. The stratified best and worst method (SBWM).

The best and worst method is a popular multi-criteria decision-making (MCDM) method developed by Rezaei [26] which solves the inconsistency problem generated with AHP [77]. Torkayesh et al. [42] recently extended this method, considering different future scenarios, and developed the SBWB as follows:

Step 1. Determine a set of decision criteria $\{c_1, c_2, .., c_n\}$ that should be used to arrive at a decision.

For example, when choosing a house, the criteria could be C1, size; C2, availability of public transportation; and C3, price.

Step 2. Possible future scenarios are identified because they can change the decision-making process.

Following the example, three scenarios could be S1, current situation; S2, family growth; and S3, workplace change.

Step 3. Probabilities for transitioning between scenarios are assessed to build the transition probability matrix. In other words, experts determine the likelihood of the occurrence of each scenario based on historical data and their expertise.

Simplifying the probabilities could be 50% in the first case, 30% in the second, and 20% in the third. The probability matrix would be (0.5, 0.3, 0.2).

Step 4. Based on expert knowledge, determine the best (e.g., most desirable, most important) and worst (e.g., least desirable, least important) criteria for each scenario. No comparison is made at this stage.

For example, the best criteria in the first scenario could be price, and the worst could be size. This evaluation must be made in each scenario because each can differ.

Step 5. Determine, for each scenario, the preference of the best criterion over other criteria using a number between 1 and 9, according to this scale:

1: equal importance, 2: between equal and moderate, 3: moderately more important than, 4: between moderate and strong, 5: strongly more important than, 6: between strong and very strong, 7: very strongly more important than, 8: between very strong and absolute, 9: absolutely more important than.

The resulting best-to-others vector would be $A_B = (a_{B1,} a_{B2,} \dots, a_{Bn})$, where a_{Bj} j indicates the preference of the best criterion B over criterion j. It is clear that $a_{BB} = 1$.

Making the pairwise comparison, an example of a best-to-others vector for the first scenario could be (7,3,1). The same is done in each of the three scenarios.

Step 6. Determine, for each scenario, the preference of all the criteria over the worst criterion using a number between 1 and 9, with the scale of step 5. The resulting others-to-worst vector would be $A_W = (a_{1W,} a_{2W,} \dots, a_{nW})^T$, where a_{jW} indicates the preference of the criterion j over the worst criterion w, and $a_{WW} = 1$.

In the example, the others-to-worst vector in the first scenario could be (1,4,6). The same is done in each of the three scenarios.

Step 7. Find the optimal weights for each scenario $(w_1^*, w_2^*, \dots, w_n^*)$. The optimal weight for the criteria is the one where, for each pair of w_B/w_j and w_j/w_W, we have $w_B/w_j = a_{Bj}$ and $w_j/w_W = a_{jW}$. To satisfy these conditions for all j, we should find a solution where the maximum absolute differences $\left|\frac{w_B}{w_j} - a_{Bj}\right|$and $\left|\frac{w_j}{w_W} - a_{jW}\right|$ for all j is minimized. Considering the non-negativity and sum condition for the weights, Eq. (1) results:

$$\min \max_j \left\{\left|\frac{w_B}{w_j} - a_{Bj}\right|, \left|\frac{w_j}{w_W} - a_{jW}\right|\right\},$$

s.t.

$$\sum_j w_j = 1 \qquad (1)$$

$$w_j \geq 0, \text{ for all } j$$

This can be transferred to the Eq. (2):

$$\min \xi$$

s.t.

$$\left|\frac{w_B}{w_j} - a_{Bj}\right| \leq \xi, \text{ for all } j \qquad (2)$$

$$\left|\frac{w_j}{w_W} - a_{jW}\right| \leq \xi, \text{ for all } j$$

$$\sum_j w_j = 1$$

$$w_j \geq 0, \text{ for all } j$$

Optimal weights $(w_1^*, w_2^*, \dots, w_n^*)$ and $\xi^*$are then obtained.

Following with the example,

$$\left|\frac{w_3}{w_1} - 7\right| \leq \xi,$$

$$\left|\frac{w_3}{w_2} - 3\right| \leq \xi,$$

$$\left|\frac{w_2}{w_1} - 4\right| \leq \xi,$$

$$w_1 + w_2 + w_3 = 1,$$

$$w_1, w_2, w_3 \geq 0.$$

So, the weights in the first scenario would be.

$w_1 = 0.0909, w_2 = 0.2545, w_3 = 0.6545, \xi = 0.4010$

The same is done in each scenario to build a matrix criteria/scenario (Table 4.2).

Step 8. The consistency ratio "*CR*" provides a measure of the consistency of a comparison. This ratio is calculated in each scenario using (3).

$$Consistency\ ratio\ (CR) = \frac{\xi}{Consistency\ index} \quad (3)$$

In the example, for the consistency ratio, $a_{Bw} = a_{31} = 7$, the consistency index is 3.37 [26] so the $CR = 0.4010/3.37 = 0.1190$, which means good consistency. The same procedure must be repeated in each scenario.

Step 9. Multiply the weightings in the scenarios using the transition probability matrix to obtain the optimal weights of the criteria.

Once we have the weights in each scenario, we build the matrix (Table 4.2).

Table 4.2. Example of weights of criteria in each scenario.

Criteria	S1	S2	S3
C1	0.0909	0.0600	0.3260
C2	0.2545	0.2560	0.1890
C3	0.6545	0.6840	0.4850

We then multiply the matrix by the transition probability matrix (see step 3), resulting in the optimal criteria weights: C1, 0.1287; C2, 0.2419 and C3, 0.6295.

Step 10. Construct an alternative criteria matrix again using SBWM. In this matrix, each option is evaluated with respect to the selection criteria, and a score is computed for each. Applying BWM in each alternative, an example of an alternative normalized decision matrix with two alternatives (house "A" and house "B") is shown in Table 4.3.

Table 4.3. Example of the alternative normalized decision matrix.

Criteria	House "A"	House "B"
C1	0.4280	0.5720
C2	0.3680	0.6320
C3	0.5040	0.4960

Step 11. Multiply the alternative normalized decision matrix by the optimal weights of the criteria matrix. These will be the final values showing the preference for each technology.

Finally, in the example proposed, we multiply the Table 4.3 matrix by the optimal criteria weights. By doing this, we obtain the final values of our alternatives: house "A" (0.4613) and house "B" (0.5386).

4.3.2. Research methodology.

Once the chosen method is explained, the methodology phases created for this work are:

Phase I. Description of the problem and the specific case study of the city of Castellon.

Phase II. Selection and description of the decision support experts.

Phase III. Identification of the technologies used in waste collection trucks and the method of choosing them, identifying the main available technologies to be evaluated (the alternatives).

Phase IV. Selection of the criteria for choosing a technology based on an academic review and decision-maker experience.

Phase V. Analysis of the feasible future scenarios that will play a role when prioritizing the alternatives.

Phase VI. Definition of the probability occurrence of these feasible scenarios and assessing each criterion by applying BWM (SBWM).

Phase VII. Determination of the optimal weights for each criterion, multiplying the weights obtained in each scenario by the probability of their occurrence.

Phase VIII. BWM application for assessing each of the evaluated technologies (alternatives) for each criterion and answering the question: which technology is better for each of the chosen criteria?

Phase IX. Ranking the available technologies from highest to lowest according to the scores obtained by multiplying the matrices obtained in phases VII and VIII.

Phase X. Conducting a sensitivity analysis.

Figure 4.1 shows a graphical scheme of the methodology followed.

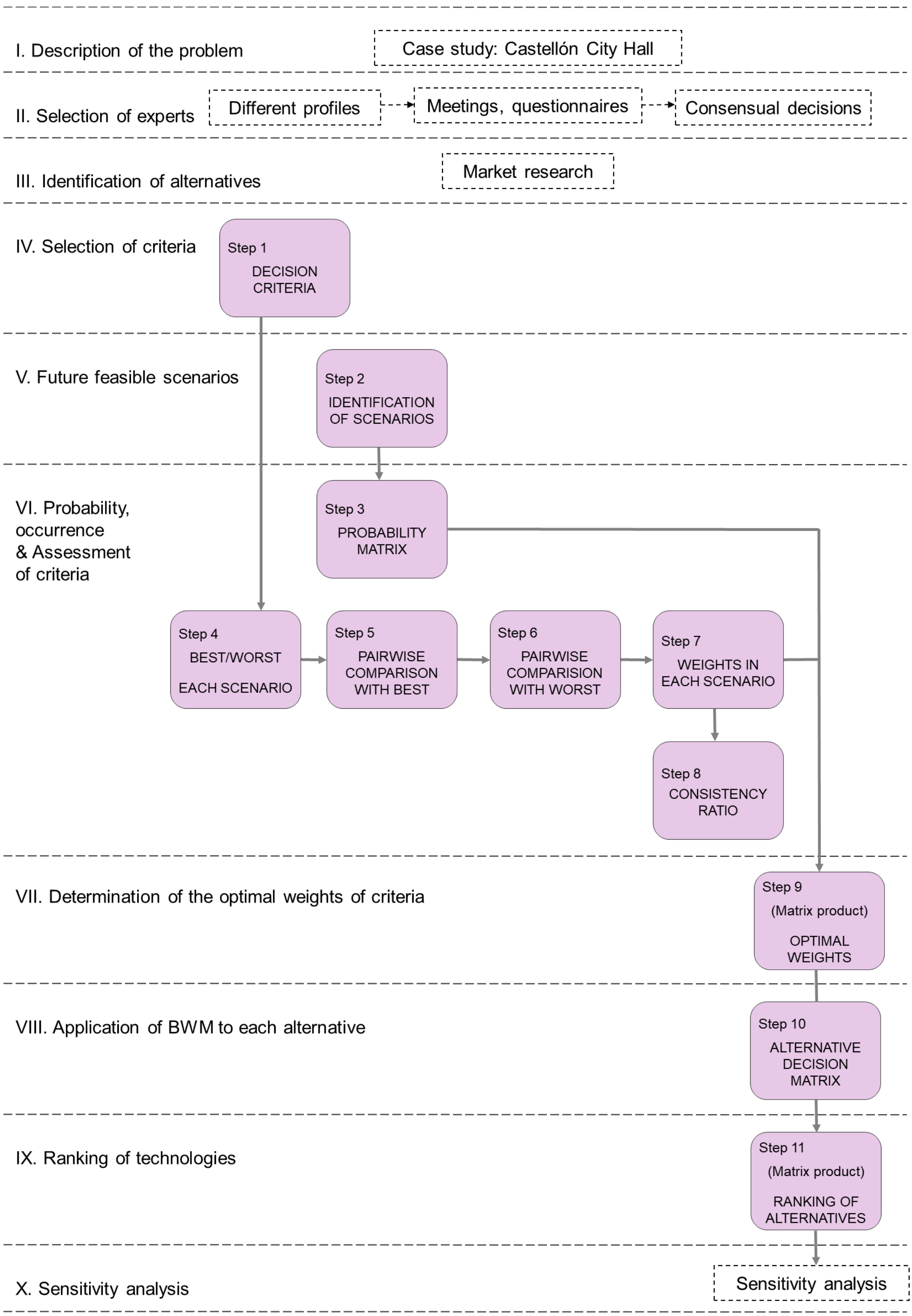

Figure 4.1. Phases of the methodology.

4.4. Case Study: Castellon City Council, Spain.

Castellon is a Spanish Mediterranean city (**Phase I**). It is the capital of the province of Castellon and is in the north of the Valencia Region with a population of 172,589 [78]. Waste generation in the city exceeds 405 kg per inhabitant and year [79]. Collection is divided into five fractions according to current regulations [80] with more than 6900 containers – a containerization ratio of 74.7 liters per inhabitant. Most collection trucks are diesel or CNG and have been in use for over ten years. For this reason, Castellon City Council is considering replacing the fleet.

A group of experts was created (**Phase II**). This group was constituted of five senior managers, one from each of the five main MSW management companies in Eastern Spain, three municipal engineers, two PhD engineers from the Jaime I University, two PhD engineers from Universitat Politècnica de València, a representative from the local transport association, an executive of the Valencian Energy Association, two local political representatives, and four environmental educators from the provincial MSW management board. It is also important to point out that all the scores introduced in the steps of the multi-criteria method – and the decisions made – were established consensually.

First, an informative meeting was held with the experts to gather the necessary data. The main objective was to obtain an initial proposal of technological alternatives, criteria, and scenarios for the case study. The facilitator then wrote and explained the proposal and sent it by email to the experts. Once this part was confirmed, in a second meeting, a questionnaire was delivered to establish the probability of occurrence of each of the scenarios and the criteria were compared in each. In the questionnaire, the questions for each scenario were phrased in this style:

- *In your opinion, what is the probability of occurrence for the different events? Which are the most/least important criteria in this scenario? Finally, compare for each scenario and using the following scale, all the rest of the criteria with the best and worst criterion.*

In a third meeting, a similar questionnaire was delivered. This time the objective was to establish the expert opinions regarding the chosen technologies, and so the following question was asked for each of the criteria:

- *In your opinion, which is the best/worst technology for C1? Finally, compare in each criterion, using the following scale, all the other technologies with the best and the worst technology.*

The experts then identified several technologies available for truck engines and evaluated the options. Currently, the leading technologies available (**Phase III**) in Europe for garbage trucks are diesel (T1), compressed natural gas – CNG (T2), hybrid electric-CNG (T3), electric (T4), and hydrogen (T5).

A series of relevant criteria (**Phase IV**) were then defined as extracted from the scientific literature and confirmed by expert experience. These criteria, fundamental when selecting an engine technology, are the following:

C1: cost of buying the vehicle [51].

C2: operating cost, that is, the servicing cost of the truck (insurance, tires, fuel, etc.) [81].

C3: polluting atmospheric emissions [82], [83].

C4: truck noise [84].

C5: social acceptance of the technology and its use [42].

C6: availability of spare parts [54].

C7: estimated lifetime of the truck. Based on their experience, the group of experts determined that this criterion was crucial for making this kind of decision.

C8 is the ease of refueling (number of service stations, refueling times, etc.) [51], [54].

C9 is flexibility in the vehicle's configuration (such as the possibility of mounting several axles, boxes, reduced chassis, and bicompartments) [85].

When setting the feasible scenarios, the choice is not limited to the current scenario and so eight scenarios are considered (**Phase V**) to determine the choice of truck technology by considering the probability of each occurring. To determine these future scenarios, the experts considered those foreseen events with a high probability of occurrence that could have meaningful repercussions on the decision process. To do this, they created a list of trends by analyzing the sector and market situation, current technologies, and legislation. They then observed the evolution of other sectors that have impacted or could directly or indirectly impact on waste management. When determining future expectations, the mentioned eight scenarios were established – from the most conservative scenario to a scenario that presents significant changes. Finally, the time horizon set by the experts was ten years as this is usually the amortization period for machinery in waste management services [86]. The eight scenarios obtained are shown in Figure 4.2.

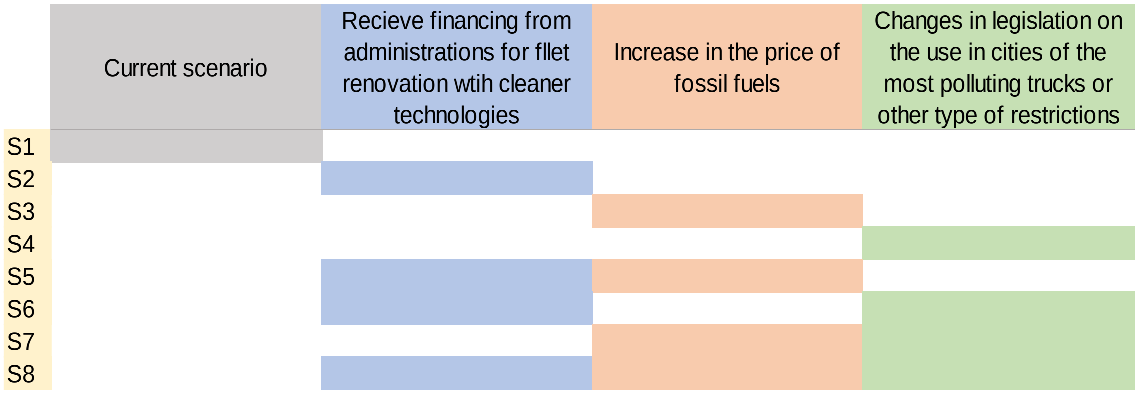

Figure 4.2. Definition of scenarios.

The occurrence probabilities for the scenarios were estimated by the experts consensually and based on their experience and observations of trends in recent years (**Phase VI**). Probabilities of 10%, 60%, 75%, and 80% were established for scenarios S1, S2, S3 and S4, respectively. The scenario with the smallest probability value (10%) is called "pS1". The remaining scenario probabilities are expressed as a function of "pS1". Considering that scenarios are independent situations, the probability of scenarios S5, S6, S7, and S8 is obtained as a product of their probabilities.

Finally, considering that the sum of the probabilities of the contemplated scenarios must be equal to 1, the following equation can be created:

$$360pS1^3+153pS1^2+22,5pS1=1$$

where pS1=0.03528.

Table 4.4 shows the transition probability between the defined scenarios based on this data.

Table 4.4. Transition probability of scenarios.

Scenario	pS1	pS2	pS3	pS4	pS5	pS6	pS7	pS8
Transition probability	0.0353	0.2117	0.2646	0.2822	0.0560	0.0597	0.0747	0.0158

As shown in Table 4.4, the experts have determined that the most foreseeable scenario for the next ten years is a series of regulatory changes in the field of waste management (S4). They have also allocated a high probability for increased fossil fuel prices (S3).

Once the transition probability is calculated, the experts determine consensually the score each criterion should have for each scenario (**Phase VI**). The objective in this phase is for the decision-maker to complete Table 4.5, choosing the best and worst criteria for each scenario and then comparing the rest of the criteria with both in pairs.

Table 4.5. SBWM. Scores of each scenario.

States	S1	S2	S3	S4	S5	S6	S7	S8
Best criterion	C1	C2	C2	C3	C2	C3	C3	C3
Worst criterion	C5	C5	C5	C5	C5	C5	C5	C5
Best to others								
C1	1	4	3	1	4	4	2	4
C2	2	1	1	1	1	2	2	2
C3	3	2	2	1	2	1	1	1
C4	3	2	2	2	2	3	3	3
C5	4	3	4	4	3	4	4	4
C6	3	2	3	2	2	2	2	2
C7	3	3	2	2	2	2	2	2
C8	2	2	2	2	2	2	2	2
C9	3	3	3	3	3	3	3	3
Others to the worst								
C1	8	3	8	7	4	4	8	4
C2	8	8	9	7	9	8	8	9
C3	6	7	4	9	6	9	9	9
C4	4	5	3	6	5	5	4	4
C5	1	1	1	1	1	1	1	1
C6	5	6	5	6	6	7	7	7
C7	5	6	6	6	6	6	6	7
C8	4	5	6	5	5	6	6	6
C9	5	5	4	4	4	4	4	3

After applying the BWM solver, the weights obtained for each scenario are shown in Table 4.6. The consistency index "*CR*" is close to zero for all of them, which means that the obtained results are robust.

Table 4.6. Weights of criteria based on SBWM.

Criteria	S1	S2	S3	S4	S5	S6	S7	S8
C1	0.2019	0.0677	0.0889	0.1440	0.0647	0.0673	0.1261	0.0678
C2	0.1442	0.1805	0.1778	0.1920	0.1727	0.1345	0.1261	0.1355
C3	0.0962	0.1353	0.1333	0.1920	0.1295	0.1883	0.1765	0.1848
C4	0.0962	0.1353	0.1333	0.0960	0.1295	0.0897	0.0840	0.0903
C5	0.0288	0.0301	0.0222	0.0240	0.0288	0.0269	0.0252	0.0246
C6	0.0962	0.1353	0.0889	0.0960	0.1295	0.1345	0.1261	0.1355
C7	0.0962	0.0902	0.1333	0.0960	0.1295	0.1345	0.1261	0.1355

C8	0.1442	0.1353	0.1333	0.0960	0.1295	0.1345	0.1261	0.1355
C9	0.0962	0.0902	0.0889	0.0640	0.0863	0.0897	0.0840	0.0903
CR	0.0865	0.0902	0.0889	0.0480	0.0863	0.0807	0.0756	0.0862

In the S1 current scenario (no change), investment costs achieve the highest weight for the decision-maker. However, in scenarios S2, S3, S4, and S5, operating costs obtain a higher weight in the decision-making process. In the rest of the scenario combinations (S6, S7, and S8), the criterion with the highest weight is atmospheric emissions (C3).

The matrix product in Tables 4.4 and 4.6 is then calculated to obtain the optimal weights for each criterion (**Phase VII**). The result is shown in Table 4.7.

Table 4.7. Optimal weights of criteria.

Criteria	C1	C2	C3	C4	C5	C6	C7	C8	C9
Weight	0.1037	0.1738	0.1561	0.1147	0.0255	0.1095	0.1117	0.1230	0.0820

Considering all the scenarios and their transition probabilities, it can be generally observed that the highest optimal weight is obtained by the operating cost criterion (C2).

The next step (**Phase VIII**) establishes which technology (T1, T2, T3, T4, and T5) is best for each criterion. For this, the technical characteristics provided by the truck manufacturers were analyzed, and BWM was again applied to obtain the alternative normalized decision matrix (Table 4.8).

Table 4.8. Alternative normalized decision matrix.

Criteria	T1. Diesel	T2. CNG	T.3 CNG-Electric	T4. Electric	T5. Hydrogen
C1	0.4213	0.2528	0.1011	0.1685	0.0562
C2	0.0800	0.1600	0.2400	0.4000	0.1200
C3	0.0396	0.0808	0.1347	0.3407	0.4041
C4	0.0406	0.1168	0.2335	0.3756	0.2335
C5	0.0374	0.0935	0.2336	0.4019	0.2336
C6	0.3043	0.2174	0.2174	0.2174	0.0435
C7	0.2677	0.3780	0.1890	0.0394	0.1260
C8	0.4757	0.1822	0.1822	0.1093	0.0506
C9	0.5000	0.2055	0.1233	0.1233	0.0479

For the decision-maker, the diesel truck is the most appropriate in four of the nine categories (C1, C6, C8, and C9), and it stands out in terms of flexibility and ease of refueling. The electric truck obtains the best weights in three categories (C3, C4, and C5) and stands out in social acceptance.

Finally (**Phase IX**), to choose the best technology, the optimal weights of each criterion (Table 4.7) are multiplied by the alternative normalized decision matrix (Table 4.8). Figure 4.3 shows the ranking of the alternatives.

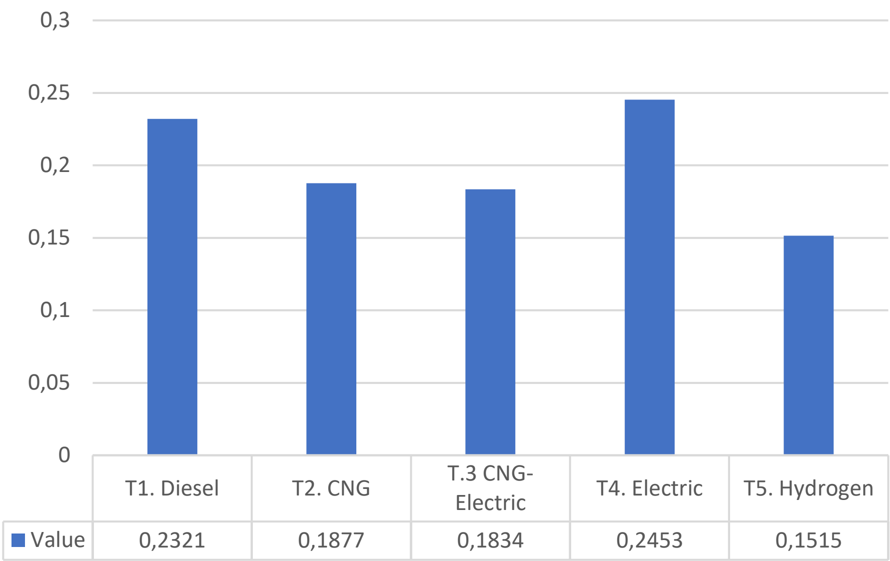

Figure 4.3. Ranking of alternatives.

In light of the results, where the differences between the first alternative and the second are small, a sensitivity analysis is proposed (**Phase X**). The process followed consists of developing an algorithm where the weight of a given criterion is successively modified in several steps, keeping the sum of criteria equal to 1. What is added or subtracted from the weight in each step of the reference criterion, is added or removed to the other criteria according to the initial proportion. At each step, the ranking of alternatives is recalculated, allowing us to observe how the orders are modified when modifying the weight of the reference criterion.

The results show a similar trend for criteria C1, C8, and C9 (see supplementary material). When the weight of these criteria is increased slightly from their original values, the T4 (electric) quickly falls in position, while the T1 (diesel) gains very quickly. In the case of criterion C6, this tendency is also fulfilled, but it is less pronounced than for the previous criteria.

The opposite happens with criteria C2, C4, and C5. When their weight is increased from the original values, technology T4 (electric) increases its ranking quickly while T1 (diesel) decreases.

In the case of C3, the more its weight increases from the original, the more the ranking of T4 (electric) increases. But simultaneously, the ranking of T5 (CNG-electric) increases, and when the weight of C3 reaches approximately 0.65, the alternative T5 takes first place. T1 (diesel) falls to last position in this situation.

In the case of C7, when its weight increases from its original value, the ranking of T4 (electric) drops rapidly, and T1 (diesel) takes the first position when the weight of C7 is approximately 0.15. In this case, T2 (CNG) also increases rapidly, taking the first position when the weight of C7 reaches about 0.38.

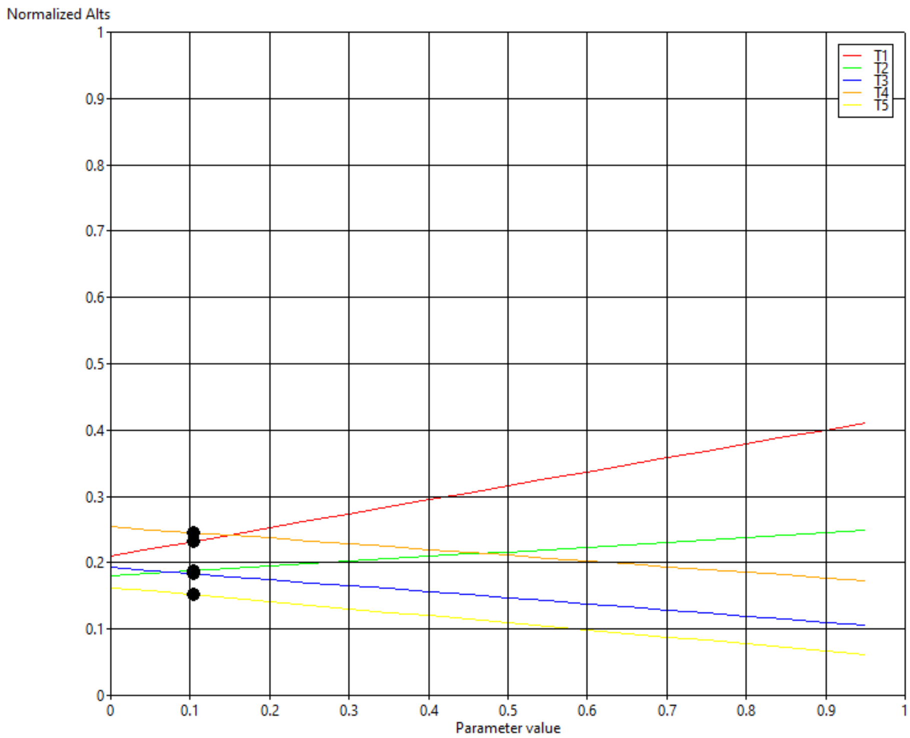

Figure 4.4. Sensitivity analysis of criteria C1.

Figure 4.4 shows the sensitivity analysis of the first criteria (C1, vehicle cost). The rest of the sensitivity analysis figures have been included in the supplementary material.

The following section analyses and discusses the results obtained.

4.5. Discussion.

The criteria chosen by the experts are aligned with those evaluated by other authors for the selection of waste management technologies in MCDM studies, according to the literature review carried out by Torkayesh [24]. That is why they can be grouped, following the dimensions of sustainability, in the categories defined by this author as economic

(C1, C2), environmental (C4, C3) and social (C5). In addition, the author recommends other technical criteria specific to each study (C6, C7, C8, and C9 in this study).

The results show that the best-valued options are electric and diesel trucks, in this order and with a small margin of difference, followed by CNG and hybrid CNG-electric, and with hydrogen-powered trucks coming last.

The competitive advantage of alternative 1, electric truck (24.53%), is determined by its specific weight in the criteria of operating costs, atmospheric emissions, quieter operation, and social acceptance, with values between 34.1% and 40.2%. This result aligns with findings by other authors [12] [87]. It should be noted that operating costs and atmospheric emissions represent 32.99% of the specific weight of the nine defined criteria. Despite the moderate and low ranking results presented by electric trucks in criteria such as configuration flexibility, ease of refueling (due to long recharge times), and lifetime (conditioned by the usually daily frequency of charging cycles for this type of vehicle), the results of the four criteria indicated above, combined with moderate specific weights in the criteria of investment costs and availability of spare parts, enable electric trucks to remain in first position.

The good results for diesel trucks, which are in second position and 1.31% behind electric vehicles (with a total 23.21%), are based precisely on their clear advantage in the rest of the criteria analyzed – with specific weights ranging between 26.8% and 50.0%. Diesel waste collection vehicles are highly developed, and their well-established position in the market (with a high level of competition) has produced machinery and spare parts at accessible prices. Almost any configuration is available, and the refueling methodology quickly recovers 100% of autonomy.

After these two alternatives, with very similar results, trucks powered by compressed natural gas (CNG) (18.77%) and hybrid CNG-electric (18.34%) are the third and fourth rankings (although based on different criteria). CNG-powered trucks have been progressively introduced in the Spanish market [88] and an increasingly wide range of configurations is available. At the same time, an increasing number of manufacturers have developed CNG vehicles and this has increased price competition – a criterion in which it obtains more specific weight than trucks that combine CNG with electric traction. The hybrid CNG-electric alternative, which uses fossil fuel to charge the batteries and electric motors for traction, shows better scores in the criteria related to environmental and social aspects and slightly better operating costs due to an optimization of the combustion engine operating regime. However, along with efficiency increments, hybrids come with other environmental impacts; for instance, they need more accessory materials per vehicle – including batteries [89] [50].

It should be noted that compressed natural gas (CNG) (mainly methane) can also have a renewable origin, for example, from anaerobic digestion waste treatments. In this case, the assessments made by the experts would indeed have been different, as fuel generation would come from waste treatment processes that contribute to the circular economy. Liquefied biogas is a potentially important substitute for fossil fuels for heavy trucks [90] that has received little attention until now [91] and the results of a recent well-to-wheel assessment show that, compared to conventional fuels, in transport applications and for all vehicle classes (including heavy-duty vehicles), the use of compressed and liquefied renewable natural gas shows an 81% greenhouse gas emission reduction per kilometer traveled [92].

Finally, with a result of 15.15%, are hydrogen-powered trucks. This type of vehicle achieves the best results for atmospheric emissions [93] and relatively good specific weights for noise and social acceptance; however, its contribution to reducing greenhouse emissions depends on the energy mix used for its production [94]. Its low valuation in the rest of the criteria determines a lower valuation in global terms. It is a technology with little current implementation and an uncertain future [95] so both the offer and the variety of configurations is limited. Furthermore, this limited offer has reduced competition and so investment costs and options for spare parts are determined by a limited number of suppliers – meaning that this alternative is relegated to last place. Finally, high hydrogen production costs, a limited supply network, and inefficiencies in conversion to and from electricity [96], make this option the least attractive for the decision-maker.

Therefore, electric trucks are positioned as the best current alternative despite limitations in battery life, vehicle autonomy, and recharging times [97]. In agreement with other authors [47] [48], electric vehicles can improve urban air quality, lessen climate change and reduce total energy usage. Diesel and compressed natural gas trucks are positioned as strong options [98] with superior evaluations in criteria such as investment costs, configuration versatility, ease of refueling, and lifetime – but fail to gain the top position due to lower social acceptance, noise, emissions [99], and operating costs (especially in the current context of rising fossil fuel prices). The hybrid combination of compressed natural gas and electric technologies is positioned close behind, as it is cleaner than pure combustion options [100]. However, it shows limitations due to the sum of the conditioning factors of compressed natural gas (supply points for refueling) and electric trucks (lifetime) and limits on possible configurations (higher weight due to CNG tanks and batteries). Finally, hydrogen trucks appear as the lowest-ranked alternative. Despite offering the lowest degree of atmospheric emissions [101] they are considered the least viable option due to their limited development, lack of competitiveness in the acquisition and aftersales market, and limited supply network.

If CST had not been used and only the current scenario (S1) had been considered, the ranking of alternatives would have been different (the diesel truck would be chosen with a considerable advantage over electric vehicles and compressed natural gas). This fact aligns with other SMCDM studies [25], [38], [102] and reveals the importance of considering the different feasible future scenarios when making decisions [39] [24].

4.6. Conclusions.

MCDM methods have often been used to deal with problems arising from MSW management, but they are usually focused on evaluating the best alternatives for waste treatment and disposal. However, from a sustainable and circular economy perspective, improving treatment techniques is insufficient, and waste collection and transport processes must also be reinforced. Municipalities are increasing MSW separation at source, and consequently, the collection routes grow in number (sometimes becoming door-to-door collections). Some MCDM studies have been made about choosing waste collection vehicles, but none that include the most recent green vehicles among the alternatives or consider feasible future scenarios.

This paper analyzes the five main vehicle motorizations in waste collection trucks (diesel, CNG, hybrid CNG-electric, electric, and hydrogen), considering sustainability criteria and using SBWM as a novel decision support model. SBWM is a multi-criteria method that combines two recently developed techniques: BWM and SMCDM. This method incorporates the probability of occurrence of feasible future scenarios in the decision-making process, which empowers decision-makers to express their judgments considering the uncertainty associated with decisions with long-term impact.

The results show that, despite their high price, electric trucks are already the best option for decision-makers, as they stand out in environmental criteria (emissions and noise) and social perception. However, the second ranked alternative, very close to the first, was diesel because of the ease of refueling, flexible configurations, and the fact that it offered the lowest investment costs.

SBWM offered reliable results and allowed dealing with uncertainty by considering different scenarios and enabling decision-makers to assign a likelihood of occurrence to possible future events. As sustainability criteria have been considered in evaluating alternatives, it can be concluded that SBWM has helped choose the best option to promote waste management sustainability by reducing the long-term impacts of mobility.

4.6.1. Limitations, recommendations, and future directions.

This study has a few limitations that can be addressed in future works. One limitation is that only a few sustainability criteria were considered, especially for the social pillar. More balanced sustainability criteria, both qualitative and quantitative, should be considered in future works. Another limitation is that the criteria were assumed independent, which may not be the case. Future studies should address this issue using some methods that allow modeling the criteria interdependencies: ANP, DEMATEL, or interpretative structural modelling (ISM), to name a few. Moreover, to deal with uncertainty in criteria weights, decision-makers should be allowed to assign rating ranges or a value more an error instead of a single number when comparing criteria. Applying such a robust BWM in the future, we will add uncertainty to pairwise comparisons, making the decision-making process more realistic in current complex and ever-changing environments. Another limitation is that the proposed probabilities of occurrence assigned to the feasible futures may significantly affect the results obtained. Future studies should better inform decisions makers about future trends and relevant drivers of the most remarkable decision-making factors to allow more informed forecasting decisions about possible scenarios.

Regarding the case study, the findings may be somewhat limited by the application in a flat medium-sized city with a specific population density. The generalizability of the results will require collecting more experts' opinions in different urban configurations and population distributions.

Finally, as future development, applying the stratification concept with other MCDM will allow comparing the results considering the consistency ratio. Comparing the results to other CST and MCDM combinations will improve the method's validation and test its applicability and usefulness.

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Conflict of Interest Statement.

The authors declare no competing interests.

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Appendix 4.A. Sensitivity analysis.

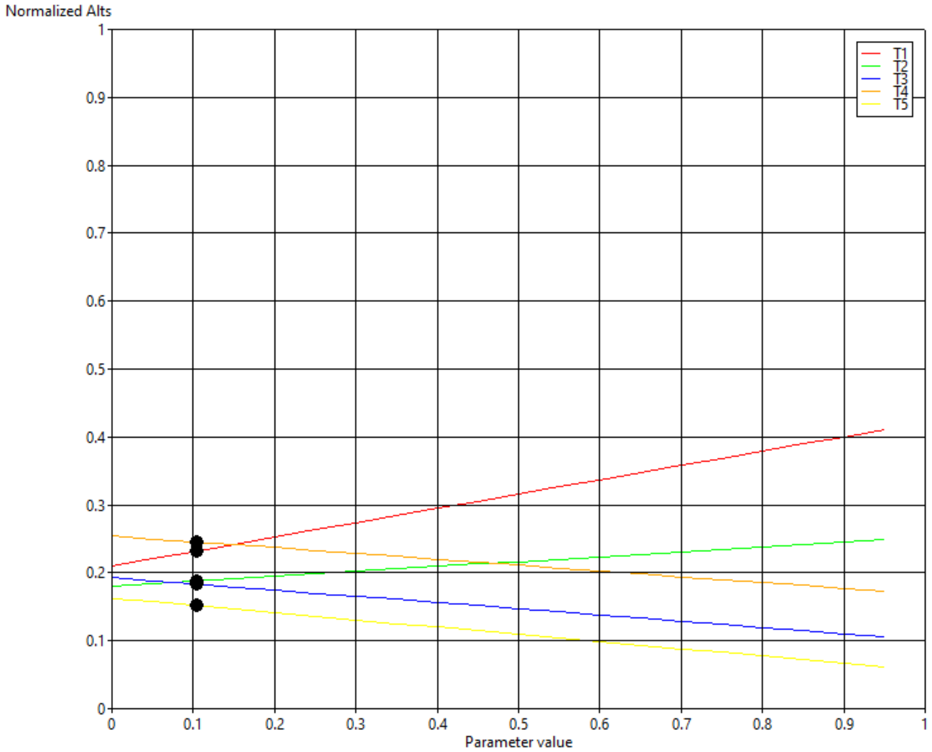
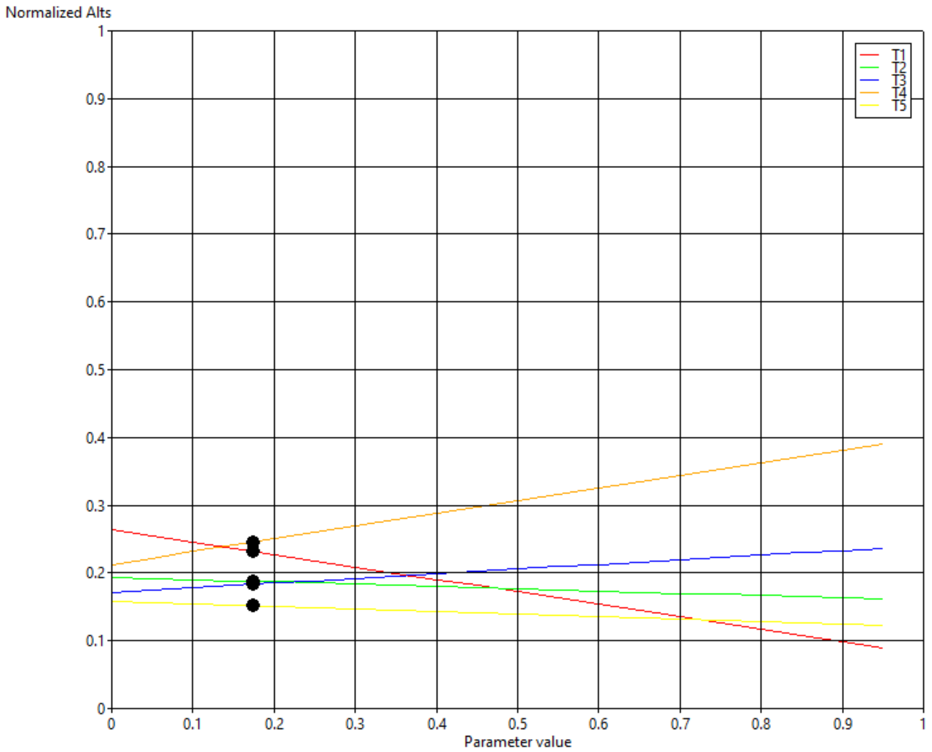


Figure 4A.1. Sensitivity analysis of criteria C1.



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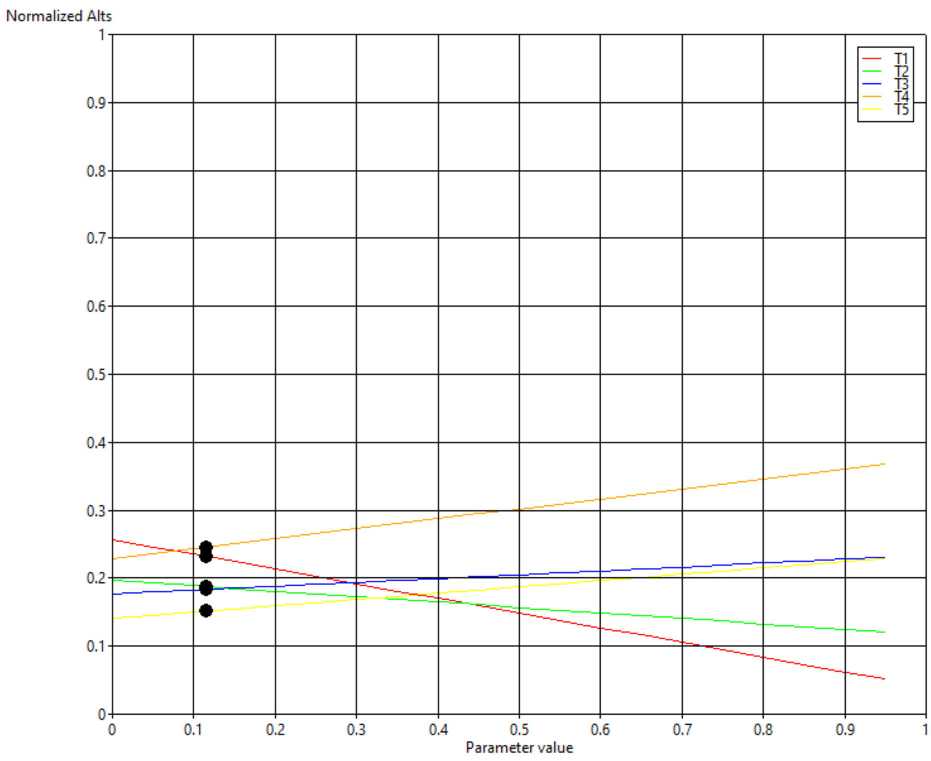

Figure 4A.3. Sensitivity analysis of criteria C3.

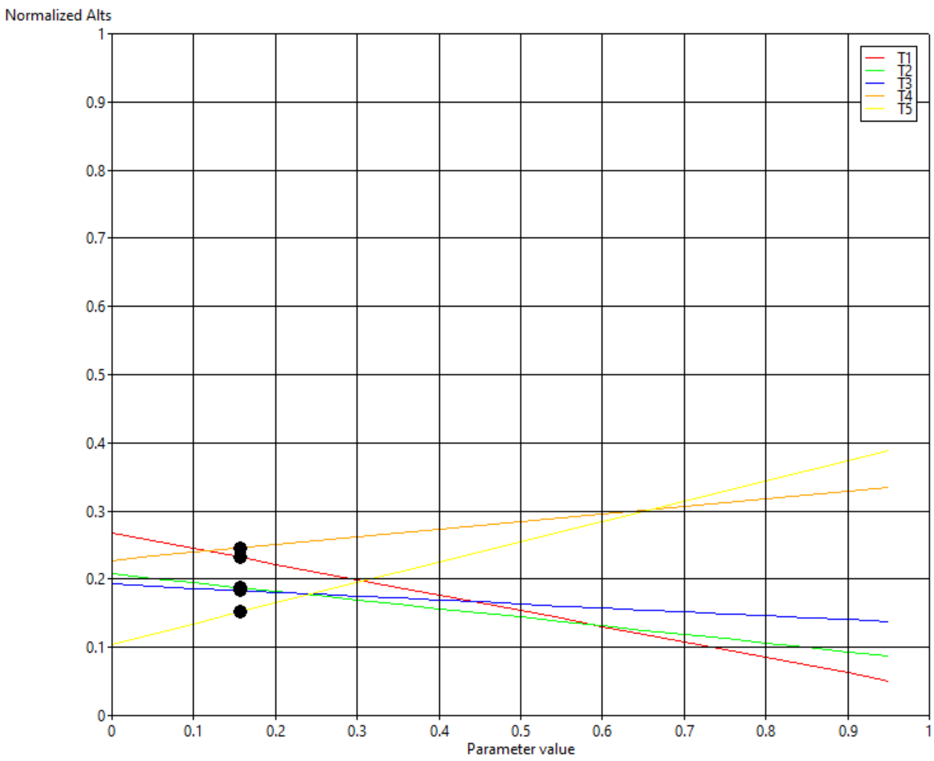

Figure 4A.4. Sensitivity analysis of criteria C4.

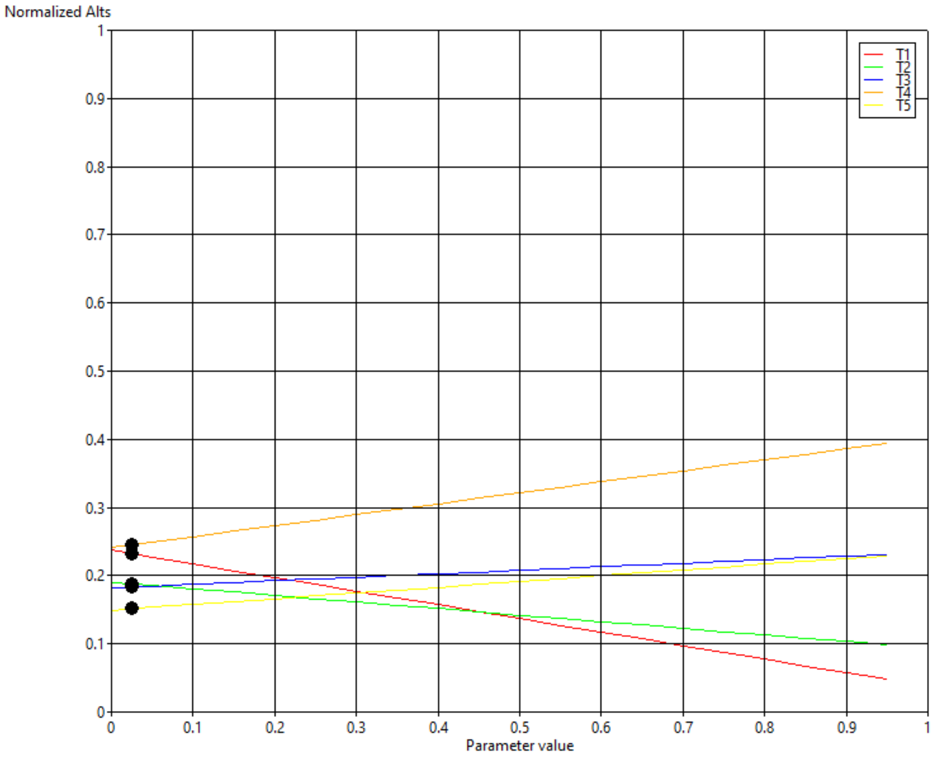

Figure 4A.5. Sensitivity analysis of criteria C5.

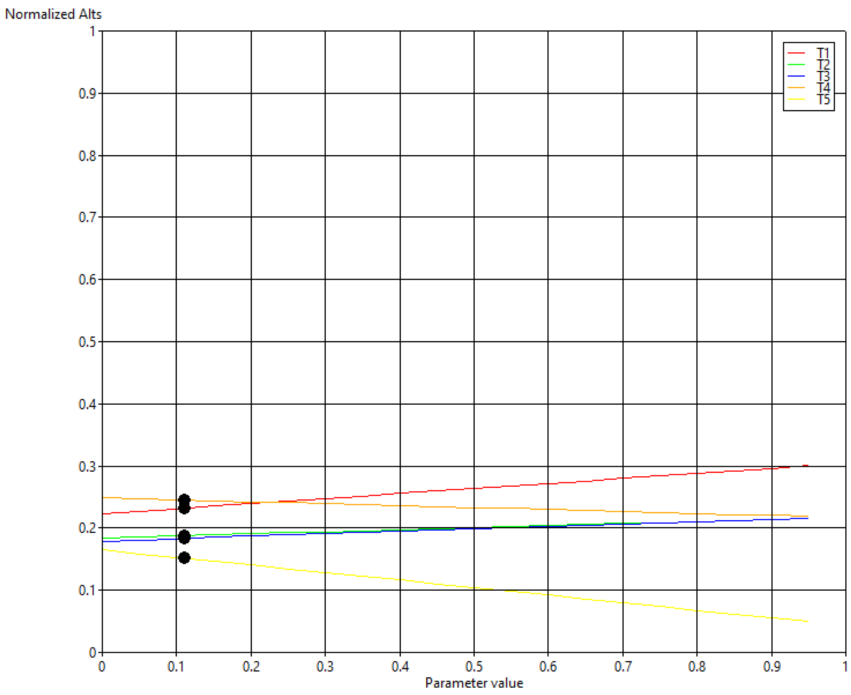

Figure 4A.6. Sensitivity analysis of criteria C6.

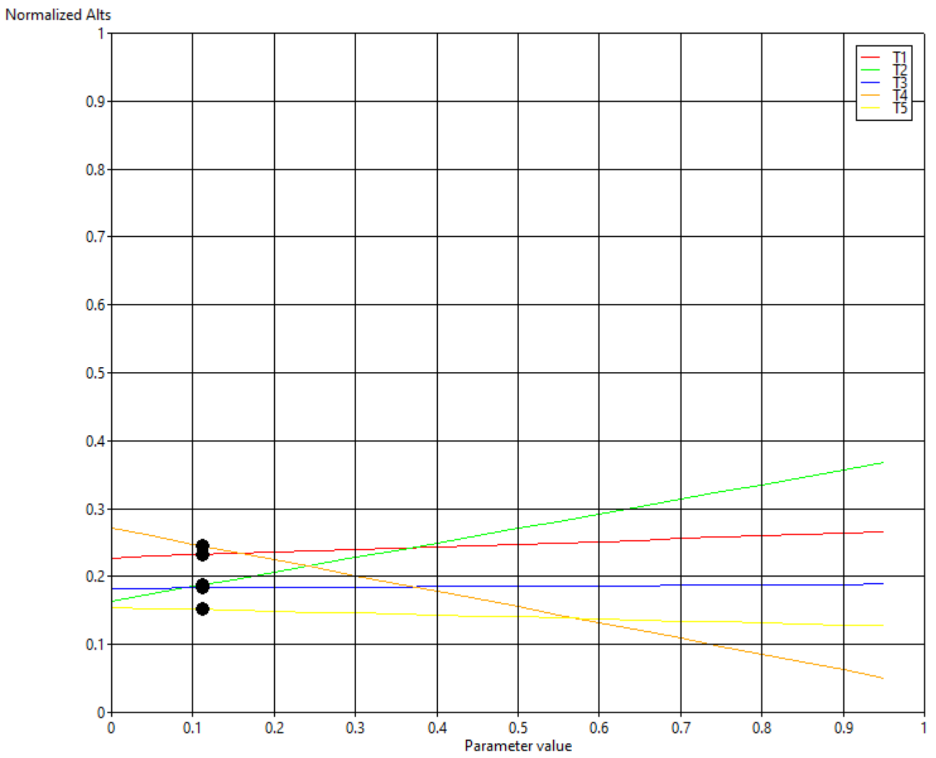

Figure 4A.7. Sensitivity analysis of criteria C7.

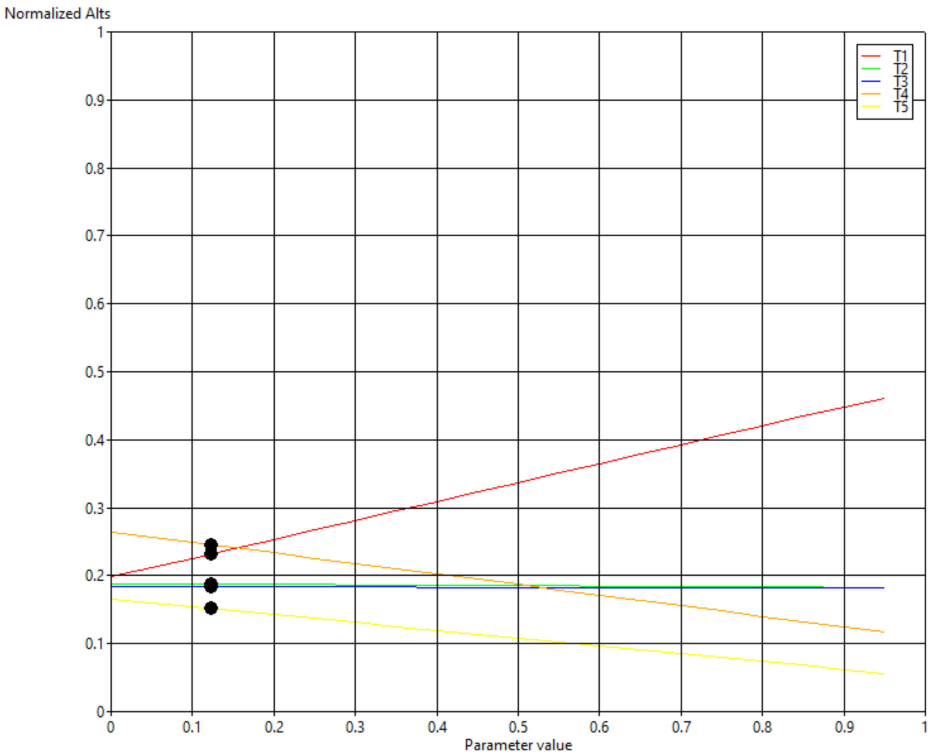

Figure 4A.8. Sensitivity analysis of criteria C8.

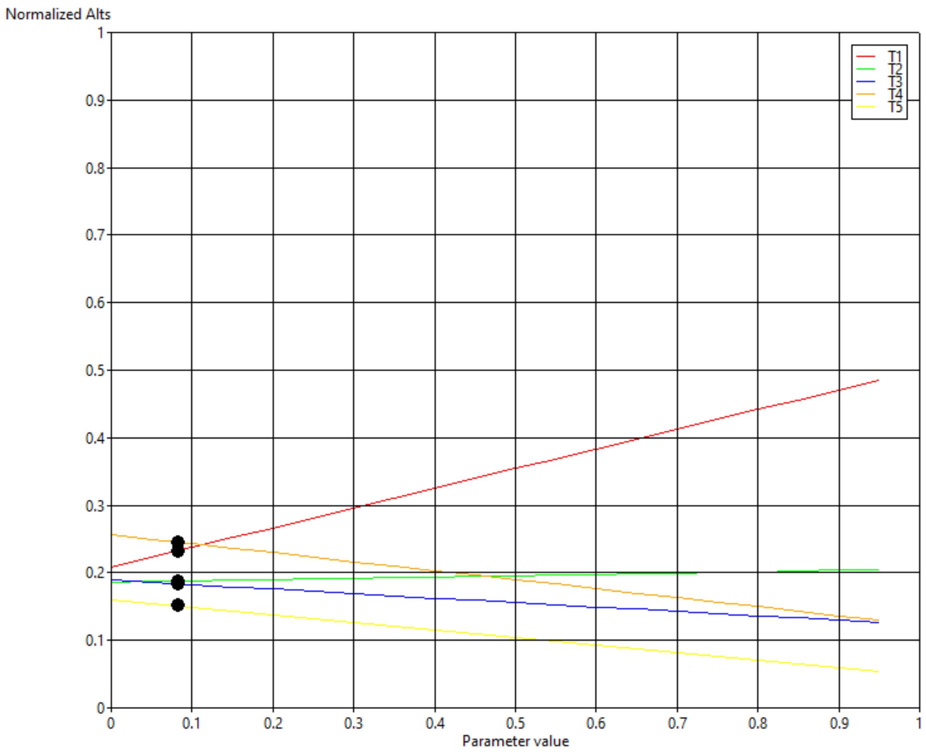

Figure 4A.9. Sensitivity analysis of criteria C9.

5. PRIORITIZING ACTION PLANS TO SAVE RESOURCES AND BETTER ACHIEVE MUNICIPAL WASTE MANAGEMENT KPIS: AN URBAN CASE STUDY.

5. PRIORITIZING ACTION PLANS TO SAVE RESOURCES AND BETTER ACHIEVE MUNICIPAL WASTE MANAGEMENT KPIS: AN URBAN CASE STUDY.

Héctor Moreno Solaz [1], *, Miguel-Ángel Artacho-Ramírez [1], Víctor-Andrés Cloquell-Ballester[1], and Cristóbal Badenes Catalán[2]

[1]Project Management, Innovation and Sustainability Research Center (PRINS), Universitat Politècnica de València, 46022 Valencia, Spain; hcmoso@gmail.com (H.M.-S); miarra@dpi.upv.es (M.-Á.A.-R.); vacloque@dpi.upv.es (V.-A.C.-B.)

[2]Dirección de Servicios Urbanos, Ayuntamiento de Castelló de la Plana, 12001 Castelló de la Plana, Spain; cribad@castello.es (C.B.-C.)

*Correspondence: hcmoso@gmail.com

Abstract.

The management of municipal solid waste (MSW) in cities is one of the most complex tasks for local administrations. For this reason, waste management performance measurement structures are increasingly implemented at both the local and national levels. These performance structures usually contain strategic objectives and associated action plans, as well as key performance indicators (KPIs) for organizations investing their resources in action plans. This study presents the results of applying a methodology to find a quantitative-based prioritization of MSW action plans for the City Council of Castelló de la Plana in Spain. In doing so, the cause-effect relationships between the KPIs have been identified by applying the principal component analysis technique, and from these relationships it was possible to prioritize those action plans which should be addressed earlier to manage public services more efficiently. This study can be useful as a tool for local administrations when addressing the actions included in their local waste plans, as it can lead to expenditure savings by public administrations.

Keywords.

MSW; action plans; KPIs; principal component analysis.

5.1. Introduction.

The increasing amount of food waste generated as a direct consequence of excessive production, mismanagement, and wasteful behavior is a challenge when promoting resource efficiency (Facchini et al., 2018). One of the objectives of European policy on waste is to move towards a circular economy (Ferronato et al., 2019). Since the publication of the community waste management strategy in 1989, the implementation of principles for material circularity and waste management has been intensifying (Singh & Ordoñez, 2016). Furthermore, governments around the world have long been committed to developing plans for the sustainable use of resources by strategies that affect waste management (Wilson et al., 2001).

In Spain, these directives have had a direct impact on municipalities, and they have been required to develop local waste management plans and programs (Spain, 2022). These plans establish the conditions and means to manage the waste produced by the activities of a city – with priority on source reduction. These plans and programs are well monitored and managed when an adequate key performance indicator (KPI) grid for assessing, controlling, and improving effectiveness is defined (de Pascale et al., 2021). Additionally, the KPIs are an element of a performance measurement structure that usually includes both objectives and action plans.

When looking at performance measurement (PM) theory and, more specifically, at the best-known and applied PM framework, the Balanced Scorecard (Kaplan & Norton, 1992), organizations interpret their strategic definition (mission, vision, and values) to firstly define their strategic objectives (what to reach) and then define action plans (how the strategic objective will be reached) and KPIs (to indicate whether the strategic objective is being reached). However, public administrations do not usually follow this performance measurement structure. These organizations manage their performance only using KPIs, and when they define the whole measurement structure, they do not apply the tools available to improve effectiveness.

There are many academic works focused on assessing sustainability KPIs (Hristov & Chirico, 2019; Kylili et al., 2016; Pinna et al., 2018; Valencia et al., 2022) including waste management KPIs (Ferreira et al., 2020). However, these works usually only address the tasks of definition and historical data collection for KPIs, and do not carry out a sound analysis of the evolution of the values of the KPIs, nor apply appropriate mathematical techniques to identify additional information for making better decisions. These practices are therefore far from being the most efficient way to proceed. In most cases, the KPIs are usually related (Carlucci, 2010), which means that changes in the values of some

KPIs produce changes in the values of other KPIs – and so change the performance of the system. Further, the identification of cause-and-effect relationships between the KPIs makes it possible to prioritize actions plans and improve the effectiveness of the whole performance system structure – as decision-makers can apply actions that enable reaching associated strategic objectives, as well as other resource-saving objectives.

This work refers to a case study in the city of Castelló de la Plana (Spain), and its main contributions are the following: a) it identifies and classifies the principal KPIs for municipal solid waste (MSW) management at the local level in the three dimensions of sustainability; b) it identifies, by applying the historical data collected by the KPI statistical techniques, the main intra and extra dimensional cause-effect relationships between KPIs; c) it prioritizes the action plans, based on these cause-effect relationships, which help optimize municipal resources since it may not be necessary to activate every action plan to reach the KPI targets – and thereby improving the efficiency of local MSW management.

The remainder of this paper is structured as follows: Section 2 provides a background of previous academic works on waste management and performance measurement. The research approach is presented in Section 3, and Section 4 shows and discusses the main results of applying such a methodology to the city of Castelló de la Plana (Spain). Finally, Section 5 provides the main conclusions, describes the limitations of the study, and suggests further research work.

5.2. Background.

Planning in the provision of public services is becoming increasingly frequent, and so the use of indicators to measure performance has also become widely used in the local sphere. Studies have been made on using KPIs in urban design (Mosca & Perini, 2022), transport (Grote et al., 2021), communications (Imoize et al., 2022), wastewater treatment (van Schaik et al., 2021), air quality (Malm et al., 2018) and MSW management (Ferreira et al., 2020).

Focusing on the latter issue, during the last five years there have been more than 3,000 references to KPIs dealing with MSW management. Some of these works focus on a specific perspective of the problem, such as the social (Ibáñez-Forés et al., 2019), the economic (Zhou et al., 2022), or the fractions that have been increasing most rapidly in recent years (Brouwer et al., 2019); while others evaluate the overall efficiency of the system (Amaral et al., 2022). There are also studies that summarize the literature about MSW KPIs and establish commonalities between different countries and years (Deus et al., 2019; Olay-Romero et al., 2020). Some go even further and use literature from other subjects for the development of communication campaigns (de Feo et al., 2019) or educational applications (Pappas et al., 2021).

However, only a few studies (Nemmour et al., 2022) analyze the relationship between indicators for waste management. Although these KPIs are often related, it is important to understand these relationships for efficient decision-making processes (AlHumid et al., 2019; Loizia et al., 2021) as well as in the management of available resources (Stricker et al., 2017).

Several studies can be found that apply statistical techniques to identify KPI cause-effect relationships in MSW management. For instance, (Hatik & Gatina, 2017) used principal component analysis (PCA) to identify similarities between local administrative areas for comparing waste composition; (Callas et al., 2012) defined an indicator of solid waste generation potential in the USA using principal component analysis and geographic information systems; (Liu et al., 2023) assessed soil pollution and identified potential sources of heavy metals with a combination of a spatial distribution and the principal component analysis model. Other studies about waste management use correlation analysis, (Barbudo et al., 2012) for example, assessed the correlation between sulphate content and leaching of sulphates in recycled aggregates from construction and demolition wastes; and (Birgen et al., 2021) developed a data analysis method based on correlations applied to waste-to-energy plants; and (Zhang et al., 2023) recently used correlational analysis to observe how digestion temperature affects the anaerobic digestion of food waste.

Finally, although there are several studies about how to undertake action plans in local waste management plans or programs, most are limited to a descriptive analysis (Asibey et al., 2021) or, at best, they use multi-criteria techniques (Andrade Arteaga et al., 2020; Coban et al., 2018; Habibollahzade & Houshfar, 2020) that are limited to expert opinions (instead of real data collected by KPIs) and are therefore completely subjective.

Some academic works from other disciplines have discussed identifying and quantifying KPI cause-effect relationships with statistical techniques to improve decision-making processes. For instance, (Rodríguez-Rodríguez et al., 2020) applied PCA and partial least squares models to draw a KPI cause-effect map for supply chains to improve operational efficiency; (Sanchez-Marquez et al., 2018) used KPI relationships to deal with data uncertainty; (Cai et al., 2009) identified KPI relationships to improve supply chain performance by analyzing iterative KPI accomplishment.

In the context of MSW management, there are no academic works that have applied statistical techniques to historical KPI datasets to identify cause-effect relationships – and then used this information to prioritize action plans within a performance measurement structure. Once this research gap has been highlighted, the next point presents the research approach followed.

5.3. Research approach.

5.3.1. Research methodology and objectives.

This research identifies the main cause-effect relationships among sustainability KPIs by analyzing the evolution of the historical data. Once the meaningful relationships have been indicated, they are projected to the action plan level, and it is then possible to rank these plans and establish which should be activated first to achieve the main KPIs.

The main research objectives are: 1) analyze the historical data collected by a set of sustainability KPIs and find sound cause-effect relationships; 2) establish which are the most important KPIs to be achieved (effect KPIs) within the KPI set; 3) establish the cause KPIs that strongly affect the effect KPIs; 4) identify the action plans that should be activated first to ensure that the effect KPIs are achieved and so save resources.

The adopted research methodology is the case study, which is adequate for the decision-making involved in this research as it can provide answers to 'why' and 'how' (Yin, 2014). Additionally, as mentioned in other academic works (Lancaster, 2007; Leon et al., 2020), the quantitative approach taken in this research is adequate as it: 1) focuses on establishing causal relationships among variables (KPIs); 2) and presents a study based on the application of statistical techniques (PCA) to find meaningful relationships among KPIs.

5.3.2. Methodology.

Figure 5.1 shows the methodology developed for this research; the main steps are the following:

- Expert group definition.
- KPIs and action plan selection.
- Data matrix.
- Data analysis.
- Results discussion.

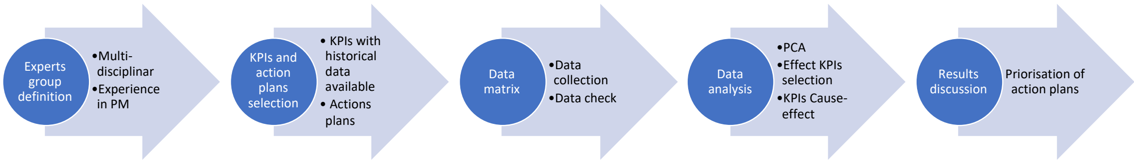

Figure 5.1.Research methodology.

This is a sequential methodology, where the outputs of one phase are the inputs of the following phase (as presented below).

Phase 1. Expert group definition.

An expert group is formed of the decision-makers who conduct the phases of the next methodology. The expert group should be both multi-disciplinary and experienced in waste management and performance measurement, mainly dealing with the definition of strategic objectives, KPIs, and action plans.

Phase 2. KPIs and action plan selection.

The expert group selects the KPIs and action plans of the performance structure to be included within the study. The selected KPIs must: 1) have collected historical data during some of the previous time periods; 2) be linked to strategic objectives; 3) be grouped into the three dimensions of sustainability: economic (E), social (S), and environmental (ENV).

Phase 3. Data matrix.

The data matrix includes the study variables (KPIs) in columns and observations in rows. Each intersection of this matrix contains the historical value of the KPI, which was collected within the period of observation. Additionally, since it is highly likely that KPIs have different collection frequencies, it is necessary to choose a common frequency and bring all the values to that frequency. For instance, the data coming from the KPIs in an annual analysis will be homogenized to an annual frequency, and it is necessary to apply different operations to the data of each KPI (for instance, the simple average) when its frequency is other than annual. The resulting frequency standardized matrix is then used for data analysis. Additionally, decision-makers will assess this data matrix from a global standpoint and may exclude some KPIs that do not have enough recent historical data or present irregularities.

Phase 4. Data analysis.

Once that the frequency standardized matrix has been calculated, it is possible to apply a statistic technique to identify relationships between the variables (KPIs in our case). Principal component analysis (PCA) is then applied to identify the main cause-effect among the data matrix KPIs. This technique has already proven its efficiency in analyzing the conjoint evolution of variables (KPIs) and the identification of meaningful cause-effect relationships in the context of this research – such as: the relative lack of historical observations of the variables compared with the number of variables; missing data in some of the time periods; and various measurement units of variables such as monetary (euros), time (minutes, hours, days, etc.) or rates (percentages) (Jackson, 2003; Rodríguez-Rodríguez et al., 2020; Wold et al., 2001). From the application of the PCA, the expert group will be able to identify the KPIs that are maintaining meaningful cause-effect relationships over time; in other words, changes in the values of some KPIs lead to changes in the values of other KPIs. Once the correlated KPIs have been identified, the decision-makers in the expert group choose which of these KPIs are the most important (effect KPIs) from an organizational point of view (sustainability in this research) and then identify the main cause KPIs associated with these effect KPIs. The main steps to apply are:

- Take the initial frequency standardized matrix (study variables, KPIs, in columns and observations in rows).
- Apply statistical software that supports PCA analysis.
- Decide, regarding the data variability explained, how many principal components to retain for the study.
- Identify the KPIs that are forming each of the retained principal components.
- Define the most important KPIs to be reached (the effect KPIs).
- Identify which are the KPIs (called cause KPIs) that most influence these effect KPIs.

Phase 5. Results discussion.

Based on the results achieved in the previous phase, decision-makers will be able to identify the action plans that are associated with the strategic objectives linked to both the cause-and-effect KPIs. They can then establish an activation prioritization of such action plans: firstly, the action plans associated with the strategic objectives linked to the KPIs that have more impacts on the most important effect KPIs; secondly, the action plans associated with the strategic objectives linked to the most important effect KPIs;

and thirdly, the remaining action plans associated with the strategic objectives linked to other KPIs. By carrying out this activation prioritization of the action plans, decision-makers will improve the probability of achieving the values of the most important effect KPIs, as well as saving organizational resources when achieving the strategic objectives.

5.4. Case study.

5.4.1. Case study description.

The case study was developed at Castelló de la Plana City Council which had just approved its local waste management plan. Castelló de la Plana is a Spanish Mediterranean city, capital of the province of Castellón, in the north of the Valencia Region, and has a population of 172,589 (INE, 2021). Waste generation in the city exceeds 1.25 kg per resident/day and waste collection is divided into five fractions (glass, packaging, paper & cardboard, biowaste, and mixed MSW) according to current regulations (Spain, 2022). The city also has a network of recycling centers, both fixed and mobile, for depositing specific waste either because of its volume (e.g., household appliances) or its hazardous nature (e.g., engine oils, solvents, X-ray sheets). Finally, it has a small number of specific bins for the collection of cooking oil, textiles, and batteries, respectively. With all these resources, the current separation rate at source is 15.30% by weight of the MSW managed.

Mixed MSW is the majority fraction by weight and is deposited in 'all-in-one' containers. These are collected with a rear-loading and side-loading collection service structured in 14 daily routes. Selective biowaste collection is carried out through six routes, with alternative frequencies, and contributes 3.66% of the total municipal weight. For the selective collection of paper & cardboard, which represents 3.59% of the total by weight, the service has three top-loading and one side-loading collection trucks, as is the case with the selective collection of packaging, which contributes 2.36% of the total municipal waste weight. The average collection frequency is three days a week. The fraction with the lowest percentage by weight of the total is glass (2.27%) , whose collection is carried out with top-loading collection trucks once a fortnight.

Regarding the main MSW fractions treatment: packaging, paper & cardboard, and glass are deposited directly at the facilities of the recyclers for sorting. Mixed MSW and biowaste collected in the city are deposited at the transfer plant of a provincial public company that manages the treatment and valorization of these fractions (covering 63% of the province's population). In this plant, bulky and improperly disposed of waste in containers is separated and the rest is compacted for transport to a composting plant. Once the waste arrives in the composting plant, the usual mechanical and biological treatments are carried out. MSW is subjected to various mechanical treatments for the recovery of metals, plastics, paper, etc. The remaining organic matter and biowaste that are collected selectively are aerobically processed through fermentation, maturation, and refining. Due to the age of the facilities, the current rejection rate is near 75% (Reciplasa, 2023) and the final destination is a controlled landfill.

5.4.2. Case study development.

Phase 1. Expert group definition.

To apply the methodology, a group of experts was created that included: three senior managers (one from each of the three main MSW management companies in Eastern Spain); two municipal engineers; a PhD engineer from the Universitat Jaume I; two PhDs engineers from the Universitat Politècnica de València; two local political representatives; and four environmental educators from the provincial MSW management board. All decisions were made consensually.

The expert group had four face-to-face meetings within a period of three months.

Phase 2. KPIs and action plan selection.

From a performance measurement perspective, the Castelló de la Plana City Council had defined the following elements in its 2022 local waste management plan (Ajuntament de Castelló, 2022):

- 36 strategic objectives.
- 98 action plans
- 36 KPIs.

An informative meeting was first held with the experts to gather data. The main objective was to obtain initial proposals for KPIs and group them into the three dimensions of sustainability. Such a proposal was written and explained by the facilitator and then emailed to the experts. Table 5.1 presents the description of the 36 KPIs classified into three sustainability dimensions.

Table 5.1. KPIs description.

Indicator	Description	Indicator	Description
E1	Cost of the biowaste collection service per resident and year (€/res.)	S6	Number of public contracts that incorporate sustainability criteria in waste management (unit)
E2	Cost of the container collection service per resident and year (€/res.)	S7	Average time for resolution of complaints in a year (days)
E3	Cost of the paper & cardboard collection service per resident and year (€/res.)	ENV1	Collection service emissions per year (kg CO^2/res.)
E4	Cost of the mixed waste collection service per resident and year (€/res.)	ENV2	Annual water footprint of the waste collection service (liters/res.)
E5	Cost of the glass waste collection service per resident and year (€/res.)	ENV3	Selective collection of biowaste percentage with respect to total household waste (%)
E6	Cost of the mixed waste disposal service per resident and year (€/res.)	ENV4	Selective collection of packaging percentage with respect to total household waste (%)
E7	Cost of the mixed waste transfer service per resident and year (€/res.)	ENV5	Selective collection of paper & cardboard percentage with respect to total household waste (%)
E8	Annual cost of maintenance and cleaning of packaging containers per resident and year (€/res.)	ENV6	Selective collection of glass percentage with respect to total household waste (%)
E9	Annual cost of maintenance and cleaning of paper & cardboard containers per resident and year (€/res.)	ENV7	Percentage of waste collected selectively in the recycling center, compared to the city total (%)
E10	Annual cost of maintenance and cleaning of glass containers per resident and year (€/res.)	ENV8	Emissions from recovery and elimination of biowaste (kg CO^2/res)
E11	Annual cost of maintenance and cleaning of mixed waste containers per resident and year (€/res.)	ENV9	Emissions from recovery and disposal of packaging waste (kg CO^2/res.)
E12	Annual investments for waste management improvement projects per resident and year (€/res.)	ENV10	Emissions from recovery and elimination of paper & cardboard waste (kg CO^2/res.)
E13	Annual investment in awareness campaigns per resident and year (€/res.)	ENV11	Emissions from recovery and disposal of glass waste (kg CO^2/res.)
S1	Number of people participating in campaigns per year (unit)	ENV12	Number of batteries collected selectively per year (kgs/res.)
S2	Number of sanctions applied per year (unit)	ENV13	Amount of vegetable oil collected selectively per year (gr./res.)
S3	Number of complaints received per year (unit)	ENV14	Percentage of complete contribution areas with all the fractions with respect to the total number of collection areas (%)
S4	Number of interactions due to the impact of communication campaigns in social media (unit)	ENV15	Amount of textile waste collected per year (kgs/res.)
S5	Number of adapted containers available for residents with functional diversity per year (unit)	ENV16	Number of uncontrolled waste dumping points in the city

Table 5.2 describes the 36 strategic objectives and their 98 associated action plans, as well as their link to the KPIs.

The KPIs were then linked with the objectives and associated action plans shown in Table 5.2.

Table 5.2. KPIs, objectives, and associated action plans.

Indicator	Objective	Action plans
E1	In five years, do not exceed a 15% increase in the annual cost of collecting this fraction in 2022	1. Study the implementation of new collection systems for which better separation ratios were verified 2. Promote and subsidize home and community composting. 3. Support the financing of a new specific transfer plant for biowaste.
E2	In five years, do not exceed a 25% increase in the annual cost of collecting this fraction in 2022	1. Increase the number of packaging containers and reach the average number for the region. 2. Install a monitoring system for packaging containers by installing fill-level sensors. 3. Promote the use of reusable packaging and bulk products.
E3	In five years, do not exceed a 25five% increase in the annual cost of collecting this fraction in 2022	1. Expand the supply of paper & cardboard containers until reaching the average supply of the region. 2. Install a monitoring system for paper & cardboard containers by installing fill-level sensors. 3. Expand commercial participation in door-to-door collection systems.
E4	In five years, reduce the costs of collecting the mixed fraction by 20%	1. Reduce the number of mixed waste containers to promote the use of separative containers. 2. Homogenize containerization to optimize collection routes. 3. Implementation of payment for the generation of mixed waste.
E5	In five years, do not exceed a 25% increase in the annual cost of collecting this fraction in 2022	1. Expand the supply of glass containers to reach the average supply of the region. 2. Install a monitoring system for glass containers by installing fill-level sensors. 3. Optimization of routes and frequencies of collection of this waste.
E6	In five years, do not exceed the annual cost of disposing this fraction in 2022	1. Implement an electronic container closure and user identification system in certain areas. 2. Optimize the warning system and programming of scheduled and unscheduled bulky waste collection routes. 3. Promote the reduction of waste generation through campaigns and incentives.
E7	In five years, do not exceed the annual cost of collecting this fraction in 2022	1. Optimize the distribution, routes, and collection frequencies of this fraction to conduct the collections when containers are full. 2. Modernize the waste management process at the transfer plant to optimize the system and improve its performance. 3. Study and project an optimal location for a new transfer plant.
E8	In five years, do not exceed a 15% increase in the annual cost of maintenance and cleaning of containers for this fraction in 2022	1. Reduce water consumption by cleaning packaging containers using machinery with water-saving technological solutions. 2. Implement an inspection system for light packaging containers that makes it possible to establish optimal cleaning frequencies. 3. Install an internal temperature monitoring system for packaging containers and an accelerometer to prevent failures.
E9	In five years, do not exceed a 15% increase in the annual cost of maintenance and cleaning of containers for this fraction in 2022	1. Reduce water consumption for cleaning paper & cardboard containers by using machinery with water-saving technological solutions. 2. Implement an inspection system for paper & cardboard containers that makes it possible to establish optimal cleaning frequencies. 3. Install an internal temperature monitoring system for packaging containers and an accelerometer to prevent failures.
E10	In five years, do not exceed the annual cost of maintenance and cleaning of containers for this fraction in 2022	1. Reduce water consumption for cleaning glass containers by using machinery with water-saving technological solutions. 2. Implement an inspection system for glass containers that makes it possible to establish optimal cleaning frequencies. 3. Install an internal temperature monitoring system for packaging containers and an accelerometer to prevent failures.
E11	In five years, do not exceed the annual cost of maintenance and cleaning of containers for this fraction in 2022	1. Reduce water consumption for cleaning biowaste containers by using machinery with water-saving technological solutions. 2. Conduct awareness campaigns on the use of closed bags for the deposit of waste in the container. 3. Introduce container model with fewer mobile elements.
E12	In five years, increase by 10% the resources allocated to investments in I+D+I projects	1. Install door-to-door systems in certain areas of the city for the fractions of biowaste, packaging, paper & cardboard, and mixed waste. 2. Implement positioning and control tools in the vehicle fleet. 3. Plan for the creation of complete collecting areas in industrial areas.
E13	In five years, reach an expense per resident and year of 0.5 euros	1. Carry out at least four campaigns a year on the prevention and separation of waste. 2. Carry out a pilot campaign on the collection of medical waste. 3. Modernization of municipal websites and social networks.
S1	In five years, reach 20,000 annual participants	1. Distribution of materials to promote separation at source. 2. Maintain an environmental education team made up of five members. 3. Improve dissemination of positive results and legal waste obligations.
S2	In five years, do not having exceeded the number of sanctions applied during the year 2022	1. Implement a control system for uncontrolled dumping points (reinforcement with drones). 2. Develop a disciplinary procedure in the new ordinance on waste management. 3. Educate on waste management.
S3	In five years, not having exceeded an increase of more than 10% in complaints received during the year 2022	1. Teach collection drivers about more efficient driving that reduces noise pollution. 2. Conduct campaigns that promote the use of the recycling center against the uncontrolled dumping of large volume waste. 3. Avoid container overflow with adequate containerization and collection frequencies.

S4	In five years, increase citizen participation in social media to 4,000 interactions per year	1. Design a social media communication plan that publishes information on the prevention and separation of waste with a suitable frequency. 2. Update the corresponding sections of the city council website that include information on waste management.
S5	In five years, having adapted 200 containers for people with functional diversity compared to those existing in 2022	1. Detect the locations where there is a need to have adapted containers. 2. Adapt and install at least 200 selective containers for packaging, paper & cardboard, and glass. 3. Improve container renewal frequency.
S6	In five years, reach 30 contracts per year that include sustainability criteria	1. Teach sustainability waste criteria to city council technicians who conduct public bidding processes 2. Design and publish a practical guide on sustainability criteria. 3. Promote sustainability criteria to construction contracts especially focused on waste separation.
S7	In five years, improve the citizen support systems to resolve every complaint within 15 days	1. Implement a procedure for handling complaints and provide the corresponding training to personnel assigned to these tasks. 2. Strengthen coordination between the service concession company and the city council by installing standardized procedures and geolocalization.
ENV1	In five years, not having exceeded a 5% increase in emissions compared to those of 2022	1. Replace 50% of the fleet of diesel and/or gas vehicles with other less polluting technologies. 2. Teach collection drivers efficient driving that reduces emissions. 3. Conduct proper vehicle maintenance and a renovation plan.
ENV2	In five years, have half the annual consumption of drinking water compared to 2022	1. Use of reclaimed water in areas of the city where this network exists. 2. Teach workers water-saving techniques. 3. Optimize cleaning frequencies so that they are carried out only when strictly necessary.
ENV3	In five years, increase the percentage of collection of this fraction by 10% compared to 2022	1. Install an electronic closure system for biowaste containers and user identification in certain areas. 2. Carry out a study on the characterization of biowaste for one year. 3. Design a campaign adapted to the need to reduce improper detections, if necessary.
ENV4	In five years, increase the collection percentage of this fraction by 10% compared to 2022	1. Install at least three mobile platforms in the city center area to deposit the separative fractions. 2. Promote selective collection at events by placing containers and their subsequent collection. 3. Carry out communication and environmental education campaigns for the correct separation of packaging waste.
ENV5	In five years, increase the collection percentage of this fraction by 10% compared to 2022	1. Expand the paper and cardboard waste door-to-door collection system to the entire downtown district, as well as the central area. 2. Strengthen the collection during the annual periods of greatest production by increasing the paper & cardboard fraction collection frequencies. 3. Carry out communication and environmental education campaigns for the correct separation of paper & cardboard waste.
ENV6	In five years, increase the collection percentage of this fraction by 10% compared to 2022	1. Implement a door-to-door glass collection system for hotels and restaurants that generate more than 25 kgs per week. 2. Glass waste separation plan at events through the temporary relocation of containers adapted to large producers. 3. Carry out communication and environmental education campaigns for the correct separation of glass waste.
ENV7	In five years, increase the collection percentage in the recycling center by 15% compared to 2022	1. Information campaign on the different locations and hours of the recycling centers through signposting of the locations, billboards, publications on social media and street action. 2. Carry out a campaign on pruning waste that encourages the use of the recycling center for this type of waste. 3. Install a computerized user identification system in the recycling center, which complies with the legislation regarding the collection of home appliances.
ENV8	In five years, do not exceed a 20% increase in emissions compared to those of 2022	1. Implement self-composting in at least 50% of urban gardens, infant and primary schools. 2. Implement self-composting in at least 25% of single-family homes. 3. Develop campaigns to avoid food waste that involve the reduction of biowaste management.
ENV9	In five years, do not exceed a 20% increase in emissions compared to those of 2022	1. Implement the container return system in certain areas of the city. 2. Carry out information campaigns that reduce the number of improper materials collected in packaging containers. 3. Encourage the use of glass packaging.
ENV10	In five years, do not exceed a 20% increase in emissions compared to those of 2022	1. Install cardboard compactors in high production areas of this waste such as industrial estates or shopping streets. 2. Inform large paper & cardboard producers of the schedules and collection points that were defined to optimize collection routes. 3. Establish a circuit between commerce and cardboard manufacturers to promote the circular economy.
ENV11	In five years, do not exceed a 20% increase in emissions compared to those of 2022	1. Optimize the distribution, routes, and collection frequencies of this fraction to carry out collections when the container is full. 2. Promote the refund and return system in hotels and restaurants to optimize the return rate through information campaigns and delivery of materials.
ENV12	In five years, reach an annual amount collected from this fraction of 1kg/res/year	1. Carry out an information campaign through street actions to publicize the locations and importance of separating batteries. 2. Implement a bonus system for the delivery of batteries in the recycling centers.
ENV13	In five years, reach an annual amount collected from this fraction of 200 g/res in a year	1. Study the distribution of oil containers and relocate, if necessary, to reach a coverage of 100% of the city. 2. Carry out an information campaign that includes the delivery of funnels to reach at least 13,000 households. 3. Reinforce the mobile recycling center services.

ENV14	In five years, at least 21% of the locations where there is a biowaste container will be full collection areas	1. Move the necessary containers of packaging, paper & cardboard, glass and mixed waste to create at least 230 complete contribution areas from the locations of the biowaste containers. 2. Implement closed contribution areas with access control for five fractions of waste in residential estates (mixed waste, biowaste, packaging, paper & cardboard and glass). 3. Reduce the number of containers for the mixed fraction.
ENV15	In five years, reach an annual amount collected from this fraction of 4.3kg/res in a year	1. Increase the number of containers until it reaches the average for the region. 2. Design a campaign to promote the use of textile containers for companies that produce this type of waste. 3. Conduct communication and environmental education campaigns for the separation of textiles.
ENV16	In five years, reduce 30% the number of illegal dumping points	1. Increase surveillance through police collaboration. 2. Removal of containers where this problem exists. 3. Promotion of the use of recycling centers.

Phase 3. Data matrix.

In this phase, annual data for the 36 KPIs was collected and the resulting data matrix is presented in Table 5.3, where it is possible to observe the 36 KPIs of the study in rows, observations in columns, and the historical value of these KPI for the years 2017-2022.

Table 5.3. Historical values KPIs.

Indicator	Description	2017	2018	2019	2020	2021	2022
E1	Cost of the biowaste collection service per resident and year (€/res.)	-	-	-	1.77	5.38	5.38
E2	Cost of the container collection service per resident and year (€/res.)	2.48	2.49	2.51	2.71	3.34	4.29
E3	Cost of the paper & cardboard collection service per resident and year (€/res.)	3.22	3.24	3.25	3.15	3.16	3.76
E4	Cost of the mixed waste collection service per resident and year (€/res.)	31.55	31.70	31.86	30.32	29.33	34.71
E5	Cost of the glass waste collection service per resident and year (€/res.)	0.65	0.65	0.66	0.64	0.64	0.75
E6	Cost of the mixed waste disposal service per resident and year (€/res.)	32.00	32.40	33.46	33.17	36.57	38.87
E7	Cost of the mixed waste transfer service per resident and year (€/res.)	5.65	5.72	5.90	5.85	6.45	6.86
E8	Annual cost of maintenance and cleaning of packaging containers per resident and year (€/res.)	0.52	0.52	0.53	0.59	0.77	1.01
E9	Annual cost of maintenance and cleaning of paper & cardboard containers per resident and year (€/res.)	0.52	0.52	0.53	0.51	0.52	0.64
E10	Annual cost of maintenance and cleaning of glass containers per resident and year (€/res.)	0.52	0.52	0.53	0.51	0.51	0.60
E11	Annual cost of maintenance and cleaning of mixed waste containers per resident and year (€/res.)	4.67	4.69	4.72	4.57	4.58	5.42
E12	Annual investments for waste management improvement projects per resident and year (€/res.)	0.63	0.63	0.62	0.62	0.62	0.62

E13	Annual investment in awareness campaigns per resident and year (€/res.)	0.37	0.37	0.37	0.36	0.37	0.37
S1	Number of people participating in campaigns per year (unit)	7651	2704	28,400	663	16,630	17,720
S2	Number of sanctions applied per year (unit)	2	2	0	1	3	15
S3	Number of complaints received per year (unit)	4182	6606	7013	8331	8833	9996
S4	Number of interactions due to the impact of communication campaigns in social media (unit)	38	27	52	2799	2968	2035
S5	Number of adapted containers available for people with functional diversity per year (unit)	25					
S6	Number of public contracts that incorporate sustainability criteria in waste management (unit)	1	3	5	6	11	12
S7	Average time for resolution of complaints in a year (days)	26.5	23.3	25.2	21.7	18.9	17.6
ENV1	Collection service emissions per year (kg CO^2/res.)	7.54	7.89	8.20	8.52	9.14	9.18
ENV2	Annual water footprint of the waste collection service (liters/res.)	22.35	22.17	22.06	23.28	26.43	26.67
ENV3	Selective collection of biowaste percentage with respect to total household waste (%)	0.00	0.00	0.09	1.26	4.11	4.27
ENV4	Selective collection of packaging percentage with respect to total household waste (%)	1.75	1.96	2.16	2.69	2.74	2.74
ENV5	Selective collection of paper & cardboard percentage with respect to total household waste (%)	3.27	3.62	4.06	4.37	4.32	4.15
ENV6	Selective collection of glass percentage with respect to total household waste (%)	2.01	2.06	2.18	2.65	2.37	2.60
ENV7	Percentage of waste collected selectively in the recycling center, compared to the city total (%)	7.55	9.92	9.74	9.37	10.71	9.59
ENV8	Emissions from recovery and elimination of biowaste (kg CO^2/res)	0.00	0.00	0.12	1,64	5.72	4.94
ENV9	Emissions from recovery and disposal of packaging waste (kg CO^2/res.)	0.81	0.92	1.04	1.20	1.31	1.09
ENV10	Emissions from recovery and elimination of paper & cardboard waste (kg CO^2/res.)	0.71	0.80	0.91	0.92	0.97	0.77
ENV11	Emissions from recovery and disposal of glass waste (kg CO^2/res.)	0.24	0.25	0.27	0.30	0.29	0.26
ENV12	Number of batteries collected selectively per year (kgs/res.)	0.08	0.07	0.08	0.06	0.04	0.04
ENV13	Amount of vegetable oil collected selectively per year (gr./res.)	8.26	38.04	101.28	113.06	112.32	86.08

ENV14	Percentage of complete contribution areas with all the fractions with respect to the total number of collection areas (%)	0.00	0.00	0.00	13.48	14.73	18.07
ENV15	Amount of textile waste collected per year (kgs/res.)	2.50	2.53	2.45	2.68	2.98	2.30
ENV16	Number of uncontrolled waste dumping points in the city	25					

The historical data is a highly compact data matrix, where most the KPIs have historical data for all six years of the study. The exceptions are S5 and ENV16 – which although included in the 2022 planning, were only measured in 2017, and so the expert group decided to exclude them from the next phase of data analysis.

Phase 4. Data analysis.

The PCA technique was applied to the data matrix, using SPSS v16.0 and following a rotation method of Varimax normalization and Kaiser criterion. Two principal components were then retained for the study as they explained 99% of the data variability – as shown in Table 5.4.

Table 5.4. Data variability explained by the principal components.

Components	Eigenvalues		
	Total	% of the variance	% Acumulated
1	25,102	73,830	73,830
2	8,898	26,170	100,000
3	1,365E-15	4,016E-15	100,000
4	8,567E-16	2,520E-15	100,000
5	7,750E-16	2,279E-15	100,000
6	6,812E-16	2,003E-15	100,000
7	5,596E-16	1,646E-15	100,000
8	5,157E-16	1,517E-15	100,000
9	4,019E-16	1,182E-15	100,000
10	3,779E-16	1,111E-15	100,000
11	3,145E-16	9,249E-16	100,000
12	2,998E-16	8,817E-16	100,000
13	2,388E-16	7,023E-16	100,000
14	1,992E-16	5,860E-16	100,000
15	1,734E-16	5,100E-16	100,000
16	1,392E-16	4,094E-16	100,000
17	7,346E-17	2,161E-16	100,000
18	5,322E-17	1,565E-16	100,000
19	1,958E-17	5,759E-17	100,000
20	-3,657E-17	-1,075E-16	100,000
21	-4,082E-17	-1,201E-16	100,000
22	-9,379E-17	-2,758E-16	100,000
23	-1,627E-16	-4,786E-16	100,000
24	-1,779E-16	-5,232E-16	100,000
25	-2,016E-16	-5,928E-16	100,000
26	-2,404E-16	-7,070E-16	100,000
27	-3,268E-16	-9,613E-16	100,000
28	-3,514E-16	-1,033E-15	100,000
29	-4,047E-16	-1,190E-15	100,000
30	-4,462E-16	-1,312E-15	100,000
31	-5,073E-16	-1,492E-15	100,000

32	-6,138E-16	-1,805E-15	100,000
33	-7,634E-16	-2,245E-15	100,000
34	-1,352E-15	-3,977E-15	100,000

The two principal components retained for the study are formed by the KPIs, and it is possible to identify which of these two principal components contribute most by making a graphical analysis of the orthogonal situation of the KPIs within the two principal components (see Figure 5.2).

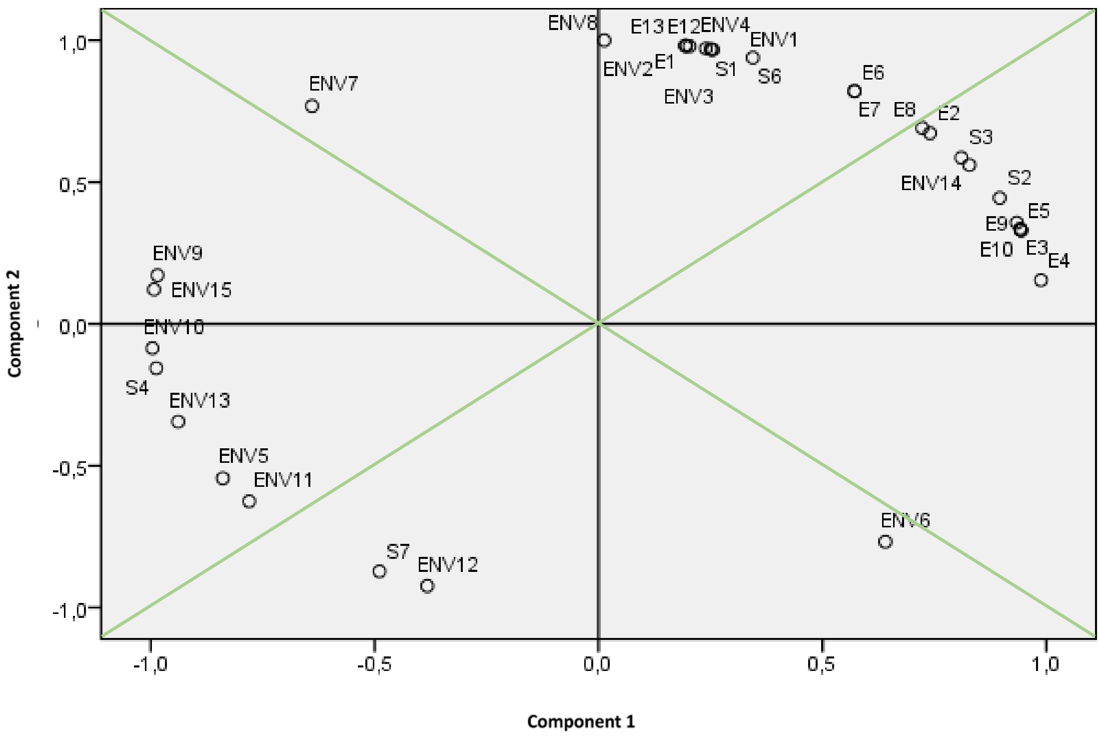

Figure 5.2. Graphic shows the KPI orthogonal situation within the principal components.

By considering the 45º line from the origin (in green in Figure 5.2), it is possible to classify an orthogonal distribution of the KPIs into one of the two principal components depending on which principal component is closest. Figure 5.2 shows how the variables (KPIs) are graphically situated within two principal components: PC1 on the x-axis and PC2 on the y-axis. Each KPI contributes to the formation of the principal components, but they can be classified as more related to one of the principal components than to another depending on the graphical proximity. Two green lines have been added to the graph to make it easier to understand to which principal component each KPI is closest:

- Principal component 1 (x-axis): E2, E3, E4, E5, E8, E9, E10, E11, S2, S3, S4, ENV5, ENV9, ENV10, ENV11, ENV13, ENV14, ENV15.
- Principal component 2 (y-axis): E1, E6, E7, E12, E13, S1, S6, S7, ENV1, ENV2, ENV3, ENV4, ENV6, ENV7, ENV8, ENV12.

The expert group used its experience and knowledge of the organization's waste management process (past and present) to identify which of the effect KPIs are most important:

- E6: This KPI represents the cost of the mixed waste disposal service per resident and year expressed in €/res. These costs include labor, materials, machinery, and indirect costs of the disposal plant for one year. Once the total cost has been obtained, it is divided by the population registered in the municipality for the year of measurement.
- S1: This KPI represents the number of people participating in each of the environmental awareness campaigns carried out in the city during a year.
- S3: This KPI measures the annual number of complaints received by the council regarding waste management (location, quantity, cleanliness and maintenance of containers, transit of the vehicle fleet, uncontrolled dumping, recycling center services, etc.).
- ENV1: This KPI represents the annual amount of CO^2 emissions (kgs) emitted by the collection services per resident. It is calculated from the sum of emissions (produced by the fractions of mixed waste, biowaste, packaging, paper & cardboard, and glass) and divided by the total population.
- ENV2: This KPI refers to the total volume of fresh clean water used by the waste collection service for cleaning containers and vehicles.
- ENV3: This KPI is the ratio obtained by dividing the annual amount of biowaste collected by the total annual amount of containerized waste collected (mixed waste, biowaste, packaging, paper & cardboard and glass).
- ENV14: This KPI is the ratio obtained from the number of complete (all waste fractions) containerized areas with respect to the total number of points on the public road with single containers (biowaste, packaging, paper & cardboard, and glass).

Once this is done, it is time to identify the main cause KPIs associated with the effect KPIs. Figure 5.2 shows the symmetric position of the KPIs with respect to the axes and so reveals the groups of KPIs with a higher cause-effect correlation (Jackson, 2003). For the effect KPIs, Table 5.5 shows the meaningful relationships between KPIs (in columns) and the seven identified effect KPIs and the main cause KPIs (in rows). This Table has been derived by following analytical procedures. Based on the results shown in the previous figure, and following the PCA basis, it is possible to identify the variables that are maintaining some meaningful relationships over time. These variables are those that are grouped around a principal component standing directly together and symmetrically. For instance, regarding the KPI E6 (column 'Effect KPI E6' in Table 5.5), which is defined as one of the most important KPIs, the KPIs that are closest graphically are:

- Directly: E1, E7, E8, E12, E13, S1, S6, ENV1, ENV2, ENV3 and ENV4.
- Symmetrically: S7 and ENV12.

Table 5.5. Cause-effect relationships between KPIs.

Cause KPI	Effect KPI E6	Effect KPI S1	Effect KPI S3	Effect KPI ENV1	Effect KPI ENV2	Effect KPI ENV3	Effect KPI ENV14
E1	X	X		X	X	X	
E2			X				X
E3			X				X
E4			X				X
E5			X				X
E6		X		X	X	X	
E7	X	X		X	X	X	
E8	X	X	X	X	X	X	X
E9			X				X
E10			X				X
E12	X	X		X	X	X	
E13	X	X		X	X	X	
S1	X			X	X	X	
S2			X				X
S3							X
S4			X				X
S6	X	X		X	X	X	
S7	X	X		X	X	X	
ENV1	X	X			X	X	
ENV2	X	X		X		X	
ENV3	X	X		X	X	X	
ENV4	X	X		X	X		
ENV5			X				X
ENV10			X				X
ENV11			X				X
ENV12	X	X		X	X	X	
ENV13			X				X
ENV14			X				

The relationships established above show that E8 is the KPI cause with the greatest influence (influencing all seven effect KPIs). After this, the following KPI causes stand out: E1, E7, E12, E13, S6, S7, ENV3 and ENV12, as well as those which influence five effect KPIs (E6, S1, ENV1, ENV2, ENV3). There is a group of KPIs (E6, S1, ENV1, ENV2, ENV4) that influences four effect KPIs and another group of KPIs (E2, E3, E4, E5, E9, E10, S2, S4, ENV5, ENV10, ENV11, ENV13) that influence two effect KPIs. The following phase establishes specific organizational recommendations that arise from this data analysis.

Phase 5. Results discussion.

Based on the results achieved in the previous phase, decision-makers were able to identify the action plans that are associated with the strategic objectives linked to both the cause-and-effect KPIs. From analyzing the results of Table 5.5, the cause KPIs are ranked from more to less influence (measuring this influence as the number of effect KPIs they influence). E8 is the most influential cause KPI, as it influences all seven effect KPIs. This means that the three action plans that are associated with the strategic objective that E8 is measuring (namely, ‘do not exceed in five years a 15% increase in the annual cost of maintenance and cleaning of containers for this fraction in 2022’) should be activated first, as these action plans will contribute to reaching the strategic objective – as well as those associated with the effect KPIs that E8 is directly affecting:

- E6: cost of the mixed waste disposal service per resident and year.
- S1: number of people participating in campaigns per year.
- S3: number of complaints received per year.
- ENV1: collection service emissions per year.
- ENV2: annual water footprint of the waste collection service.
- ENV3: selective collection of biowaste percentage with respect to total household waste.
- ENV14: percentage of complete contribution areas with all the fractions with respect to the total number of collection areas.

Table 5.6 shows the action plan prioritization produced when carrying out this analysis for all the identified cause KPIs. Table 5.6 also shows the main KPI causes identified (E8, E1, E7, E12, E13, S6, S7, ENV3 and ENV12), the KPIs they affect (from the seven identified in the previous phase as the most important to be achieved), and the 25 action plans associated with the strategic objectives of the cause KPIs. These plans are then prioritized in the order of activation.

Table 5.6. Action plan prioritization.

KPI cause	KPI effect	Action plan prioritization
E8	E6, S1, S3, ENV1, ENV2, ENV3, ENV14	1. Reduce water use for cleaning packaging containers by using machinery with water-saving technological solutions. 2. Implement an inspection system for light packaging containers that enables optimal cleaning frequencies. 3. Install an internal temperature monitoring system for packaging containers and an accelerometer to prevent failures.
E1	E6, S1, ENV1, ENV2, ENV3	1. Study new collection systems for better separation ratios. 2. Promote and subsidize home and community composting. 3. Support the financing of a new specific transfer plant for biowaste.
E7	E6, S1, ENV1, ENV2, ENV3	1. Optimize the distribution, routes, and collection frequencies of this fraction to conduct collections when the containers are full. 2. Modernize the waste management process at the transfer plant to optimize the system and improve performance. 3. Study and project an optimal location for a new transfer plant.
E12	E6, S1, ENV1, ENV2, ENV3	1. Install door-to-door systems in certain areas of the city for the fractions of biowaste, packaging, paper & cardboard, and mixed waste. 2. Implement positioning and control tools in vehicle fleet. 3. Plan for the creation of complete collecting areas in industrial areas.
E13	E6, S1, ENV1, ENV2, ENV3	1. Conduct at least four campaigns a year on the prevention and separation of waste. 2. Carry out a pilot campaign on collection of medical waste. 3. Modernization of municipal websites and social networks.
S6	E6, S1, ENV1, ENV2, ENV3	1. Teach city council technicians who conduct public bidding processes about sustainability waste criteria. 2. Design and publish a practical guide on sustainability criteria. 3. Promote sustainability criteria to construction contracts especially focused on waste separation.
S7	E6, S1, ENV1, ENV2, ENV3	1. Implement a procedure for handling complaints and provide the corresponding training to personnel assigned to these tasks. 2. Strengthen coordination between the service concession company and the city council by installing standardized procedures and geo-localization.
ENV3	E6, S1, ENV1, ENV2, ENV3	1. Install electronic closure systems for biowaste containers and user identification in certain areas. 2. Carry out a study on the characterization of biowaste for one year. 3. Design a campaign adapted to the need to reduce improper detections, if necessary.
ENV12	E6, S1, ENV1, ENV2, ENV3	1. Conduct an information campaign through street actions to publicize the locations and importance of separating batteries. 2. Implement a bonus system for delivery of batteries in recycling centers.

Decision-makers will then have available a prioritization of action plans for the whole performance system that have practical and theoretical implications.

Practical implications.

The main aim of any performance measurement system is to ensure that the defined strategic objectives are reached in the most efficient way. The proposed methodology provides a novel and efficient approach for MSW decision-makers because it identifies – with the application of objective rather than subjective analytical procedures – the order of activation for action plans associated with strategic objectives. It enables reaching all the defined strategic objectives by activating some of the action plans in the performance measurement system and this can provide the organization with notable resource savings. However, like all performance measurement systems, this approach must consider some specific points from a practical point of view:

- Exogeneous variables/events and how they affect the performance measurement system in the present and future. There are some interesting academic works discussing this point but the approaches are always subjective, as we do not know the future and to what extent external changes will affect future developments/performance.
- As a result of the application of this methodology, some actions plan may not be activated. This will result in cost-savings for the organization, but it is necessary to ensure that all the defined strategic objectives for the period (usually one year) are reached despite the activation of fewer action plans. Otherwise, the application of this methodology will mean that an organization achieves short-term cost savings, but compromises the achievement of other sustainability strategic objectives.
- Additionally, it is necessary to keep in mind that an effective follow-up should be carried out in the short-term to ensure that the activation of these analytically chosen action plans is truly helping achieve all the defined strategic objectives of the performance measurement system.

The application of this methodology provided the Castelló de la Plana city council with an order of activation for its 98 action plans. The council was recommended to first activate the 25 action plans associated with the strategic objectives of the cause KPIs. This will make it possible to achieve the meta values of the cause KPIs they are associated with for strategic objectives – as well as those associated with the effect KPIs. With the initial activation of these 25 action plans, the city council can later check whether it is achieving the meta values of both cause-and-effect KPIs. If so, it would not need to activate the action plans associated with the strategic objectives of the effect KPIs (whose estimated cost is €3.2m for 2022) and the funds could be used elsewhere within the city council. If it is necessary to activate some of the action plans associated with the strategic objectives of the effect KPIs, the council would still save some money if it does not need to activate all of the plans. Therefore, the activation times of the action plans should follow Table 5.6 and have control and check points.

Theoretical implications.

It is well known that numerous aspects (operational, economic, environmental, and social) should be considered for the optimization of MSW systems from collection to ultimate disposal (Teixeira et al., 2014). KPIs are an important tool for evaluating performance, but they provide only partial productivity measurements. Without an appropriate aggregation metric, an analysis of KPIs may result in misleading conclusions about MSW service performance (Ferreira et al., 2020). For this reason, standardized methods – such as life cycle assessment (Feiz et al., 2020), life cycle costing, cost-benefit analysis, risk assessment, eco-efficiency analysis, and social life cycle cost (Allesch & Brunner, 2014) – have frequently been used. In addition to these standardized methods, multi-criteria analysis has become increasingly used in recent years (Andrade Arteaga et al., 2020; Coban et al., 2018; Habibollahzade & Houshfar, 2020) for finding relationships between performance elements. However, multiple-criteria decision analysis always harbors doubts about the subjectivity of expert opinions or about the selection of KPIs (Amaral et al., 2022).

This case study has presented the results of applying a methodology for prioritizing waste management action plans which has proven effective in similar approaches found in the literature (Cai et al., 2009; Rodríguez-Rodríguez et al., 2020; Sanchez-Marquez et al., 2018) and could become an efficient tool for MSW management. The methodology enables objectifying decision-making since it is based on employing historical data from a wide variety of parameters to establish cause-effect relationships using statistical analysis. Combining KPIs further removes bias in evaluation (De La Barrera et al., 2016), especially when appropriate correlations have been defined for contributing to synergistic decision-making (Papamichael et al., 2022).

The potential limitations of this study are mainly that it is applied to just one waste management organization, and that the results of following the suggested action plan order of activation are unavailable (which would have shown to what extent the intended resource savings are produced). This is relevant because the MSW performance measurement system is multi-dimensional and, as was observed by (Parekh et al., 2015): “the performance of some indicators is influenced by the performance of other indicators, similarly to how the cost of transportation does not only depend on manpower, machinery, spare vehicles but also depends on distance to landfill site, mode of operation i.e., departmental, contractual or public private partnership mode”. This means that the recommended actions must always be followed up.

5.5. Conclusions, limitations, and future research work.

This paper has presented the results of applying a methodology to prioritize the waste management action plans of the Castelló de la Plana City Council in Spain. Such a methodology is based on the performance structure of strategic objectives, action plans, and KPIs – and their structural relationships. For the study, 36 KPIs were classified into three sustainability dimensions and six years of historical values were gathered. The main cause-effect KPI relationships were identified by applying principal component analysis, and once the most important effect KPIs were identified, the main cause KPIs were indicated. Finally, a prioritized list of 25 action plans (linked to the cause KPIs via the strategic objectives) that should be activated first (from a total of 98 action plans) was produced. Activating these plans first will ensure that their values are reached, as well as the values of the chosen effect KPIs. Following this order of activation enables the city council to save resources, as the values of the effect KPIs can be achieved without activating some (or all) of the action plans linked via the strategic objectives.

Future work could include the application of other statistical techniques to find KPI cause and effects (such as factor analysis or partial least squares) and other implementations of the methodology to improve and generalize its use for any MWS organization.

Data availability statement.

The data that supports the findings of this study are available from the corresponding author [H.M.-S.] on request.

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6. DISCUSIÓN GENERAL DE LOS RESULTADOS.

6. DISCUSIÓN GENERAL DE LOS RESULTADOS.

6.1. Contribuciones de la primera publicación.

En el primero de los artículos se evaluó, mediante análisis ANOVA de medidas repetidas, la evolución de los pesajes diarios de las diferentes fracciones de residuos recogidas selectivamente, tanto en contenedor de vía pública como en los puntos limpios de la ciudad; para evaluar el comportamiento de la generación de residuos en una situación de crisis sanitaria, como la vivida recientemente por el SARS-COV2. Adicionalmente, se utilizó el test de comparaciones múltiples de Bonferroni para asegurar el nivel de confianza e identificar en qué pares de años aparecían diferencias. Los resultados obtenidos mostraron diferentes comportamientos dependiendo de la fracción analizada, y por ello se clasificaron en tres grupos según el número de diferencias estadísticamente significativas encontradas entre los años.

Así, el primer grupo de fracciones estaba compuesto por aquéllas en las que aparecieron diferencias en todas las comparaciones año a año (envases, mercados, voluminosos, voluminosos en punto limpio). El segundo grupo lo formaban las fracciones que, en alguno de sus años, no presentaban diferencias significativas (playas, domiciliaria, residuos de clínicas/hospitales, vidrio, papel/cartón, poda del punto limpio) y el tercer grupo estaba compuesto por las fracciones que únicamente presentaban diferencias estadísticamente significativas en el año 2020 (residuos de limpieza viaria y residuos totales).

En el primer grupo, se observó una tendencia creciente estadísticamente significativa para la recogida de envases ligeros desde el año 2017 hasta el 2020. Sin duda, los envases son una de las fracciones que más está creciendo en todas las ciudades y está obligando a realizar un esfuerzo para evitar su desbordamiento en contenedor. Pero el enorme crecimiento experimentado en el año 2020 se atribuye al auge de los residuos plásticos durante la pandemia, ya que los plásticos de un sólo uso, los equipos de protección individual (mascarillas, geles, etc.) y los productos envasados aumentaron considerablemente, por la sensación de higiene que presentaban frente a los que se adquirían sin envoltorio. Además, el confinamiento domiciliario provocó que el comercio on-line creciera más aún, incrementando igualmente los embalajes de plástico de los productos.

Siguiendo con el primer grupo, respecto a los residuos procedentes de mercados municipales, la tendencia creciente se detiene y sufre un descenso significativo en el año 2020. Ello se debió, en parte, al descenso de la actividad económica y comercial, así como a los protocolos establecidos por las autoridades sanitarias en materia de desinfección u otras medidas de difícil cumplimiento que llevaron al cese temporal de muchos puestos. No deben olvidarse tampoco las restricciones de movilidad impuestas a toda la población, así como los límites de aforo y las distancias de seguridad, que sin duda alguna limitaron el uso de estos recintos. Por último, debe destacarse, en los momentos más duros de la crisis sanitaria, la gran desconfianza hacia los productos frescos no envasados de los mercados por parte de la ciudadanía.

Para cerrar el análisis del primer grupo de residuos, se encuentran los residuos domésticos de gran tamaño (voluminosos). Estos residuos pueden depositarse en el punto limpio o recogerse de forma programada en vía pública mediante un servicio a demanda. Respecto a las aportaciones realizadas en el punto limpio, la tendencia creciente se detuvo en 2018 con una disminución significativa de la cantidad de residuos depositados en 2019 y en 2020. Ello se atribuye a una mejora de los servicios programados de recogida "puerta a puerta" a partir del año 2019. No obstante, esta recogida programada sufrió un descenso significativo en 2020 que puede estar relacionada con el descenso de la actividad economica y, en consecuencia, de las pequeñas obras y reformas que generalmente conllevan la sustitución del mobiliario y electrodomésticos en los domicilios.

En el segundo grupo, comenzando por la recogida selectiva de vidrio, ésta no mostró diferencias entre 2017 y 2018, pero creció significativamente en 2019 y 2020. Ello pudo deberse al cierre temporal de la actividad en hoteles y restaurantes ya que el vidrio que dejó de consumirse en estos establecimientos (dónde tiene un canal de retorno al envasador) se consumió en los hogares, terminando finalmente en el contenedor-iglú de vidrio.

Respecto al papel/cartón no se observaron diferencias significativas en la media de residuos entre 2019 y 2020, poniendo fin a una tendencia de crecimiento constante en los años anteriores. La ralentización de la actividad económica de los grandes productores de papel/cartón (comercios, hostelería, sector industrial, etc.) explicarían los datos obtenidos en el año 2020.

La fracción resto (o todo en uno) en Castelló de la Plana presentó un descenso estadísticamente significativo en 2020. En este sentido, existen estudios que predecían lo contrario, pero se centraban principalmente en los periodos de confinamiento, lo que dificultaba su extrapolación a largo plazo. Estos resultados podrían estar relacionados con una disminución generalizada del consumo familiar debido a la recesión económica provocada por la pandemia y serían una muestra más de la vinculación entre crecimiento económico y generación de residuos.

Los residuos de clínicas y hospitales también mostraron un descenso estadísticamente significativo en 2020. Esta tendencia podría deberse a que los residuos de esta procedencia gestionados por los Ayuntamientos deben ser asimilables a domésticos y, por tanto, no plantean requisitos especiales de gestión, ya que sólo son utilizados por pacientes no infecciosos. Hay que tener en cuenta que los residuos hospitalarios no asimilables a domésticos (residuos peligrosos), que suelen representar el 15% de los residuos de los centros sanitarios, no se recogen a través de los servicios municipales y tienen un canal específico para su gestión. Estos últimos, probablemente crecieron exponencialmente, como ocurrió en otras ciudades y no han sido objeto de este estudio al no ser de competencia municipal.

En cuanto a los residuos de poda depositados en los puntos limpios, la reducción en el año 2020 podría estar relacionada de nuevo con las restricciones de movilidad que, sin duda, dificultaron el transporte de residuos hasta estas instalaciones.

En el caso de los residuos de playas, generalmente se trata de materia vegetal y algas depositadas en la arena. Éstas últimas han ido creciendo en los últimos años debido al aumento de la temperatura del mar, no obstante, desde el año 2018 la mejora en la gestión de estos residuos permitió una notable disminución. Desde ese año, el material de playa retirado se acumula en puntos alejados de la orilla donde se deja secar, reduciendo su humedad, para posteriormente cribar la arena que lleva mezclada. Entre 2019 y 2020 no existen diferencias significativas en los pesajes de esta fracción.

Por último, en el tercer grupo de fracciones (limpieza viaria y la generación total de residuos) no aparecieron diferencias significativas en ningún año entre 2017 y 2019, mientras que el valor medio descendió significativamente en 2020. El importante descenso de los residuos recogidos en la limpieza de la vía pública debió estar directamente relacionado con el confinamiento domiciliario, las restricciones a la movilidad y el cierre temporal de la hostelería. Pero al contrario de lo que se pueda pensar, eso no hizo que las necesidades de limpieza disminuyeran, ya que pese a que la cantidad de residuos era inferior, las desinfecciones, baldeos e higienizaciones impuestas por los protocolos sanitarios desembocaron en un refuerzo de los medios disponibles.

Respecto a la generación total de residuos, algunos estudios preliminares predecían un aumento considerable (Charlebois et al., 2020; Zand and Heir, 2020) debido al pánico inicial (exceso de compras, de higiene, etc.), sin embargo, los resultados obtenidos en Castelló de la Plana mostraron justo lo contrario. Y es que, siendo el sector servicios el más importante en la economía de la ciudad, podría decirse que la paralización de la mayor parte de las actividades productivas y comerciales debido a la crisis de COVID-19 provocó importantes pérdidas económicas que, a su vez, derivaron en una disminución de los residuos a largo plazo.

En resumen, considerando el año previo a la pandemia (2019) y el año de pandemia (2020), la recogida de residuos creció significativamente en las fracciones vidrio y envases; se mantuvo sin cambios en los residuos de playas y papel/cartón; y disminuyó significativamente para los residuos domiciliarios, la limpieza viaria, los residuos de mercados, los de clínicas/hospitales, la poda y los voluminosos depositados en los puntos limpios y en el total de residuos de la ciudad. La pandemia provocó una mejora en las ratios de separación en origen de las fracciones recogidas en contenedor (vidrio, envases ligeros y papel/cartón), porque además de aumentar éstas en su conjunto, la generación total de RSU disminuyó.

Respecto a la hipótesis inicial planteada en la introducción de la Tesis Doctoral, se ha confirmado cómo un acontecimiento totalmente inesperado y que alteró los hábitos de la ciudadanía, también produjo diferencias estadísticamente significativas en todas las fracciones que se analizaron y en un periodo de cuatro años. Quedó demostrado, por tanto, que la generación de RSU se vio alterada en los escenarios comparados (pre-COVID-19 y COVID-19) y ello afectó seriamente a la programación de los servicios.

Para concluir, se debe destacar que el conocimiento de los cambios provocados por la pandemia en la generación de RSU, resulta de gran utilidad de cara a hacer frente a posibles acontecimientos similares que alteren sustancialmente los hábitos de la ciudadanía. Así, estos datos pueden ser provechosos tanto para los operadores de servicios de recogida y limpieza, como para las administraciones públicas, ya que de alguna manera pretenden reflejar lo ocurrido en una ciudad de tamaño medio cuando se imponen determinadas restricciones en una situación de crisis. Efectivamente, los servicios de recogida de residuos y limpieza viaria resultan afectados y deben dotarse de la flexibilidad necesaria para poder reprogramarse, reforzando algunos en detrimento de otros.

6.2. Contribuciones de la segunda publicación.

En la segunda publicación se evaluó la composición de los biorresiduos recogidos selectivamente durante el primer año de implantación de esta fracción en la ciudad de

Castelló de la Plana. Los resultados obtenidos permitieron ajustar tanto las frecuencias de recogida, como adaptar las campañas de sensibilización medioambiental para reducir los residuos impropios. Para ello, se tuvo en cuenta la evolución de los pesajes mensuales obtenidos, la tasa de recogida por habitante y la composición de los residuos depositados a través de la caracterización macroscópica realizada.

Respecto a la generación de biorresiduos en la ciudad, la cantidad bruta total recogida selectivamente desde diciembre de 2020 hasta noviembre de 2021 fue de 2.813.510 kg, lo que supone una media mensual de 234.456 kg. Este dato representa aproximadamente un 4% del total de los residuos generados en Castelló de la Plana mensualmente, lejos de las previsiones iniciales y de la composición globalmente aceptada de que los residuos mezclados contienen un 40%-50% de biorresiduos (Treadwell et al., 2018). Todo ello lleva a pensar que no se está llevando a cabo una correcta separación en origen y que, por motivos diversos, no se está haciendo el uso esperado del contenedor marrón. En cuanto a su evolución anual, destaca la tendencia ascendente en la cantidad recogida inicialmente, como consecuencia de la buena acogida y de las campañas de sensibilización previas realizadas. No obstante, esta tendencia se estabilizó posteriormente y descendió en los meses de verano debido a la población flotante negativa de la ciudad en dicho periodo.

En cuanto a la tasa global de impropios (entorno al 40%) derivó en una cantidad neta de materia orgánica compostable durante el primer año de 1.690.930 kg; esto incluye restos de comida, restos vegetales y otros materiales aptos para su compostaje. En comparación con los estudios anteriores en la ciudad, las caracterizaciones realizadas en experiencias piloto mostraban un porcentaje de impropios muy inferior al detectado durante el primer año de implantación global. Así en los distritos Centro, Norte y Oeste, que eran los que peores resultados mostraban en las experiencias piloto (20% de impropios) en esta ocasión se encontraron por encima del 34% y en dos de ellos se superó el 40%. Por su parte, los resultados de los distritos Este y Grao, que mostraban porcentajes de impropios inferiores al 10% en las pruebas realizadas, revelan que durante el primer año de implantación dichos impropios también están en sintonía con el resto de la ciudad rondando el 40%.

En comparación con otras ciudades de tamaño similar y también con recogida selectiva contenerizada en contenedor de carga lateral, los porcentajes de impropios de Castelló de la Plana fueron bastante más elevados. Debe destacarse, llegados a este punto, que la reciente Ley 7/2022 de Residuos de 8 de abril de residuos y suelos contaminados para una economía circular en su artículo 25 establece que, para los biorresiduos, el porcentaje máximo de impropios permitido es del 20% desde 2022 y del 15% desde 2027. En este sentido, los Ayuntamientos podrán ser sancionados conforme al Art. 108 si la pureza en su composición no alcanza el 80%.

En referencia a la hipótesis de partida planteada, ésta debe ser rechazada ya que la generación de biorresiduos durante el primer año de implantación de esta fracción estuvo muy por debajo de lo esperado, si se tiene en cuenta la composición habitual de los residuos municipales. Además, tampoco se cumplió la hipótesis de que los residuos impropios estuvieran próximos a los objetivos establecidos en la Ley 7/2022 de residuos y suelos contaminados para una economía circular (20% para el año 2022).

Por ello, el estudio ha resultado muy útil para el Ayuntamiento de Castelló de la Plana como "bandera roja" para persuadir a la ciudadanía en el buen uso del contenedor marrón ya que, en caso de excederse el porcentaje de impropios indicado anteriormente, la fracción orgánica recogida selectivamente es considerada como mezcla de residuos y ello repercutirá directamente en la tasa que se traslada al ciudadano. Además, desde el punto de vista medioambiental, la calidad del compost producido en las plantas de tratamiento biológico está directamente relacionada con la composición de la fracción orgánica recogida selectivamente de los residuos municipales, así como de otras características intrínsecas de las propias plantas (como el tipo de tratamiento utilizado o la duración de los procesos de descomposición y maduración). Y es que la aplicabilidad del compost como abono orgánico en agricultura o jardinería necesita cumplir con determinados parámetros de calidad, como el bajo contenido de metales pesados, de acuerdo con lo especificado en el Real Decreto 506/2013, de 28 de junio, sobre productos fertilizantes. De ahí la importancia de conocer las características de la materia prima con la que se producirá el compost.

Respecto a la composición por distritos, el distrito donde se obtuvo mayor calidad para el compostaje fue el distrito Oeste, puesto que el contenido en materia orgánica se encontraba cercano al 70%. Este distrito es el que presenta una edad media menor, lo que hace pensar que es en las franjas de edad inferiores donde la concienciación es mayor. En el resto de los distritos, se obtuvo una calidad muy baja (alrededor del 56% de materia orgánica) con un contenido de impropios muy elevado, superior al 40%.

Para finalizar, la tasa bruta media de recogida fue de 0,045 kg/hab-día un dato algo superior al de las experiencias previas, pero muy inferior al de otras ciudades dónde la implantación fue anterior, como Madrid o Barcelona (0,17 kg/hab-día y 0,15 Kg/hab-día, respectivamente). No obstante, si se comparan los datos con ciudades donde la implantación ha sido más reciente, como Valencia con 0,07 kg/hab-día (Valencia, 2021) o Bilbao con 0,02 kg/hab-día (Bizkaia, 2021), las ratios están más próximas.

El dato negativo de esta experiencia, llevada a cabo durante un año, fue el elevado porcentaje de restos impropios que hace necesaria una reflexión profunda sobre el sistema en su conjunto.

6.3. Contribuciones de la tercera publicación.

En la tercera publicación se ha empleado un método multicriterio de apoyo a la toma de decisiones, el Stratified Best and Worst Method, para elegir la mejor manera de renovar la flota de vehículos recolectores. Estos métodos son muy frecuentes en la gestión de RSU, ya que son útiles para analizar sistemas complejos con una gran cantidad de variables, permitiendo una priorización de las alternativas objeto de estudio. Sin embargo, su aplicación generalmente se ha empleado para elegir ubicaciones de plantas o tecnologías de tratamiento, pese al papel fundamental que representa la recogida y transporte de residuos en la sostenibilidad de los núcleos urbanos. De este modo, en los últimos años, la normativa europea incide en la separación en origen y en consecuencia en el aumento del número de rutas, así como de los vehículos necesarios para recoger las cinco fracciones obligatorias hasta la fecha (vidrio, papel y cartón, envases, biorresiduos y residuos mezclados). Asimismo, los municipios cuyas ratios de separación en origen sean muy inferiores a la media, deben implantar recogidas "puerta a puerta", lo que incrementa aún más las necesidades de vehículos. Por lo tanto, el diseño óptimo de las rutas, la ubicación de las plantas de transferencia y el tipo de camión de recogida son vitales para obtener soluciones rentables y respetuosas con el medio ambiente.

Además, cuando se diseña un servicio de recogida de residuos para una ciudad, los costes de inversión y amortización de la maquinaria representan un porcentaje muy elevado del presupuesto total. Igualmente, los costes de explotación van a depender directamente de la elección de una u otra alternativa. Pero, junto con el gasto, las administraciones públicas, cada vez con más frecuencia, consideran otros factores, ya que estos servicios son motivo de quejas ciudadanas por emisiones, ruidos, afección al tráfico, etc. Por ello, cuando una ciudad se plantea renovar la flota de vehículos de recogida de residuos, deben tenerse en cuenta todas las alternativas disponibles y varios criterios que permitan tomar la decisión más adecuada en función de las necesidades.

Por ello, se analizaron diferentes motorizaciones de los camiones de recogida de residuos (diésel, gas natural comprimido (GNC), híbrido GNC-eléctrico, eléctrico y de hidrógeno), empleando criterios de sostenibilidad y un método (SBWM) que permitía considerar la incertidumbre asociada a eventos futuros para establecer diversos escenarios; siendo esto último la principal novedad de la publicación. Así, se definieron un total de ocho escenarios distintos a partir de posibles eventos futuros, tales como la inflación, los cambios en la legislación, posibles subvenciones y combinaciones de todos ellos.

El objetivo del grupo de expertos formado fue conocer cuál de las tecnologías disponibles era más adecuada para las necesidades de la ciudad de Castelló de la Plana. Así, algunos de los criterios elegidos coincidieron con los empleados por otros autores para la selección de tecnologías de gestión de residuos, sin embargo, otros son propios del caso de estudio de la ciudad.

Los resultados muestran que las opciones mejor valoradas fueron los camiones eléctricos y diésel, por este orden, seguidos por los propulsados por GNC y los híbridos GNC-eléctricos, quedando en último lugar los camiones propulsados por hidrógeno. Los camiones eléctricos fueron los mejor valorados respecto a sus costes de explotación, emisiones atmosféricas, ruido y aceptación social. Siendo estos unos de los criterios con mayor peso, le permitieron alcanzar la primera posición pese a los resultados no tan buenos que presentaba esta alternativa en criterios de flexibilidad en la configuración del vehículo, la facilidad de repostaje (debido a los largos tiempos de recarga) o la vida útil (condicionada por la frecuencia habitualmente diaria de los ciclos de carga para este tipo de vehículos). De este modo, se posicionaron como la mejor alternativa a pesar de las limitaciones en autonomía o tiempos de recarga, ya que de acuerdo con otros autores los vehículos eléctricos pueden ayudar a mejorar la calidad de las ciudades y en consecuencia los efectos del cambio climático.

Los buenos resultados de los camiones diésel, que se situaron en segunda posición y muy cerca de la primera, se basan precisamente en su clara ventaja respecto al resto de criterios citados anteriormente. Los vehículos diésel de recogida de residuos están muy consolidados en el mercado, obteniendo repuestos a precios muy accesibles. Además, están disponibles en casi cualquier configuración (carga trasera, lateral, superior, etc.) y sus repostajes son accesibles, fáciles y rápidos.

Tras estas dos alternativas (posiciones 3 y 4), con resultados muy similares, aparecen los camiones propulsados por gas natural comprimido (GNC) y los híbridos GNC-eléctricos. Los camiones propulsados por GNC se han ido introduciendo progresivamente en España y cada vez se dispone de una gama más amplia de configuraciones. Al mismo tiempo, un número cada vez mayor de fabricantes ha desarrollado vehículos de GNC y esto ha aumentado la competencia en precios, criterio en el que obtienen mayor peso que los camiones que combinan GNC con la tracción eléctrica. La alternativa híbrida GNC-eléctrica, que utiliza combustible fósil para cargar las baterías y motores eléctricos para la tracción, muestra mejores puntuaciones en los criterios relacionados con los aspectos medioambientales y sociales, así como unos costes de explotación ligeramente inferiores debido a una optimización del régimen de funcionamiento del motor de combustión. Sin embargo, muestra limitaciones debidas a la suma de los condicionantes del gas natural comprimido (menos puntos de repostaje) y de los camiones eléctricos (vida útil) y a los límites en las configuraciones posibles (mayor peso debido a los depósitos de GNC y las baterías).

Llegados a este punto, es importante destacar que no se ha tenido en cuenta el origen renovable que puede tener el gas natural comprimido (GNC), ya que en la provincia las instalaciones de digestión anaeróbica son escasas y de no ser así, seguramente la valoración de los expertos habría sido distinta por sus beneficios medioambientales, teniendo en cuenta la totalidad del sistema.

En última posición resultaron los camiones propulsados por hidrógeno, ya que, aunque sus resultados en algunos de los criterios (ruido, emisiones, aceptación social), fueron buenos; existen dudas sobre la generación y distribución de este combustible, ya que en la actualidad se obtiene principalmente como derivado del petróleo. Además, es una tecnología con poca implantación actual por lo que tanto la oferta como la variedad de configuraciones es limitada. Por ello, a pesar de contar con las menores emisiones atmosféricas, se consideró la opción menos viable debido a su escaso desarrollo, la falta de competitividad en el mercado en cuanto a adquisición, servicio postventa y la limitada red de repostaje.

Respecto al método de estratificación empleado, debe reseñarse que si no se hubieran considerado y evaluado las alternativas en diferentes escenarios el ranking habría sido diferente. Por tanto, la tercera de las hipótesis iniciales sí se ha cumplido, ya que ha quedado demostrado que el uso de criterios de sostenibilidad y el planteamiento de diferentes escenarios futuros en la toma de decisión, han servido para obtener resultados más fiables y concluyentes.

6.4. Contribuciones de la cuarta publicación.

En esta publicación, se ha desarrollado y aplicado una metodología para priorizar los planes de acción contenidos en el PLR de la ciudad, a partir de un análisis estadístico de los datos históricos de algunos de sus KPIs.

Para la optimización de los sistemas de gestión de RSU se deben considerar diferentes factores operativos, económicos, ambientales y sociales. Por ello, los KPIs son una herramienta importante para evaluar su rendimiento, sin embargo, un análisis adecuado y avanzado basado en datos objetivos, como el desarrollado en esta investigación proporciona información adicional latente que puede ser empleada para mejorar el grado de eficacia del sistema de gestión del rendimiento integral y, por extensión, para racionalizar los recursos empleados por la administración.

La metodología que se ha utilizado ha demostrado buenos resultados en otros campos, pero nunca se había empleado en la gestión de RSU, siendo este uno de los servicios más complejos que prestan las administraciones locales. Así, se han identificado las relaciones causa-efecto entre los principales KPIs aplicando la técnica de análisis de componentes principales (PCA), y a partir de estas relaciones se han podido priorizar aquellos planes de acción que deberían abordarse con anterioridad, para gestionar los recursos públicos de forma más eficiente. De este modo, tras formar los componentes principales mediante métodos de rotación, las variables (KPIs) se situaron gráficamente alrededor de estos ejes. Entonces, se pudo observar cómo cada KPI contribuía a la formación de dichos componentes principales, clasificándolos dependiendo de su proximidad gráfica a cada uno de los componentes principales, tanto directa como simétricamente (Jackson, 2003).

El principal objetivo en cualquier sistema de medición del rendimiento es asegurarse de que los objetivos estratégicos definidos se alcanzan adecuadamente y de la forma más eficiente. Con esta publicación se aporta un enfoque novedoso para que los responsables en la toma de decisiones en la gestión de RSU dispongan de una herramienta que utiliza procedimientos analíticos objetivos, en lugar de subjetivos, para definir el orden de activación de los planes de acción asociados a los objetivos estratégicos, mediante la identificación de relaciones causa-efecto entre KPIs.

Una de las principales contribuciones de esta metodología, es que demuestra que es posible alcanzar todos los objetivos estratégicos definidos, sin llegar a activar todos los planes de acción del sistema, lo que revierte directamente en un importante ahorro económico. La forma de conseguirlo es, una vez definida las relaciones causa-efecto entre indicadores, actuar sobre los planes de acción más importantes (los vinculados a los KPIs causa con mayor número de efectos).

Por lo tanto, se ha demostrado el cumplimiento de la última hipótesis planteada en la introducción, ya que mediante el análisis de las relaciones causa-efecto entre KPIs, utilizando PCA, y partiendo de los datos históricos desde el año 2017, se ha podido establecer un orden de prioridad de las acciones incluidas en el PLR. En consecuencia, la aplicación de esta metodología proporciona al Ayuntamiento de Castelló de la Plana un orden de activación para los 98 planes de acción incluidos en su PLR.

De este modo, se recomendó activar en primer lugar los 25 planes de acción asociados a los objetivos estratégicos de los KPIs causa, ya que ello permitirá alcanzar los valores objetivo tanto de los objetivos estratégicos asociados a los KPI causa como los de los asociados a los KPIs efecto. Con la activación inicial de estos 25 planes de acción, el Ayuntamiento podrá comprobar posteriormente si está alcanzando dichos objetivos tanto en los vinculados a KPIs causa, como en los vinculados a KPIs efecto. En ese caso, no sería necesario activar los planes de acción asociados a los objetivos estratégicos de los KPI efecto, cuyo coste estimado es de 3,2 millones de euros.

No obstante, para su implementación será necesario un seguimiento eficaz a corto plazo, con el fin de asegurarse de que la activación de estos planes de acción elegidos analíticamente está ayudando realmente a alcanzar todos los objetivos estratégicos definidos, de lo contrario podría darse la contradicción de que, obteniendo un ahorro de costes a corto plazo, se viera comprometida la consecución de otros objetivos estratégicos de sostenibilidad.

Este estudio puede ser útil a la hora de abordar las actuaciones incluidas en los documentos estratégicos de gestión local de residuos, ya que puede suponer un ahorro de tiempo y de recursos para las administraciones públicas.

6.5. Implicaciones y utilidad de los resultados obtenidos.

En la presente Tesis Doctoral, partiendo de un acontecimiento totalmente inesperado y disruptivo que afectó a los hábitos personales y sociales de la ciudadanía, como fue la pandemia por COVID-19, se estudió la variación en la generación de RSU y cómo ésta afectó a los servicios de recogida asociados. A continuación, y debido a las imposiciones normativas, se analizó la composición de la que debe convertirse en la fracción mayoritaria de la ciudad (los biorresiduos), con el objetivo de evaluar su idoneidad para el compostaje. Seguidamente, de cara a una futura renovación de los servicios de recogida municipales, se han evaluado diferentes alternativas de vehículos recolectores con el fin de elegir el más adecuado en base a criterios de sostenibilidad. Para finalizar, y siguiendo con futuras operaciones, se ha aplicado una metodología para proponer un orden de actuación de las acciones estratégicas recogidas en el PLR de la ciudad.

Los resultados obtenidos en esta investigación pueden tener importantes implicaciones para otros casos de estudio dentro del ámbito de la gestión local de RSU ya que, al estar basados en un enfoque metodológico sólido y datos representativos, es factible su aplicación en ciudades de características similares, proporcionando información valiosa a las administraciones públicas y en particular a los responsables locales en la gestión de RSU.

De este modo, las variaciones observadas en la generación de RSU motivadas por acontecimientos extraordinarios han puesto de manifiesto la rigidez de algunos contratos, ya que para alterar servicios y programaciones el procedimiento administrativo es largo y complejo. Por ello, deben abordarse otras posibles vías, a través de los pliegos de condiciones, que permitan tratar esta problemática de una manera más ágil, dentro de los márgenes de la Ley 9/2017, de 8 de noviembre, de Contratos del Sector Público. Asimismo, el estudio realizado supone un buen punto de partida para ayudar a reducir los tiempos necesarios para ejecutar nuevas planificaciones o reprogramaciones en situaciones similares.

Respecto a los bajos resultados obtenidos, tanto en cantidad como en calidad, de los biorresiduos, el Ayuntamiento de Castelló de la Plana está valorando la implantación de sistemas de identificación del productor, ya sea mediante la adopción de otros modelos de recogida o mediante el cierre de contenedores y el uso de dispositivos de apertura individualizada. Estos sistemas se han implantado con éxito en otras ciudades, ayudando a mejorar las ratios de separación en origen. Además, junto con estas acciones, se están planteando cambios en la recogida de la fracción resto; ya que el tamaño de dicho contenedor hace necesaria una elevada dotación que redunda en una mayor proximidad de éstos a los domicilios. Este hecho puede estar repercutiendo de forma negativa en las aportaciones al resto de fracciones.

De los resultados del estudio de alternativas para la renovación de la flota de vehículos, el Ayuntamiento de Castelló de la Plana está valorando la opción eléctrica para la futura licitación del servicio, tanto en maquinaria de limpieza viaria como en vehículos recolectores. Esto afectará tanto a la consignación presupuestaria del servicio, como a los requisitos técnicos de las instalaciones del futuro adjudicatario; debiendo prever las infraestructuras necesarias para la recarga de dichos vehículos.

Por último, respecto a la última de las publicaciones, sus resultados están sirviendo para evaluar el orden de actuación en las acciones pendientes de ejecución del PLR de la ciudad, así como para el diseño del nuevo plan estratégico de RSU de la ciudad, ya que la vigencia del actual finaliza en el año 2026.

De esta forma, este estudio puede representar un avance en el marco de la gestión de RSU en la esfera local, ya que anteriormente las metodologías empleadas en la Tesis Doctoral no habían sido aplicadas directamente en este campo. La contribución más notable podría ser la propuesta de mejora del sistema mediante la identificación y análisis en profundidad de diversos factores que influyen en su eficacia a nivel municipal. Como se ha mencionado, el estudio emplea enfoques novedosos en la materia, como modelos estadísticos o análisis de decisión multicriterio, que ayudan a proporcionar una visión más completa y detallada de la dinámica subyacente en la gestión de RSU, y que no habían sido previamente utilizados para este fin.

Así, se puede afirmar que los resultados de la investigación tienen una utilidad práctica para mejorar los sistemas de gestión de RSU de las ciudades, al identificar algunos de los factores críticos que afectan a su rendimiento y proporcionando herramientas para su análisis y mejora.

En resumen, en este apartado se han sintetizado las principales contribuciones de cada una de las publicaciones que forman esta Tesis Doctoral, contrastando las hipótesis iniciales y enfatizando su relevancia más allá del ámbito específico del caso de estudio. De este modo, se han identificado implicaciones, avances y utilidades que ayudan a resaltar cómo los hallazgos obtenidos pueden contribuir al conocimiento existente en el campo de los RSU, ofreciendo pautas aplicables a otros casos de estudio y facilitando herramientas prácticas para mejorar los sistemas de gestión de residuos en diversos contextos.

7. CONCLUSIONES, LIMITACIONES Y DESARROLLOS FUTUROS.

7. CONCLUSIONES, LIMITACIONES Y DESARROLLOS FUTUROS.

7.1. Conclusiones.

La gestión de residuos desempeña un papel fundamental en la economía circular y en la consecución de los Objetivos de Desarrollo Sostenible (ODS). Una gestión adecuada pasa por el uso racional de los recursos naturales y la minimización en la generación de RSU. Así, la economía circular pretende que los residuos se consideren como recursos potenciales para que se introduzcan de nuevo en la cadena de valor como materias primas o para su valorización energética, por lo que la adecuada gestión de los RSU se ha convertido en una de las prioridades en el desarrollo de la economía circular.

En este sentido, la presente Tesis Doctoral es el resultado del compendio de cuatro publicaciones en las que se han analizado diferentes dimensiones del sistema de gestión de RSU de la ciudad de Castelló de la Plana, poniendo el foco en las que son de plena competencia local y que pueden ayudar a mejorar su rendimiento, tales como: la generación, la composición, los sistemas de recogida y la planificación estratégica.

Así, se ha estudiado el impacto de una situación extraordinaria, la crisis del COVID-19, que derivó en la declaración de estado de alarma en todo el territorio nacional, en la generación de RSU de la ciudad. Observando que, mientras la cantidad total de residuos se veía drásticamente reducida debido a las medidas sanitarias y su impacto en la economía, algunas fracciones como los envases y el vidrio aumentaron notablemente, debiendo reorganizar los recursos y adaptar las rutas de recogida. De este modo, se observaron cambios estadísticamente significativos en la generación de residuos en el año 2020, que rompieron la tendencia de los últimos cuatro años, mostrando que la pandemia provocó cambios en la cantidad, composición y distribución de los RSU y, en consecuencia, dificultando su gestión. Además, debido a las restricciones de movilidad, los residuos procedentes de la limpieza viaria disminuyeron, alterando la programación de los barridos y aumentando los servicios de limpieza húmeda y desinfección en mercados, hospitales, mobiliario urbano, etc. Todos estos cambios se tuvieron que adoptar de forma reactiva, mientras que, si se hubiera contado con datos objetivos y fiables sobre la predicción de cambios en la generación de RSU obtenidos en este estudio, se podrían haber planificado mejor las acciones, reorganizando los recursos de una forma más eficiente. Las lecciones aprendidas serán de utilidad frente a acontecimientos similares.

Respecto a la composición de biorresiduos, los datos pusieron de manifiesto que su cantidad recogida durante el primer año fue reducida y de baja calidad, imposibilitando las operaciones de compostaje de manera directa, que es el objetivo que se persigue con la recogida selectiva de la fracción orgánica. El desglose de datos por distritos puso de manifiesto que los mejores datos se encontraban en el distrito con edad media menor, lo que hace necesaria una profunda reflexión sobre los hábitos de separación en origen tradicionales y la importancia de la educación ambiental.

Con los datos obtenidos, la ciudad de Castelló de la Plana debe explorar otras vías para mejorar la recogida de biorresiduos, tales como la recogida puerta a puerta, la implantación de bonificaciones, el uso de sistemas de cierre e identificación en el contenedor, u otras acciones dirigidas a grupos específicos como por ejemplo, los grandes productores.

En relación con la flota de vehículos para la recogida de RSU, ha quedado demostrada la importancia del transporte sostenible para el beneficio medioambiental de la ciudad. Por tanto, no basta con centrarse únicamente en evaluar las mejores alternativas de tratamiento y eliminación, como hacen la mayoría de estudios, sino que la movilidad en el marco de los RSU, también representa un problema que debe ser abordado en profundidad, y teniendo en cuenta diferentes escenarios.

Así, se han analizado las alternativas de vehículos disponibles en el mercado (diésel, GNC, híbrido GNC-eléctrico, eléctrico e hidrógeno) considerando escenarios futuros factibles y bajo criterios de sostenibilidad (económicos, sociales y medioambientales); mediante una novedosa técnica de análisis multicriterio. Este método permitió a los responsables expresar sus juicios teniendo en cuenta la incertidumbre asociada a las decisiones con repercusiones a largo plazo. Los resultados mostraron que, a pesar de su elevado precio, los camiones eléctricos son ya la mejor opción destacando por sus bajas emisiones (atmosféricas y sonoras), así como en la aceptación social ya que favorecen la sostenibilidad en de la gestión de RSU.

Por último, respecto a la planificación estratégica de la ciudad en el marco de los residuos, se ha analizado el PLR de la ciudad de Castelló de la Plana y se ha aplicado una metodología utilizada con éxito en otros campos, para priorizar los planes de acción que en éste se incluyen. Dicha metodología está basada en las estructuras de rendimiento de los objetivos estratégicos, los planes de acción y los principales KPIs, a través de sus relaciones estructurales.

De este modo, se han clasificado los principales indicadores del PLR en las tres dimensiones de la sostenibilidad y se recopilaron sus valores históricos de los últimos seis años. Aplicando el análisis de componentes principales (PCA), se identificaron las principales relaciones causa-efecto entre indicadores que sirvieron para elaborar una lista priorizada de 25 planes de acción (vinculados a los KPI-causa a través de los objetivos estratégicos) que deberían activarse en primer lugar, permitiendo al Ayuntamiento de Castelló de la Plana optimizar sus recursos, ya que los objetivos vinculados a los KPI-efecto podrían alcanzarse sin activar algunos de sus planes de acción.

A modo de síntesis, mediante los estudios realizados se han abordado diferentes dimensiones relevantes dentro del sistema de gestión de residuos de la ciudad de Castelló de la Plana, dónde la principal competencia es la recogida y transporte, para poder mejorarlo de forma integral, atendiendo a las exigencias de sostenibilidad y circularidad que se plantean en las ciudades.

7.2. Limitaciones y futuras líneas de investigación.

La presente Tesis Doctoral presenta una serie de limitaciones que deben ser reflejadas, ya que se ha fundamentado sobre el caso de estudio concreto de una ciudad de tamaño medio con una determinada densidad de población. Estudios anteriores han demostrado que la generación y la composición de los residuos puede variar en función de la ubicación, los factores socioeconómicos o factores climáticos. Por tanto, para que los resultados sean más robustos y replicables, deberían realizarse más estudios en ciudades de distintos tamaños y con una distribución diferente de los sectores económicos.

En cuanto a la elección de los vehículos de recogida mediante técnicas multicriterio, debe reseñarse que sólo se han tenido en cuenta una serie de criterios de sostenibilidad, especialmente escasos respecto a la dimensión social. En futuros trabajos deberían tenerse en cuenta criterios de sostenibilidad más equilibrados, tanto cualitativos como cuantitativos. Otra limitación reside en que se asumió que todos ellos eran independientes, lo que puede no ser exactamente así. Los estudios futuros deberían abordar esta cuestión utilizando métodos que permitan modelizar las interdependencias entre criterios. Además, podrían emplearse otras metodologías que manejan el componente de incertidumbre como, por ejemplo, técnicas fuzzy.

Además, se debe destacar que los métodos multicriterio son una herramienta de trabajo muy interesante en la gestión de residuos y que, pese a su subjetividad, no significa que sean arbitrarios. Para hacer frente a la incertidumbre en las ponderaciones de los criterios, los estudios futuros deberían centrarse en la evaluación rigurosa de las tendencias futuras con el objetivo de obtener decisiones más robustas.

Respecto al PLR de la ciudad, no se dispone de los resultados de haber seguido el orden de activación de planes de acción sugerido. Ello habría mostrado hasta qué punto se puede producir el ahorro previsto. Esto es muy relevante, ya que el sistema de gestión de residuos es multidimensional y hace que el seguimiento de las acciones recomendadas sea una actividad a controlar, siempre que sea posible. Trabajos futuros podrían incluir la aplicación de otras técnicas estadísticas para encontrar relaciones causa-efecto de estos mismos indicadores, y así poder comparar y generalizar los resultados. Algunas de ellas podrían ser otras técnicas de reducción de la dimensionalidad, tales como el análisis factorial.

Por último, este trabajo debe servir para continuar fomentando la investigación sobre los sistemas de gestión de RSU, ya que son un pilar fundamental para el desarrollo sostenible y la economía circular de las ciudades.

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ANEXO 1. VERSIÓN EDITORIAL DE LOS ARTÍCULOS PUBLICADOS.

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MDPI

Article

Statistical Analysis of the Long-Term Influence of COVID-19 on Waste Generation—A Case Study of Castellón in Spain

Miguel-Ángel Artacho-Ramírez [1], Héctor Moreno-Solaz [2,*], Vanesa G. Lo-Iacono-Ferreira [1] and Víctor-Andrés Cloquell-Ballester [1]

[1] Project Management, Innovation and Sustainability Research Center (PRINS), Universitat Politècnica de València, 46022 Valencia, Spain; miarra@dpi.upv.es (M.-Á.A.-R.); valoia@upv.es (V.G.L.-I.-F.); vacloque@dpi.upv.es (V.-A.C.-B.)
[2] Ayuntamiento de Castelló de la Plana, 12001 Castelló de la Plana, Spain
* Correspondence: hcmoso@gmail.com

Abstract: Existing research recognizes the COVID-19 impact on waste generation. However, the preliminary studies were made at an early pandemic stage, focused on the household waste fraction, and employed descriptive statistics that lacked statistical support. This study tries to fill this gap by providing a reliable statistical analysis setting inferential confidence in the waste generation differences found in Castellón. Repeated measures ANOVA were carried out for all the waste fractions collected and recorded in the city landfill database from 2017 to 2020. Additionally, Bonferroni's multiple comparison test ($p < 0.05$) was used to assure confidence level correction and identify which pairs of years' differences appeared. The longitudinal study identified trends for each waste fraction before the pandemic and showed how they changed with the advent of the crisis. Compared to 2019, waste collection in 2020 significantly grew for glass and packaging; remained unchanged for beaches, paper and cardboard, and dropped substantially for households, streets, markets, bulky waste, hospitals, and recycling centres. Total waste showed no differences between 2017 and 2019 but dropped significantly in 2020. These findings may help us better understand the long-term implications of COVID-19 and improve municipal solid waste management in a similar crisis.

Keywords: COVID-19; waste generation; inferential analysis; long term effects

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1. Introduction

The management of municipal solid waste (MSW) has become an increasing global concern as urban populations continue to grow and consumption patterns change. MSW is one of the essential human activities with social and environmental effects [1]. For that reason, the health and environmental implications associated with MSW management are being increasingly analysed and studied [2].

Once the World Health Organization (WHO) declared the coronavirus disease of 2019 (COVID-19) a global pandemic on 11 March 2020, governments worldwide implemented measures to control the spread of the virus [3,4]. From nationwide lockdowns to access limitations or travel restrictions, various disruptive measures seriously affected global supply chains, industries, services, and financial markets—and there was an unprecedented impact on the economy, environment, and people's lives [5,6]. People had to change the way they worked, studied, and interacted, abruptly modifying habits and the methods in which they consumed products and services [7–9].

The COVID-19 crisis was expected to influence waste generation, given the relationship that MSW has with socioeconomic changes, behaviour, and lifestyle [10–13]. A considerable amount of literature has been published recently analysing COVID-19's impact on waste generation in several cities and countries. However, most of these preliminary studies were made at an early stage of the pandemic when the situation was still developing, leading to controversial results in the amount of waste generated compared with a pre-pandemic scenario. For example, Charlebois et al. [14] and Zand and Heir [15] found an increase in food waste in Canada and Tehran, respectively, and Principato et al. [16] and Fan et al. [17] found the opposite in Italy and Shanghai, respectively. These pioneering studies, with some exceptions [3,18], gathered data during the lockdown for short periods (a few months) and were focused on the household fraction [19–22].

Moreover, these studies employed interviews, focus groups [23], secondary data [24], and surveys without reaching representative sample sizes and non-probabilistic sampling methods, thus affecting the representativeness of the findings. Additionally, up to date studies, with some exceptions [3], are focused on measuring the amount of waste [25] without considering changes in waste fractions and composition, which is crucial for analysing the influence of COVID-19 on waste management [17]. Thus, despite the fact that these pioneering works provided a preliminary and valuable understanding of the potential impacts of COVID-19 on waste collection and disposal behaviour, many were descriptive in nature and lacked statistical support. Therefore, the generalisability of their findings is limited. Table 1 provides a summary of these preliminary works, showing the mentioned limitations, e.g., their focus on short periods (lockdowns), their reliance on self-reported and indirect data, the prevalence of the analysis of the household waste fraction, and the derivation of results and conclusions from descriptive data analyses. It is worth noting that information about statistical analyses in Table 1 only refers to the methods used in previous works to analyse differences in the waste generation between the pre-COVID-19 and COVID-19 scenarios.

The present work tries to fill this gap by providing a reliable statistical analysis setting inferential confidence in the waste generation differences found in Castellón, a medium-sized city in the Valencia region of Spain. Specifically, the authors compared waste generation in the city from 2017 to 2020, considering all waste fractions as recorded in municipal landfill data. Thus, the starting hypothesis is statistically significant differences in the waste generation between pre-COVID-19 and COVID-19 scenarios in the long term. These differences will depend on the analysed fractions.

The remainder of this paper is structured as follows: Section 2 is concerned with the case study description and the used methods for data analysis in this study, Section 3 presents and discusses the obtained results for each one of the waste fractions analysed, and finally, Section 4 provides the conclusions drawn from findings, the impact they may have on MSW management, the limitations of the study and further work to be carried out.

Table 1. Summary of preliminary works on waste generation differences found between pre-COVID-19 and COVID-19 scenarios.

Work	Country	Period Analysed	Methodology	Waste Fractions	Statistical Analysis
Amicarelli & Bux [21]	Italy	March to May 2020	Food diaries	Household	Descriptive (sum of reported data)
Charlebois et al. [14]	Canada	August 2020	Survey	Household	Descriptive (percentages)
NZWC & LFHW [26]	Canada	June 2020	Survey	Household	Descriptive (percentages)
Principato et al. [16]	Italy	March to April 2020	Survey	Household	Descriptive (percentages)
Bogevska et al. [27]	North Macedonia	May to June 2020	Survey	Household	Descriptive (percentages)
Aldaco et al. [24]	Spain	March to April 2020	Secondary data	Household	Descriptive (Difference)
Jribi et al. [19]	Tunisia	March to April 2020	Survey	Household	Descriptive (percentages)
Ben Hassen et al. [28]	Qatar	May to June 2020	Survey	Household	Descriptive (means, variation ratio, frequencies, and percentages)
Ismail et al. [20]	Malaysia	March to April 2020	Secondary data	Household	Descriptive and One-way ANOVA
Brizi & Biraglia [22]	India & USA	Lockdowns	Survey	Household	Descriptive and Sequential Mediation Model
Richter et al. [8]	Canada	March to September 2020	Landfill database	Household/Total Waste	Descriptive (measures of central tendency)
Ikiz et al. [23]	Canada	May 2020	Interviews & focus group	Household	Qualitative analysis
Zand & Heir [15]	Iran	Not reported	Estimation	Total Waste/Medical Waste	Descriptive
Fan et al. [17]	China, Singapore, Czech Republic	March to May 2020	Survey and Secondary Data	Plastic/Household	Descriptive
Cai et al. [18]	USA, Brazil, Canada, UK, France, and Italy	2019, 2020, 2021	Secondary data	Total Waste	Descriptive (variation ratio)
Richter et al. [3]	Canada	January 2018 to September 2020	Landfill database	Solid/Mixed Solid/Construction/Grit/Mixes Asphalt Shingles/Biomedical	Descriptive (boxplots)
Filho et al. [29]	41 countries	Lockdowns	Survey	Plastic	Descriptive

Table 1. *Cont.*

Work	Country	Period Analysed	Methodology	Waste Fractions	Statistical Analysis
Olatayo et al. [30]	South Africa	2019 to 2020	Estimations from secondary data	Plastic (PPE)	Descriptive (Material Flow Analysis)
Babbitt et al. [31]	USA	March to July 2020	Survey	Household	Descriptive
Urban & Nakada [32]	Brazil	2010 to 2020	Secondary data	Household/Recyclables/Streets	Descriptive (means)
Vittuary et al. [33]	Italy	May 2020	Survey	Household (food)	Descriptive (percentages)
Strotman et al. [34]	Germany	October 2020	Survey	Household (Food)	Descriptive (percentages)
Kasim et al. [35]	Guyana and Nigenria	Lockdowns	Survey/Interviews	Household (Food)	Descriptive
Laila et al. [36]	Canada	February to August 2020	Survey/Interviews/Audits	Household (Food)	Descriptive/Non-parametric test (Wilcoxon)

2. Materials and Methods

2.1. Case Study

The research was undertaken in Castellón. The city's population increased 2.7% between 2017 and 2020 and reached 174,262 inhabitants [37]. Castellón is not a tourist town. It has a negative floating population of about 15,000 inhabitants who move to other tourist destinations during July and August. In the distribution of companies according to activity, the services sector, in which the HORECA (hotel, restaurant, and catering) channel predominates, is the most important (68%), followed by construction (21%) and, finally, industry (11%) [37].

The city was in lockdown along with all of Spain from 15 March until 21 June 2020. All non-essential establishments were closed, such as cafes, restaurants, hotels, and commercial and retail businesses, but internet commerce and catering services continued to operate. Food stores and supermarkets, considered essential establishments, were open while open-air markets were closed. Regarding health centres and hospitals, consultations were made by telephone, with visits to health centres only allowed when hospitalisation was necessary or in other exceptional cases [38,39].

On 28 April 2020, a national plan for asymmetric de-escalation began. Some establishments (such as hospitals, restaurants, and coffee shops) opened with some commercial shops with a restricted capacity [40]. On 21 June 2020, the state of alarm ended, and Spain entered a situation called the "new normal". A capacity limit of 75% was generally enforced in all spaces, both outdoors and indoors, including markets, beaches, and pools [41]. The Spanish government decreed the second state of alarm on 25 October 2020, established a curfew between 12:00 a.m. and 6:00 a.m., and announced restrictions on travel between regions [42]. Measures changed during this period. From 21 December 2020, establishments were allowed to accommodate larger groups of people and stay open until 11:00 p.m. The second state of alarm ended on 9 May 2021 [43].

Figure 1 shows the six districts of Castellón. Between the port district and the main nucleus of Castellón, there is the Marjalería area with dispersed single-family houses.

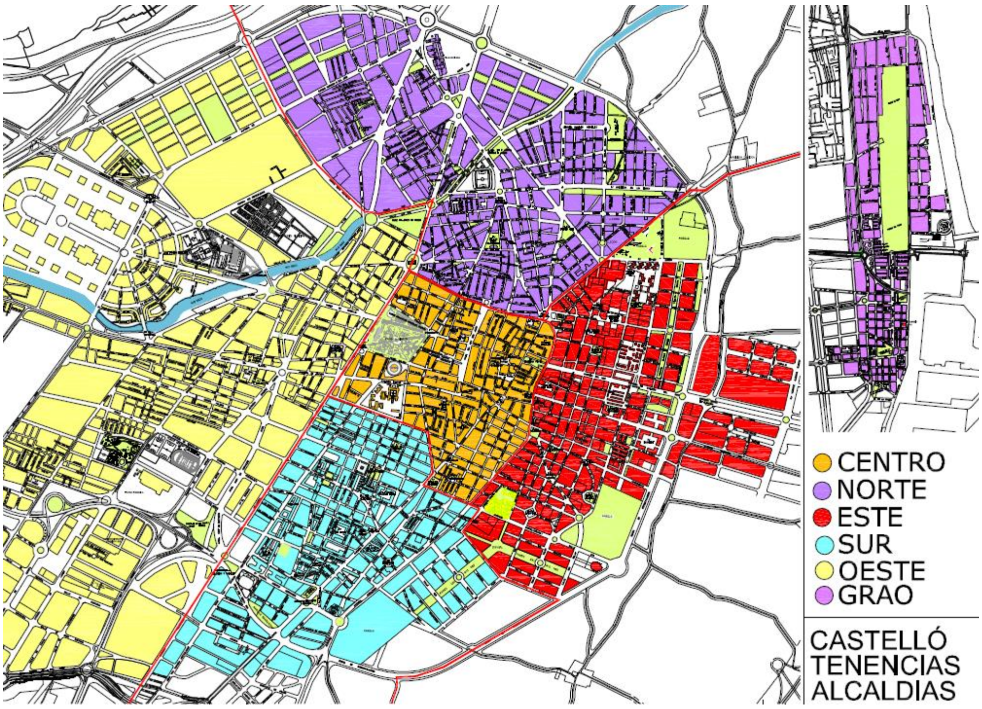

Figure 1. Castellón map with districts (39°59.1402′ N, 0°2.961′ W). Adapted with permission from Ayuntamiento de Castelló de la Plana [44].

A similar urban composition can be found around the periphery. The industrial sector is concentrated around the urban nucleus, except for the service sector that is within. From a waste manager's point of view, the service is highly heterogeneous and must cover nearly four kilometres of beach managed by the municipality.

Waste managed by Castellón falls into two categories: Containerized, which includes waste deposited in containers on public roads or in public places, e.g., markets, hospitals, etc., and non-containerized which is waste from cleaning services or special wastes, e.g., beach cleaning, street cleaning, bulky waste, etc. This fraction is commonly called "Other MSW".

All waste is categorised as MSW, including all origins (HORECA channel establishments, markets, hospitals, and industry), providing it meets the definition set by the Spanish Act 22/2011 [45].

Containerized waste is categorised as recyclable or non-recyclable (mixed). Recyclable waste refers to waste separated from the waste stream and set aside for purposes of recovery, reuse, or recycling. Mixed MSW includes urban garbage (domestic and HORECA), itinerant markets, the hospital fraction that can be assimilated to urban waste, and daily collections from grey containers. This waste is destined for a two-phase treatment plant with a semi-automatic mechanical separation and a composting tunnel [46]. The recyclable fraction is divided into four categories by colour and delivered to each corresponding treatment plant for management. Table 2 shows the frequency and characteristics of the analysed waste fractions in this study. It should be noted that bio-waste was implemented in September 2020, so it is not included in this analysis.

In addition to these fractions, other types of waste such as batteries, asbestos, tires, or construction and demolition waste are collected by special collection services.

2.2. Data Collection and Statistical Analysis

Information was gathered from a system connected to the scales used by the collector trucks for each fraction. The total waste per year was calculated as the sum of all the waste fractions analysed. The period under analysis is from 1 January 2017 to 31 December 2020 for all six city districts. Waste collected in 2021 was excluded because bio-waste was included as a new waste fraction in the city, thus altering the amount of waste collected in other waste fractions and avoiding comparability with previous years.

A repeated-measures analysis of variance (RM ANOVA) with the waste fractions as dependent variables was conducted to analyse if statistically significant differences in the mean for waste appeared over the years. RM ANOVA can be used for investigating changes in mean scores over three or more time points [47]. Thus, the collection of all waste fractions for 2017, 2018, 2019 and 2020 were compared with significant levels of differences set at $p < 0.05$. Data were explored to identify and exclude outliers. To test if data are normally distributed, the Kolmogorov-Smirnov test and the Shapiro-Wilk test were used for waste fractions recorded daily (>50 cases) and for waste fractions recorded every month (<50 cases), respectively [48]. Mauchly's criterion test was used to assess if the covariance structure satisfies the sphericity condition [47]. If the sphericity assumption was violated, a Greenhouse-Geisser correction was used. Bonferroni's multiple comparison test ($p < 0.05$) was used to assure confidence level correction and identify between the pair of years in which the differences appeared. The Eta squared value (η^2) was calculated to measure the effect size, setting the size of the differences found ($\eta^2 = SS_{effect}/SS_{total}$, where: SS_{effect} is the sum of squares for the effect that is being studied, and SS_{total} is the total sum of squares for all effects, errors, and interactions in the RM ANOVA study).

All data analyses were performed using the SPSS 16 statistical application for Windows.

Table 2. Waste fraction characteristics of Castellón.

Waste Fraction	Category (Bin Colour)	Collection Frequency	Nº Containers in Street	Waste Volume Capacity (l)	Description of Waste Fraction
Packaging	Recyclable, containerized (yellow)	Two to three times a week, depending on location	713	2,139,000	Plastic bottles and bags, metal cans, mixed packaging (e.g., aluminium and paperboard)
Glass	Recyclable, containerized (green)	Every 14 days	718	2,154,000	Bottles, tins, jars, etc. glass items.
Paper and cardboard	Recyclable, containerized (blue)	Two to three times a week, depending on location	560	1,680,000	Cardboard, paper, newspapers, labels, etc.
Household	Mixed MSW, containerized (grey)	Every day	3,379	3,379,000	Traditional waste system 'All in one'. According to law, it should only contain waste that is non-admissible in other fractions
Hospitals	Mixed MSW, containerized (grey)	Every day	140	140,000	Domestic assimilable hospital waste (paper, food, textile, etc.)
Markets	Mixed MSW, containerized (grey)	Every day	80	80,000	Domestic assimilable market waste (paperboard, food, etc.)
Streets	Non-containerized	Every day	-	-	Waste collected from ground and street litter bins
Beaches	Non-containerized	Monday to Saturday	-	-	Waste collected from sand and beach litter bins
Recycling centre bulky	Non-containerized	On demand	-	277,000	Bulky waste (furniture, home appliances, wood, etc.) deposited in recycling centre
Recycling centre pruning	Non-containerized	On demand	-	40,000	Pruning (branches, trunks, leaves) disposed in recycling centre
Bulky waste	Non-containerized	Monday to Saturday	-	-	Bulky waste disposed in streets with (or without) previous order

Adapted with permission from Ayuntamiento de Castelló de la Plana [44].

3. Results and Discussion

Outliers appeared in all the waste fractions recorded daily for at least one year (households, hospitals, markets, and streets). After excluding those outliers, all the waste fractions analysed were normally distributed ($p > 0.05$ in all the normality tests performed). RM ANOVAs carried out for all the waste fractions show significant differences between years. The significance of Mauchly's test, F values, significance, and η^2 values are shown in Table 3. Mauchly's test of sphericity for hospital, beach, and glass waste indicated that the assumption of sphericity had been violated (Mauchly's test (sig.) < 0.05) and, therefore, a Greenhouse-Geisser correction was used.

Table 3. RM ANOVA.

	Mauchly Test (sig.)	F	Sig.	η^2
Household	0.087	74.626	0.000	0.908
Hospitals	0.029 *	3,489,815 *	0.000 *	0.923
Markets	0.092	3230.795	0.000	0.784
Streets	0.199	12.072	0.000	0.421
Beaches	0.000 *	31,600 *	0.000 *	0.276
Recycling centre bulky	0.189	1426.977	0.000	0.939
Recycling centre pruning	0.090	217.996	0.000	0.889
Bulky	0.201	201.264	0.000	0.970
Packaging	0.692	154.700	0.000	0.991
Paper and cardboard	0.828	53.844	0.000	0.947
Glass	0.027 *	37.150 *	0.000 *	0.772
Total waste	0.150	8616.609	0.000	0.961

* Greenhouse-Geisser correction.

Waste fractions were classified into three groups according to the number of statistically significant differences found in their means among the years. Group 1 is defined by fractions of waste in which statistically significant differences appeared for all pairwise comparisons (see Figure 2, and Table 4). In Group 1, a statistically significant increasing trend is observed for packaging collection from 2017 to 2020. In the case of markets and bulky waste, the increasing trend stops with a significant decrease in the amount of waste collected in 2020. In the case of the recycling centre bulky waste, the increasing trend stopped in 2018 with a significant decrease in the amount of waste collected in 2019 and in 2020. Implementing the scheduled "door-to-door" collection service for the bulky waste in 2019 could explain both the increase in bulky waste and the significant decrease in the bulky waste from recycling centres.

Table 4. Significant differences in packaging, markets, bulky and recycling centre bulky waste collection from Bonferroni's comparison test.

		Packaging	Markets	Bulky	Recycling C. Bulky
Years		Monthly Means Difference	Daily Means Difference	Daily Means Difference	Daily Means Difference
(I)	(J)	(I) − (J)	(I) − (J)	(I) − (J)	(I) − (J)
2020	2017	50,327.500 **	−1136.159 **	617.700 **	−548.864 **
	2018	36,108.333 **	−1209.272 **	235.272 **	−1257.436 **
	2019	22,183.333 **	−1677.881 **	−228.754 **	−228.132 **
2018	2019	−13,925.000 **	−648.609 **	−464.026 **	1029.304 **
2017	2018	−14,219.167 **	−73.113 **	−382.428 **	−708.571 **
	2019	−28,144.167 **	−541.722 **	−846.454 **	320.733 **

** $p < 0.01$.

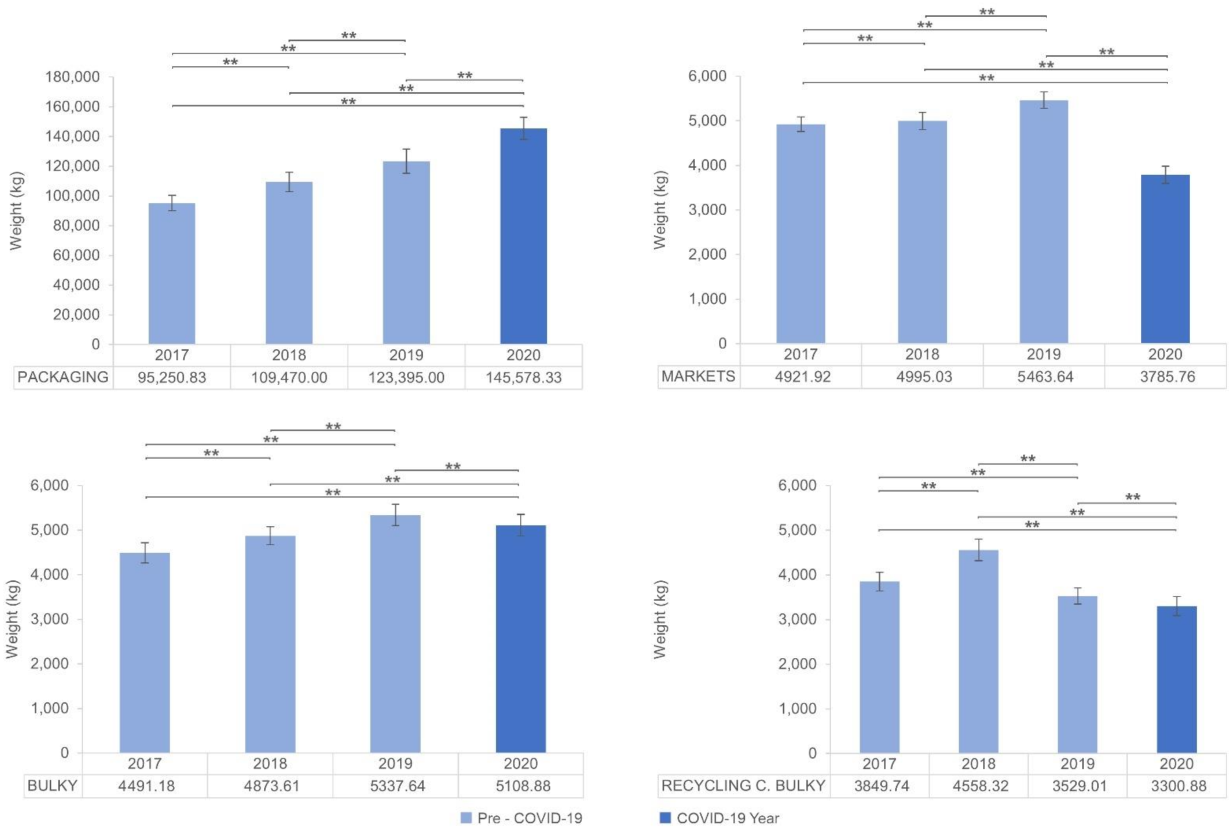

Figure 2. Mean and 95% CI for each year in waste fractions of Group 1: packaging, markets, bulky and recycling centre bulky waste collection. (**) for $p < 0.01$.

The environmental awareness campaigns conducted by administrations and non-governmental organisations in the years preceding the COVID-19 pandemic have led to a steadily growing collection of recyclable waste fractions (packaging, glass, and paper). However, the results in the packaging fraction in 2020 should be explained by the plastic waste boom during the pandemic. Many factors contributed to this increase in plastic waste. The pandemic induced impulsive and irrational stockpiling of groceries and essential plastic packaged products [49]. A loss of faith in unpackaged products in a new hyper hygienic approach significantly increased the use of single-use plastic (SUP) [50]. The temporary relaxation of bans on SUP bags in supermarkets also contributed to this trend [51,52]. Moreover, lockdowns and quarantines increased online food delivery and e-shopping, increasing the use of plastic-based packing materials [53,54]. Finally, the remarkable increase in the use of masks, gloves, protective suits, hand sanitizer bottles, and all kinds of personal protection equipment (PPE), along with the increase in pharmaceutical packaging waste, led to more plastic packaging waste [55–57]. This increase in plastic pollution poses new challenges for effective plastic waste management that need to be addressed with new strategies and directives [50,58].

In the specific route of the municipal markets, the trend for waste had been upward in recent years, except for 2020, with a significant drop in the average daily collection. This is partly due to the decline in economic and commercial activity and the protocols established by the health authorities regarding the disinfection of posts and other measures that were difficult to comply with and that led to the temporary closure of many market stalls. The drop in collection could also be related to the increase in the packaging waste fraction. The loss of faith in unpackaged products could partly explain this, along with the increased buying of less-perishable products [49,59], the closure of restaurants, and the increase in online food delivery forced by lockdowns. The wish to avoid densely populated places led people to buy food and groceries from smaller nearby outlets, limiting the purchase time spent, and fewer family members were involved in offline grocery shopping [60], which may have played a role in reducing activity in municipal markets.

Bulky waste collection in 2020 may be related to lockdowns and a drop in domestic refurbishments and economic activity. Lockdowns and mobility restrictions can also be responsible for the decrease in bulky waste taken to recycling centres by the public.

Group 2 contains fractions of waste in which no differences were found for a few years (Figure 3, Table 5). The glass fraction of waste showed no differences between 2017 and 2018 but grew significantly in 2019 and 2020. For household, hospitals, and recycling centre pruning, waste grew and showed statistically significant differences between 2017 and 2018. Such a difference disappeared between 2018 and 2019. Finally, waste decreased significantly in 2020. Finally, both paper and cardboard and beaches showed no differences in mean waste between 2019 and 2020, respectively, putting an end to a steadily growing and steadily decreasing trend in previous years.

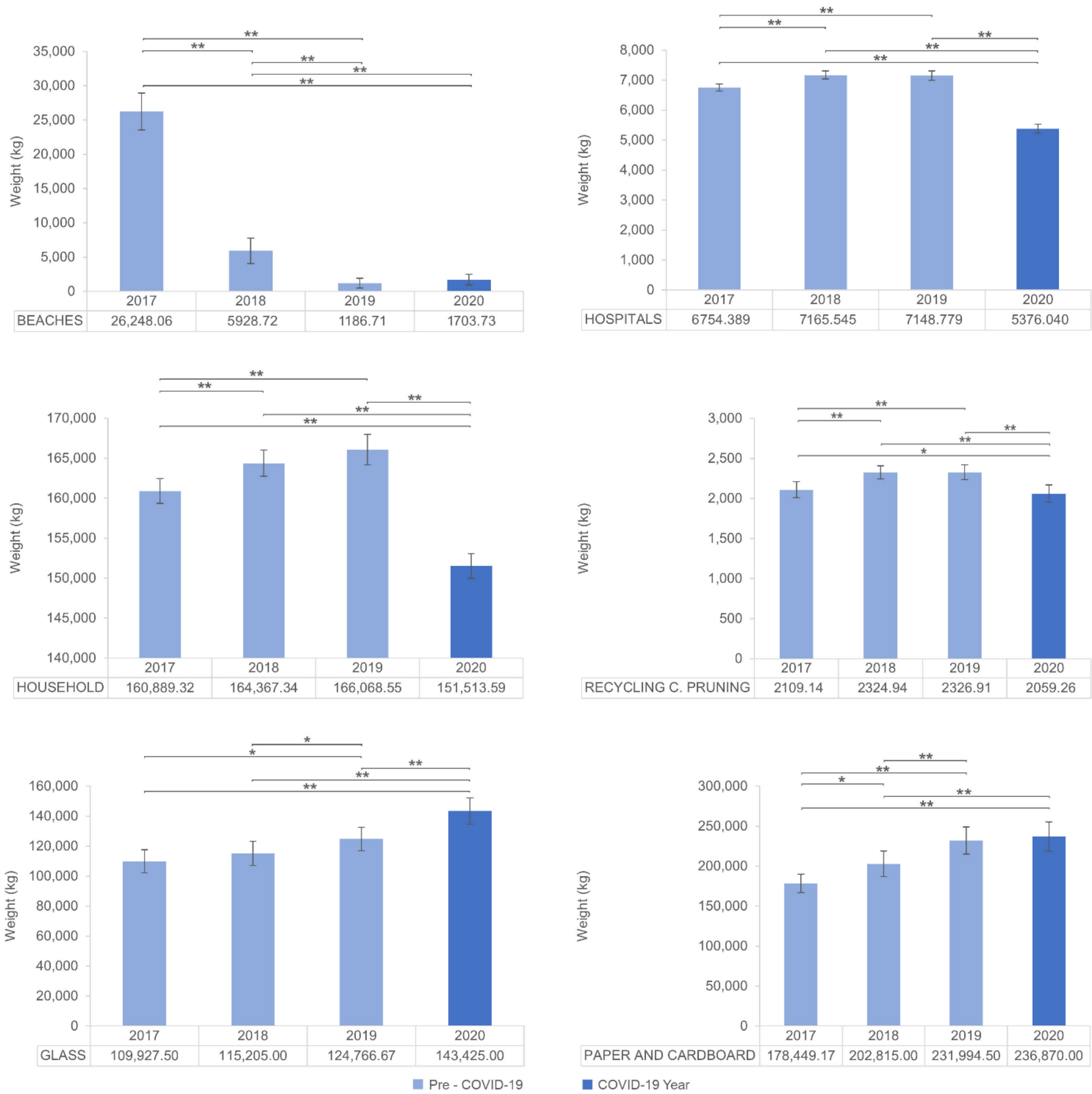

Figure 3. Mean and 95% CI for each year in waste fractions of Group 2: glass, household, hospitals, recycling centre pruning, paper and cardboard and beaches waste collection. (*) is used for $p < 0.05$ and (**) for $p < 0.01$.

Table 5. Significant differences for glass, household, hospitals, recycling centre pruning, paper and cardboard and beach waste from Bonferroni's comparison test.

		Glass	Household	Hospitals	Recycling C. Pruning	Paper and Cardboard	Beaches
Years		Monthly Mean Differences	Daily Mean Differences	Daily Mean Differences	Daily Mean Differences	Monthly Mean Differences	Daily Mean Differences
(I)	(J)	(I) − (J)	(I) − (J)	(I) − (J)	(I) − (J)	(I) − (J)	(I) − (J)
2020	2017	33,497.500 **	−9375.726 **	−1378.350 **	−49.877 *	58,420.833 **	−24,544.327 **
	2018	28,220.000 **	−12,853.753 **	−1789.505 **	−265.654 **	34,055.000 **	−4224.993 **
2018	2019	18,658.333 **	−14,554.959 **	−1772.739 **	−267.654 **	−29,179.500 **	4742.011 **
2017	2018	−9561.667 *	−3478.027 **	−411.155 **	−215.802 **	−24,365.833 *	20,319.335 **
	2019	−14,839.167 *	−5179.233 **	−394.389 **	−217.778 **	−53,545.333 **	25,061.345 **

** $p < 0.01$. * $p < 0.05$.

The remarkable increase of glass collected in 2020 is in line with the findings of Filho et al. [29]. This increase could partly be explained by the decline in activity in hotels and restaurants. Lockdowns and reduced activity due to indoor capacity restrictions meant glass consumed at restaurants and hotels that used to be repackaged and sent back to beverage companies was consumed at home and placed in glass waste containers. Moreover, according to Tchetchik et al. [9], the COVID-19 crisis made people more prone to increase recycling and further reduce consumption. The authors found that the perceived link between exposure to the pandemic threat and climate change and economic vulnerability increased pro-environmental behaviour. An increase in recycling at home could also explain the increased volumes of paper and cardboard, although with no significant differences compared to 2019. The slowdown in economic activity for the leading paper and cardboard producers like shops, the hospitality industry, and industrial sectors [61] could explain the reduced volume of paper and cardboard waste in 2020.

The household fraction shows a statistically significant decrease in 2020. As said in the introduction, previous studies analysing the influence of pandemics on household waste led to controversial results. The descriptive nature of these studies mainly focused on lockdown periods, which made it difficult to evaluate such an influence in the long term. This work enables us to state that household waste volume in a pandemic was significantly lower than in pre-pandemic years. These results could be related to a generalised decrease in family consumption from the economic contraction provoked by the pandemic. Moreover, several authors found that changes to family routines (e.g., working from home, better time management, more organised purchase and cooking habits, greater use of 'smart food delivery') due to the pandemic may have also played a role in the observed reduction in household waste [21,36,62].

The hospital fraction also showed a statistically significant decrease in 2020, which is in line with the observed household trend. This parallel trend could be because the waste from hospitals managed by city councils can be assimilated into urban waste and does not pose any special management requirements since it was only used by non-infectious patients. It should be noted that hospital waste that is not assimilable to domestic waste (hazardous waste) which used to represent 15% of waste in healthcare facilities [63] is not collected through municipal services and has a specific channel for its management. Hazardous waste in Castellón probably grew exponentially, as happened in other cities such as Wuhan (0.6 kg/patient to 2.5 kg/patient) [64] or countries like Jordan (3.95 kg/patient to 14.16 kg/patient) [65], and this should be analysed in future studies because the pandemic has created a huge burden of healthcare systems that must also treat and properly dispose of all the waste that could further spread the SARS-CoV-2 virus [66].

Regarding recycling centre pruning waste, the reduction in 2020 could be again related to mobility restrictions which may have hampered disposals at recycling facilities. In the case of beach waste, the collection includes vegetable matter washed ashore and the elimination of algae in the sand, which has been growing in recent years due to an increase in sea temperatures. A new collection procedure set in 2018 led to a remarkable decrease in waste. Since then, the beach material removed is accumulated in points far from the shore, where it is allowed to dry to reduce the moisture content, leading to a weight reduction in the waste to be managed. Once the material has dried, it is transported to a screening plant to recover the maximum amount of sand for spreading again on the beach, thereby significantly reducing the amount of final waste. Finally, following the Ministry of Ecological Transition recommendations to enhance the circular economy, part of the algae is buried in the beach dunes to reinforce and regenerate them. These algae serve as an organic substrate that contributes to their recovery. No significant differences appeared between 2019 and 2020 despite cleaner beaches being reported as one of the positive side effects of COVID-19 on the environment [67].

Finally, Group 3 contains fractions of waste whose collection values showed no significant differences in mean values over four years. These waste fractions were streets and total waste, in which no differences appeared between 2017 and 2019, whereas the mean value significantly dropped in 2020 (see Figure 4 and Table 6).

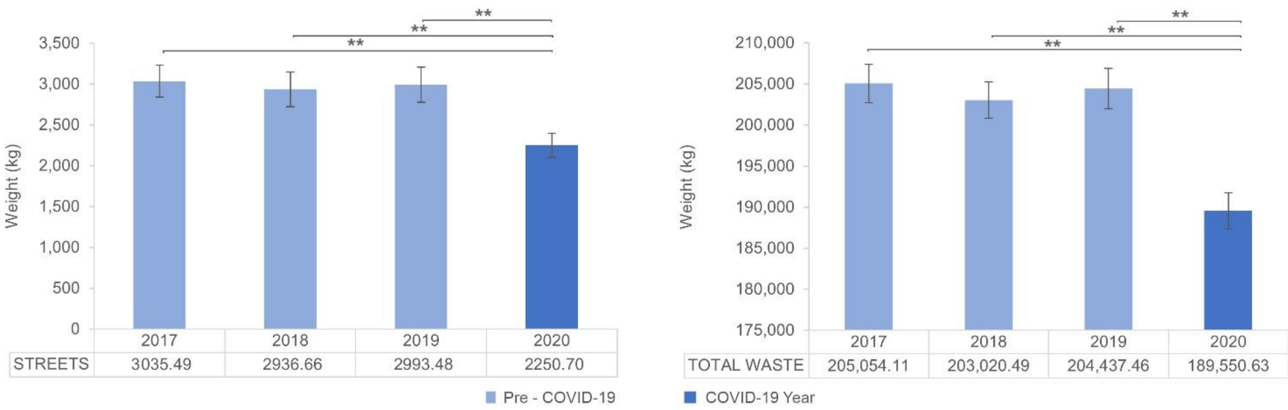

Figure 4. Mean and 95% CI for each year in waste fractions of Group 3: streets and total waste collection. (**) for $p < 0.01$.

Table 6. Significant differences in streets and total waste collection from Bonferroni's comparison test.

		Streets	Total Waste
Years		Daily Means Difference	Daily Means Difference
(I)	(J)	(I) − (J)	(I) − (J)
2020	2017	−784.791 **	−15,503.484 **
	2018	−685.961 **	−13,469.868 **
	2019	−742.789 **	−14,886.838 **

** $p < 0.01$.

The significant drop in street waste collected from public roads could be related to the lockdowns, mobility restrictions, and the closure of the hotel, restaurant, and nightlife industries. Total waste shows the same trend as streets. Some preliminary studies predicted an increase in MSW due to the COVID-19 pandemic, and may be influenced by the initial panic buying experienced worldwide [68,69]. However, the results obtained considering one year for the city of Castellón (with statistical support) show the opposite. These results are in line with Cai et al. [18]. These authors found that compared to normal periods in 2019, significant decreases in total waste were observed in most of the months in 2020 in Montreal (e.g., by 9.5% in May 2020) and Trento (e.g., by 13.7%, 25.3%, 14.7% from March to May 2020 and 16.5% in January 2021). Thus, it could be said that the shutdown of most of the productive and commercial activities due to the COVID-19 crisis resulted in significant economic losses which, in turn, led to a waste decrease in the long term.

Considering only 2019 and 2020, waste collection for 2020 significantly grew for glass and packaging; it remained unchanged for beaches and paper and cardboard, and significantly decreased for households, streets, markets, hospitals, recycling centre pruning, recycling centre bulky waste, and total waste.

4. Conclusions

This study sheds further light on the influence of the COVID-19 crisis on the generation of MSW. It complements the abundant previous descriptive studies in the literature with a longitudinal study based on the statistical inference that enables the quantitative establishment of the long-term impact of the pandemic on the generation of the waste fractions collected by the municipality of Castellón.

The comparison performed on waste fractions from 2017 to 2020 using RM ANOVA enables establishing waste trends and how these vary because of the effect of the pandemic. The results show that waste collection patterns significantly changed in Castellón city in 2020 because of the impact of COVID-19. Thus, the starting hypothesis has been confirmed, as statistically significant changes in waste generation appeared, and the analysed waste fractions were affected in different ways. Considering only 2019 and 2020, waste in 2020 significantly grew for glass and packaging; remained unchanged for beaches and paper and cardboard; and significantly dropped for households, streets, markets, hospitals, recycling centre pruning, and recycling centre bulky. Finally, total waste showed no differences from 2017 to 2019 but significantly dropped in 2020.

The start of the COVID-19 pandemic provoked changes in the waste amount, composition and distribution, safety and infection risk, and disposal rate, increasing the complexity of waste management worldwide. Changes in waste generation resulted in storage, transportation, disposal, and treatment challenges. The response of public authorities and municipal waste operators in Castellón was to quickly adapt their waste management systems and procedures to the new scenario. Ensuring the safety of the staff was a priority, followed by guaranteeing collection services with the same frequency as usual, including on-demand collection. Municipal waste collection staff were provided with additional personal protective equipment (PPE) and trained about safety measures and new protocols for disinfection equipment and vehicles. Differences in waste generation among fractions forced MSW managers to reorganise resources and adapt routes. For example, the increase in packaging and glass fractions in Castellón led to increasing collection frequencies to avoid container overflow. Given the reduction of the street waste fraction, the scheduled operations in streets were reduced and reorganized to improve wet cleaning services, such as sweeping and disinfection in markets, hospitals, and public roads, cleaning litter bins, and washing containers. The pandemic crisis mainly affected collection systems, but it progressively reached other players such as recyclers in the long term. Sorting and treatment systems also experienced some disruptions because new restrictions appeared for manual sorting and recycling due to safety precautions. Daily waste operations were also affected by increased monitoring to avoid illegal dumping, shortages of personnel, and increased communication to inform citizens about adequately managing their waste. As can be seen, despite the fact that the total waste dropped, the issues to be considered by MSW managers significantly increased in number and difficulty. Despite the agile adaptation of the administration and MSW managers, all the changes were made reactively. If they had had the objective and reliable data about changes in material flows obtained in this study, they could have planned their actions better, reorganizing resources more efficiently. Additionally, the present paper's findings might better help understand the long-term implications of COVID-19 and prepare planners and policymakers for changes in the waste stream due to pandemics or other unprecedented emergencies.

However, a note of caution is due here since previous studies showed that waste generation and composition might vary depending on the location [70], socioeconomic factors, or climatic factors [10,12,71,72]. Thus, further studies should be carried out in cities of different sizes and with different economic activities. Such studies should include the analysis of hazardous medical waste not analysed in the present study. Moreover, the pandemic persists, so further studies should analyse whether the results remain visible, return to the previous trend, or whether there is a rebound effect after returning to normality. Thus, long-term analyses of the total impact of COVID-19 on resources and waste management and the dynamics of material flow seem necessary. Finally, waste management and planning practices applied after the advent of the pandemic should be evaluated with the goal of identifying managerial improvements.

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04-023

CHARACTERIZATION AND ANALYSIS OF THE FORSU: LESSONS LEARNED AFTER A YEAR OF IMPLEMENTATION OF SELECTIVE COLLECTION (CASTELLÓN DE LA PLANA)

Moreno Solaz, Héctor (1); Cloquell-Ballester, V.A. (2); Edo Alcón, Natalia (3); Badenes Catalán, Cristóbal (1); Artacho-Ramírez, M.A. (2)

(1) Dirección de Servicios Urbanos, Infraestructuras y Medio Ambiente. Ayuntamiento Castellón de la Plana, (2) PRINS (Centro de Investigación en Dirección de Proyectos, Innovación y Sostenibilidad). Universitat Politècnica de València., (3) Eurofins Iproma

Bio-waste is the majority component of the different fractions of domestic waste, accounting for approximately 40% by weight of the total (PEMAR, 2016). In the context of the European Union, Directive 2008/98/EC includes in Article 22 the separate collection of biowaste for its correct treatment and recovery. The purpose of the following article is to analyze the results obtained during the first year of implementation of the selective collection service for the organic fraction of solid urban waste (FORSU) in the city of Castelló de la Plana. The evolution of the monthly weighings obtained, the collection rate per inhabitant and the composition of the waste deposited have been taken into account. For this, a monthly characterization has been carried out, through the random sampling of a container per district in each of the twelve months that the experience lasted. The results reveal a generation of selectively collected bio-waste of 0.045 kilograms per inhabitant per day, and an average rate of improper waste of 39.86%. These results have been compared with those obtained in pilot experiences prior to the final implementation that took place at the end of 2020.

Keywords: Urban solid waste; organic fraction; biowaste; characterization; FORSU

CARACTERIZACIÓN Y ANÁLISIS DE LA FORSU: LECCIONES APRENDIDAS TRAS UN AÑO DE IMPLANTACIÓN DE RECOGIDA SELECTIVA (CASTELLÓN DE LA PLANA)

Los biorresiduos son el componente mayoritario de las distintas fracciones de residuos domésticos ya que suponen aproximadamente un 40 % en peso con respecto al total (PEMAR, 2016). En el contexto de la Unión Europea, la Directiva 2008/98/CE incluye en el Artículo 22 la recogida separada de biorresiduos para su correcto tratamiento y valorización. El siguiente artículo tiene como objeto el análisis de los resultados obtenidos durante el primer año de implantación del servicio de recogida selectiva de fracción orgánica de los residuos sólidos urbanos (FORSU) en la ciudad de Castelló de la Plana. Se han tenido en cuenta la evolución de los pesajes mensuales obtenidos, la tasa de recogida por habitante y la composición de los residuos depositados. Para ello se ha realizado una caracterización mensual, mediante el muestreo aleatorio de un contenedor por distrito en cada uno de los doce meses que duró la experiencia. Los resultados revelan una generación de biorresiduos recogidos de manera selectiva de 0,045 kilogramos por habitante y día, y una tasa media de impropios del 39,86%. Estos resultados se han comparado con los obtenidos en experiencias piloto previas a la implantación definitiva que tuvo lugar a finales del año 2020.

Palabras clave: Residuo sólido urbano; fracción orgánica; biorresiduos; caracterización; FORSU

Correspondencia: Victor Cloquell Ballester. Correo: vacloque@dpi.upv.es

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1. Introducción

La cantidad de residuos generados en las ciudades está en constante aumento y éstos son cada vez más diversos y peligrosos. La calidad en la gestión de residuos, por lo tanto, se ha vuelto más importante debido a su impacto directo en el medio ambiente y la salud humana. (Fasihi & Parizadi, 2021).

En este sentido, la Directiva 2008/98/CE Marco de Residuos, del Parlamento Europeo y del Consejo de 19 de noviembre, dispone que los Estados miembros deberán adoptar las medidas necesarias para aumentar un 50% en peso la preparación para la reutilización y reciclado de residuos domésticos a corto plazo. Así, la Unión Europa está fomentando los tratamientos biológicos de los residuos orgánicos como alternativa a los vertederos y también a mejorar el reciclaje de la materia orgánica. La composición de estos residuos es muy importante para obtener un compostaje de buena calidad. (Huerta-Pujol et al., 2011)

El Plan Estatal Marco de Gestión de Residuos (PEMAR, 2016), en la búsqueda de una economía circular, apuesta por la reincorporación a los procesos productivos los materiales contenidos en los residuos, fomentando acciones para mejorar la gestión de la fracción orgánica de los residuos municipales.

En el ámbito de la Comunidad Valenciana, Plan Integral de Residuos (Comunidad Valenciana, 2019), establece el objetivo de que antes del 2020 todos los municipios y entidades locales responsables de los servicios de recogida de residuos, deben tener implantada una recogida de biorresiduos, con el fin de reducir la emisión de gases de efecto invernadero originados por la eliminación de residuos en vertederos, así como la recogida separada y el tratamiento adecuado de los biorresiduos, para producir compost seguro para el medio ambiente y otros materiales producidos a partir de los biorresiduos .

Castelló de la Plana es una ciudad mediterránea, capital de la provincia de Castellón, ubicada al norte de la Comunidad Valencia con una población de 172.589 habitantes en 2021 (INE, 2021). En el siguiente artículo se analiza la evolución de la generación de bioresiduos en la ciudad de Castelló de la Plana, tras un año desde su implantación. Para ello, se han utilizado dos variables fundamentales, la tasa bruta de recogida por habitante y día (TRD-B), y tras caracterizar una muestra mensual de dichos biorresiduos se ha podido determinar también la tasa neta de recogida por habitante y día (TRD-N). Los resultados, en cuanto a cantidad y calidad, se han comparado con tres experiencias piloto anteriores que se habían desarrollado en la ciudad en los años 2017, 2018 y 2019, respectivamente donde se obtuvo de media una TRD-N de 0,03 kg/hab.día. (Gallardo et al. 2017, 2019, 2021) como se desarrolla en la tabla 1.

Tabla 1. Resumen Experiencias piloto previas a la implantación

Zona	Centro	Norte	Oeste	Grao	Este	Colegios
Población	3.956	1.451	2.244	843	1.820	14.084
Duración	179	179	179	182	182	91
Contenerización (l)	9.600	11.000	14.400	11.000	14.400	96.000
Cont/habitante (l)	2,43	7,58	6,42	13,05	7,91	6,82
Generación bruta (kg)	5.180	12.080	9.200	13.421	14.280	28.526
Generación neta (kg)	4.184	10.051	7.491	12.223	13.969	23.893
% impropios	19 %	17 %	19 %	9 %	2 %	16 %
TRD_B (kg/hab.día)	0,007	0,047	0,023	0,087	0,043	0,022

TRD_N (kg/hab.día)	0,006	0,039	0,019	0,080	0,042	0,019

Resumen	Experiencia 1	Experiencia 2	Experiencia 3*
Población	7.651	2.663	14.084
Lcont/hab	4,57	9,54	6,82
% impropios	18 %	5 %	16 %
TRD_B (kg/hab.día)	0,019	0,057	0,022
TRD_N (kg/hab.día)	0,016	0,054	0,019

Nota: La columna únicamente incluye los datos correspondientes a la experiencia en los colegios.

2. Metodología

2.1 La implantación en la ciudad

La implantación progresiva del sistema de recogida de la fracción orgánica en la ciudad de Castelló de la Plana comenzó en septiembre de 2020. Tras los primeros meses de implantación, en diciembre de ese mismo año se comenzó a caracterizar durante un año los biorresiduos depositados en contenedor específico mediante muestras mensuales.

La implantación de este nuevo servicio incrementó los costes de la recogida de residuos de la ciudad en casi un 9% (Ayuntamiento Castelló, 2020) y se puede resumir de la siguiente manera:

- Suministro instalación y mantenimiento de 1.098 contenedores de 2.000 litros de capacidad y carga lateral automática (12,72 litros/habitante).
- Pre-recogida diaria de forma manual de los restos depositados fuera de los contenedores, mediante dos camiones volquete baúl, de 4,5 m³.
- Recogida mecanizada diaria, con frecuencia alterna, mediante tres camiones robotizados recolectores de 19 m³ de carga lateral.
- Limpieza de contenedores con una frecuencia mensual, con vehículo robotizado lava contenedores de carga lateral.
- Reducción del servicio de recogida de la fracción resto (o todo en uno), mediante retirada de 400 contenedores de 1100 litros dicha fracción.

2.2 Caracterización de la fracción orgánica

El objetivo principal de las caracterizaciones fue llevar a cabo un seguimiento de la implantación de la recogida selectiva de la FORSU en la ciudad durante un año, lo que permitiría detectar las fortalezas, debilidades y necesidades del sistema, así como orientar las tareas de educación ambiental a poner en marcha con la ciudadanía. Los impropios por definición, son residuos que no deberían estar en el contenedor objeto de estudio, en este caso serán plásticos, vidrio, cartón, textil, etc.

En la actualidad no existe ninguna metodología estandarizada para calcular el número mínimo de muestras en la caracterización de residuos sólidos urbanos, sino que se han desarrollado una gran variedad de métodos distintos que se aplican en función de las condiciones de cada caso y la información que se quiere obtener. De todas ellas, se ha utilizado la metodología desarrollada por la Comisión Europea (2004) para el análisis de residuos sólidos (SWA-Tool).

En ella se establecen una serie de recomendaciones y mínimo estándares para correcta caracterización de RSU.

Esta metodología utiliza datos sobre la composición de los residuos (medias y desviaciones estándar) procedentes de estudios piloto o de estudios que se hayan realizado con anterioridad, según la siguiente fórmula:

$$n = \left(\frac{t_{\alpha;n-1} \cdot CV}{\varepsilon}\right)^2 \quad (1)$$

Donde:

n: Número mínimo de muestras

$t_{\alpha;n-1}$: Desviación del valor medio que se acepta para lograr el nivel de confianza deseado (1-α). *Viene expresado por el coeficiente de confianza de la distribución "t" para un nivel de significación "α" y n-1 grados de libertad. En función del nivel de confianza se usa un valor diferente que viene dado por la forma que tiene la distribución "t" cuando n-1 =∞. Los valores más frecuentes son:*

- *Nivel de confianza 90% → = 1,645*
- *Nivel de confianza 95% → = 1,960*
- *Nivel de confianza 99% → = 2,576*

CV: Es la varianza que esperamos encontrar en la población, expresada mediante el coeficiente de Variación (en tanto por uno):

$$CV = \frac{s}{-x}$$

Los datos de medias (x) y desviaciones estándar (s) se deben obtener de un estudio piloto previo.

ε *:* Margen de error máximo que se admite (en tanto por uno).

A la hora de calcular el número mínimo de muestras para determinar la composición de la FORSU recogida selectivamente en Castellón, se ha escogido un nivel de confianza del 95% según lo indicado por la herramienta y un error del 10%. Respecto al error elegido, Pehlken, et al. (2000) consideran adecuado tomar un error del 10% en los muestreos de RSU. Las medias y desviaciones estándar necesarias del contenedor de FORSU se han obtenido de los datos del estudio piloto más reciente realizado en el año 2019 (Gallardo et al., 2021).

En la tabla 2 se muestra el número mínimo de muestras obtenido y todos los datos implicados en la realización del cálculo tras la aplicación de la ecuación 1 a las fracciones consideradas.

Tabla 2. Cálculo del número mínimo de muestras

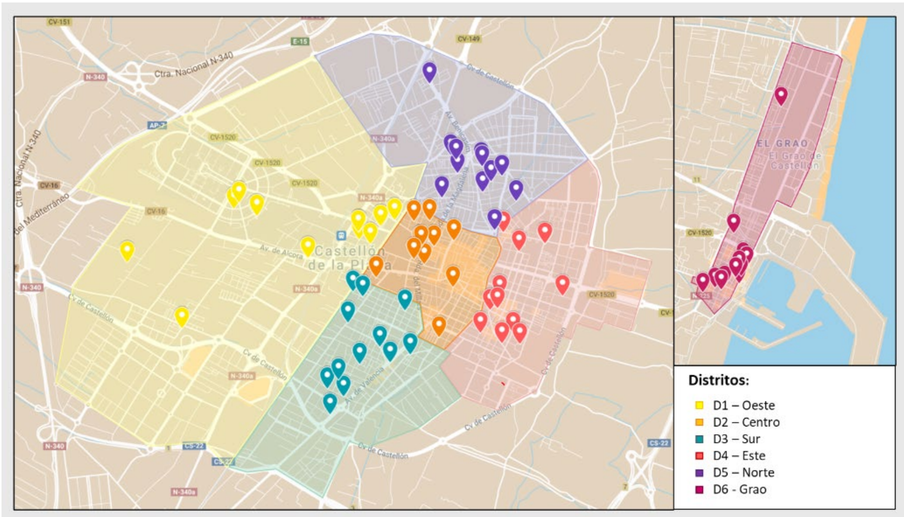
FRACCIÓN	**Experiencia 3 (2019)**			$t_{0,05;\infty}$	**ε (‰)**	**n**
	Media (%)	**Desv. St. (%)**	**CV (‰)**			
Materia Orgánica	74,83	22,86	0,305	1,96	0,1	36

Como se observa en la tabla 2, el número mínimo de muestras necesarias para obtener resultados representativos es de 36 en el caso de la materia orgánica

Por otro lado, la SWA-Tool indica que es fundamental evaluar los factores que pueden influir en la composición de los residuos, algunos de ellos son: la estacionalidad, la estructura residencial (zona rural, suburbana, centro de ciudad, etc.), el tamaño del contenedor, el sistema de recogida, el origen de los residuos, los factores socioeconómicos o la frecuencia de recogida. Así pues, siguiendo las directrices de la metodología, para poder tener en cuenta la estacionalidad se decidió tomar muestras mensuales a lo largo de todo un año. Mientras que para poder considerar la estructura residencial y los factores socioeconómicos se decidió tomar muestras en cada uno de los 6 distritos en los que se divide la ciudad de Castellón. En total se han realizado 72 caracterizaciones (1 caracterización al mes en cada distrito), por lo que se puede decir que los resultados obtenidos de composición del contenedor de la FORSU son representativos, ya que cumplen con el número mínimo de muestras necesarias (tabla 2).

Por último, una vez conocido el número de caracterizaciones realizadas, se pueden calcular el error exacto que se ha cometido despejando de la ecuación 1 el error (Ɛ). Así pues, cuando n=72, el error asumido es del 5%.

Figura 1. Ubicación de la muestra de contenedores elegida para su caracterización



Por lo tanto, la muestra que se caracteriza para cada distrito corresponde a un contenedor procedente de cada uno de ellos. Además, como se ha indicado anteriormente, el tamaño de muestra es un contenedor de fracción orgánica de 2.000 litros, sin tener en cuenta la cantidad de residuos contenidos dentro del mismo. Para su caracterización, estos contenedores fueron llevados a la planta de transferencia de RSU de RECIPLASA en Almazora. El periodo de análisis fue el comprendido entre el 1 de diciembre de 2020 y el 30 de noviembre de 2021.

Figura 2. Contenedores FORSU preparados para su caracterización

3. Resultados

3.1. Análisis cuantitativo. Generación de biorresiduos en la ciudad

En la tabla 3 se muestran los pesajes y ratios obtenidos respecto a la fracción orgánica a lo largo de periodo indicado. Debe reseñarse que, dado que las rutas de recogida comprenden varios distritos, no ha sido posible obtener los pesajes de cada uno de ellos de manera diferenciada.

Tabla 3. Recogida selectiva de biorresiduos en contenedor marrón

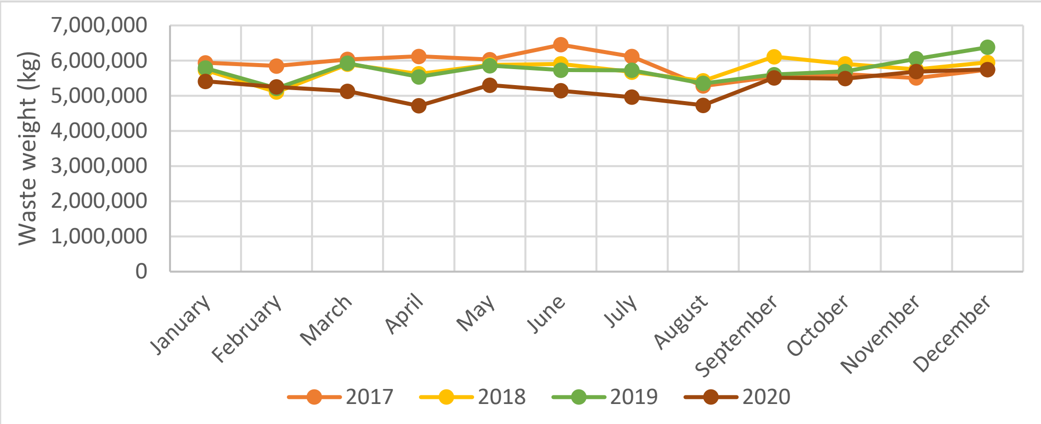
Año	Mes	FORSU (kg)	TRD-B (kg/hab-dia)
2020	**Diciembre**	230.720	0,045
2021	**Enero**	240.880	0,045
	Febrero	231.000	0,048
	Marzo	251.600	0,047
	Abril	246.420	0,048
	Mayo	251.880	0,047
	Junio	239.500	0,046
	Julio	205.800	0,038
	Agosto	196.870	0,037
	Septiembre	243.800	0,047
	Octubre	244.200	0,046
	Noviembre	230.840	0,045
TOTAL		**2.813.510**	**-**
MEDIA MENSUAL		**234.456**	**0,045**

La cantidad de FORSU bruta total recogida selectivamente en la Ciudad de Castellón, desde diciembre de 2020 hasta noviembre de 2021 ha sido 2.813.510 kg, lo que supone una media mensual de 234.456 kg. Este dato representa aproximadamente un 4% del total de los residuos generados en Castelló de la Plana mensualmente, ello que confirma que las áreas densamente pobladas tienen dificultades para lograr altas tasas de recogida selectiva de sólidos municipales. (Rolewicz-Kalinska et al., 2020).

En cuanto a su evolución, destaca la tendencia ascendente en la cantidad recogida desde la implantación del contenedor marrón hasta marzo, como consecuencia de la buena acogida y de las campañas de sensibilización previas realizadas. Así, los meses donde la recogida de FORSU bruta a ha sido mayor corresponden a marzo, abril y mayo.

Su posterior estabilización y su descenso en los meses de verano son consecuencia del periodo vacacional, y es idéntico a lo que ocurre con la generación global de residuos en la ciudad (Figura 3) debido a la población flotante negativa que tiene la ciudad en los meses de verano. Finalmente, la cantidad de FORSU bruta recogida vuelve a valores parecidos a los de primavera a partir de septiembre.

Figura 3. Estacionalidad en la generación total de residuos de Castelló de la Plana



3.2. Análisis cualitativo. Tasas de impropios

Tras las caracterizaciones realizadas, en la tabla 4 se muestran los porcentajes de materiales impropios obtenidos en las muestras mensuales de cada uno de los seis distritos de la ciudad de Castelló de la Plana, así como los pesajes brutos y netos de la FORSU.

Tabla 4. Caracterización de la FORSU recogida selectivamente

Impropios (%)	Oeste	Centro	Sur	Este	Norte	Grao	Global	FORSU Bruta (kg)	FORSU Neta (kg)	TRDn (kg/hab.-día)
Diciembre	14.95	35.94	41.41	22.35	7.89	6.80	25.80	230,720	**171,203**	**0.033**
Enero	28.82	46.38	18.57	30.48	27.29	51.05	34.47	240,880	**157,855**	**0.030**
Febrero	44.43	22.81	37.94	44.24	43.83	40.36	38.74	231,000	**141,512**	**0.029**
Marzo	42.53	43.84	58.37	22.27	46.30	32.71	43.02	251,600	**143,371**	**0.027**
Abril	32.07	39.96	45.46	46.43	71.32	29.64	41.44	246,420	**144,292**	**0.028**
Mayo	58.80	40.80	37.35	18.22	38.86	47.11	37.19	251,880	**158,212**	**0.030**
Junio	23.20	87.32	50.13	37.55	57.80	61.33	47.72	239,580	**125,200**	**0.024**
Julio	36.97	44.56	58.22	39.47	58.69	0.00	38.35	205,800	**126,879**	**0.024**
Agosto	32.22	45.05	46.53	40.20	42.09	56.31	42.78	196,860	**112,657**	**0.021**
Septiembre	45.33	52.05	52.46	40.85	27.68	72.50	46.86	243,800	**129,545**	**0.025**
Octubre	12.05	48.66	29.99	60.58	56.23	56.28	36.99	244,220	**153,877**	**0.029**
Noviembre	32.92	47.52	68.77	53.60	30.43	54.80	45.28	230,840	**126,327**	**0.024**
Media	31.02	43.68	43.53	36.28	43.76	43.55	39.86	234,467	**140,911**	**0.027**

En cuanto a la FORSU neta recogida, se han recogido 1.690.930 kg de materia orgánica compostables que incluye: restos de comida, restos vegetales y otros materiales aptos para su compostaje. Esto supone una recogida media mensual de 140.911 kg de materia orgánica (Tabla 4). Respecto a su evolución, se observa un descenso desde diciembre hasta febrero, estabilizándose y volviendo a aumentar en mayo. La menor cantidad de FORSU neta recogida se da en el periodo de junio a noviembre, salvo por un pequeño ascenso puntual en octubre.

En comparación con los estudios anteriores, las caracterizaciones realizadas en las experiencias piloto mostraban un porcentaje de impropios muy inferior al detectado durante el primer año de implantación global en la ciudad. Así en los distritos Centro, Norte y Oeste que eran los que peores resultados mostraban en las experiencias piloto (20% de impropios) en esta ocasión se encuentran por encima del 34% y en dos de ellos se supera el 40% de impropios. Por su parte, los distritos Este y Grao que mostraban porcentajes de impropios inferiores al 10% en las pruebas realizadas, revelan que durante el primer año de implantación dichos impropios también están en sintonía con el resto de la ciudad rondando el 40%. A destacar el incremento de impropios hallado en el distrito Este, que de un 2% en su experiencia piloto, pasa a un 38% de residuos impropios.

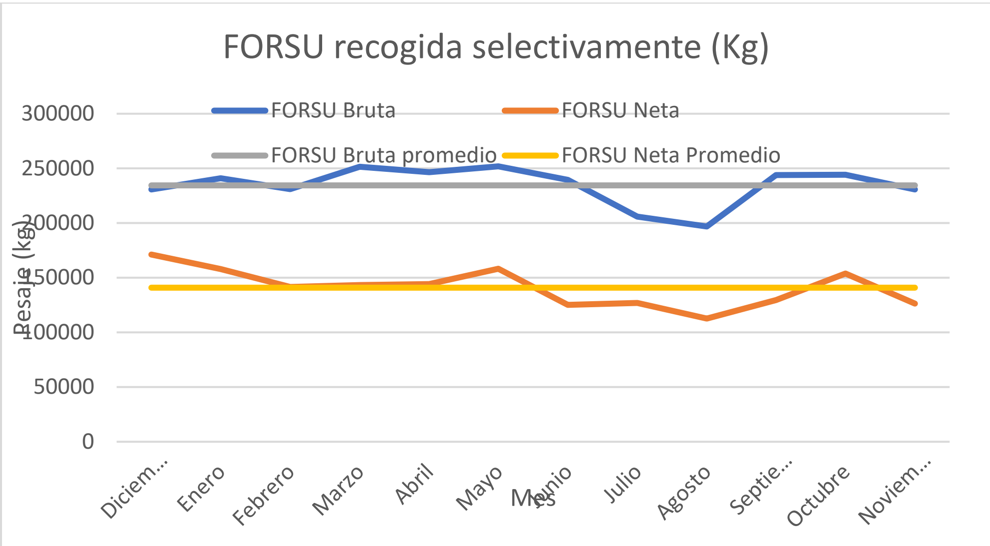
En comparación con otras ciudades de tamaño similar y también con recogida contenerizada en carga lateral, como el núcleo urbano de Terrasa (10,69% impropios), Santa Coloma de Gramanet (7,56% de impropios) u Hospitalet del Llobregat (5,39% de impropios) (SDR, 2021), los porcentajes de impropios de Castelló de la Plana son más elevados.

De media, el distrito donde la FORSU recogida selectivamente tiene mayor calidad para su compostaje es el distrito Oeste, puesto que el contenido en materia orgánica se encuentra cercano al 70%. En el resto de los distritos, se ha obtenido una calidad muy baja (alrededor del 56% de materia orgánica) con un contenido en impropios muy elevado, superior al 40%.

Si se observan los datos mensuales, es durante el mes de diciembre dónde mejores porcentajes de impropios se han obtenido. Ello debe llevar a una reflexión profunda sobre la influencia de la pandemia declarada en marzo de 2020, por COVID-19 y en particular la tercera ola que fue la que golpeó con fuerza en el país. Tal vez, la ergonomía de este nuevo contenedor (pedal, palanca, etc.) haya motivado que a él se deriven residuos que deben ir en el contenedor resto, siendo éste en la ciudad de Castelló de la Plana de apertura manual con tapa de 1x1 metros, aproximadamente. Este hecho podría ser objeto de análisis en futuros estudios.

En cuanto a los pesajes netos (FORSU neta), diciembre, enero, mayo y octubre corresponden con los meses donde la cantidad de materia orgánica compostable recogida ha sido más alta; por el contrario, en agosto esta recogida ha sido la menor. Respecto a la evolución, se observa un descenso en la cantidad de materia orgánica neta recogida desde diciembre hasta febrero lo que indica que la calidad de la FORSU va disminuyendo desde el inicio del estudio. Entre los meses de febrero a abril se produce una estabilización de la cantidad recogida, ascendiendo de nuevo en mayo. A continuación, en el periodo estival que va desde junio hasta septiembre, la FORSU neta cae por debajo de la media, recogiéndose para esos meses la menor cantidad de materia orgánica compostable y por ende la mayor cantidad de impropios. Finalmente, entre agosto y octubre vuelve a aumentar, para descender de nuevo en el mes de noviembre.

Figura 4. Evolución de la FORSU recogida selectivamente en Castellón de diciembre 2020 a noviembre 2021



3.3 Evolución de las TRD

Respecto a la tasa bruta, como se muestra en la Figura 5, para el periodo de diciembre 2020 a noviembre 2021, la TRD-B media ha sido de 0,045 kg/hab-día. Los meses donde esta tasa ha sido mayor corresponden a febrero, marzo, abril, mayo y septiembre de 2021 con tasas del 0,047 – 0,048 kg/hab-día; mientras que en septiembre y octubre de 2020 y julio y agosto del 2021 se obtuvieron los valores más bajos, por debajo de 0,040 kg/hab-día. Si se atiende a su evolución, se observa un claro ascenso en la TRD-B hasta febrero, el cual corresponde al periodo de adaptación de los ciudadanos a este nuevo tipo de recogida y al aumento paulatino de su colaboración. Como ocurre con la cantidad bruta recogida, la tasa se estabiliza entre los meses de febrero a junio, desciende durante los meses estivales (julio y agosto) y aumenta de nuevo tras el verano. Cabe señalar que en los meses de octubre y noviembre de 2021 se aprecia de nuevo un leve descenso.

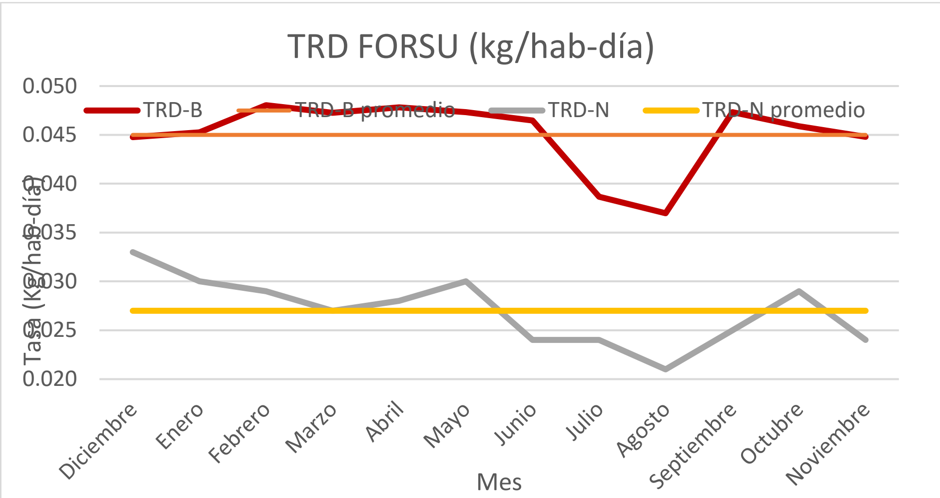
De manera global, la TRD-B obtenida es ligeramente inferior a los valores obtenidos en la prueba piloto del año 2018 donde se obtenía una tasa bruta de recogida diaria por habitante y día de 0,054. No obstante, se han superado ampliamente los valores de las experiencias 1 y 3, que no alcanzaban los 0,02 kg/hab-día (Tabla 1).

En comparación con las ratios de otras ciudades en las que el contenedor marrón se implantó hace más de cinco años, como Barcelona (ARC, 2021) o Madrid (Madrid, 2021), los datos de Castelló de la Plana todavía se encuentran lejos de alcanzar sus TRD-B (0,17 kg/hab-día y 0,15 Kg/hab-día, respectivamente). No obstante, si se comparan los datos con ciudades donde la implantación ha sido más reciente, como Valencia con 0,07 kg/hab-día (Valencia, 2021) o Bilbao con 0,02 kg/hab-día (Bizkaia, 2021), las ratios están más próximas.

Respecto a la tasa neta de recogida por habitante y día, al no disponerse de pesajes por distritos la valoración debe realizarse en el global de la ciudad. En este sentido, la TRD-N obtenida (0,027 kg/hab-día) supera a las que se obtuvieron en los años 2017 y 2019, pero es sensiblemente inferior a prueba piloto del año 2018 realizada en los distritos Este y Grao (0,054 kg/hab-día). La TRD-N fue más alta en los meses iniciales del estudio (diciembre y enero), junto con mayo, con valores entre el 0,030 – 0,033 kg/hab-día; por el contrario, en agosto se obtuvo la más pequeña, 0,021 kg/hab-día, igual que ocurre con la TRD-B.

Respecto a la evolución (Figura 5), se observa un descenso en la TRD-N desde diciembre hasta marzo, lo que a su vez indica una disminución de la calidad de la FORSU recogida, ya que en ese mismo periodo la TRD-B aumenta. Entre los meses de marzo a mayo la TRD-N crece levemente, sin embargo, vuelve a descender con valores por debajo de la media desde junio hasta septiembre, alcanzando su mínimo en agosto. Finalmente, en septiembre y octubre se produce un aumento de la TRD-N, para volver a bajar en noviembre. Así pues, de forma general, el gráfico muestra una tendencia descendente de la TRD-N durante el periodo que dura el estudio.

Figura 5. Evolución de la TRD de la FORSU de diciembre 2020 a noviembre 2021



4. Conclusiones

Las experiencias piloto llevadas a cabo en la ciudad durante los años 2017, 2018 y 2019 de entre tres y meses de duración, pusieron de manifiesto algunos datos a tener en cuenta de cara a la implantación definitiva del contenedor marrón en la ciudad de Castelló de la Plana. De ellas, se observó que cuanto más alta era la ratio de contenerización (litros/habitante) mejores TRD bruta y neta se obtenían. Por ello, durante la implantación de la fracción orgánica se en la ciudad se estableció una cifra final de 12,72 litros por habitante.

En cuanto a los resultados cuantitativos, durante el primer año de implantación se han recogido selectivamente 2.813.510 kg de birresiduos, con una tasa por habitante y día (TRD-B) de 0,045 próxima a ciudades con implantación reciente del contenedor marrón.

En cuanto a la calidad de los biorresiduos, globalmente, la FORSU recogida de manera selectiva para la ciudad de Castellón de media está compuesta por un 60,14% de materia orgánica y un 39,86% de impropios, lo que supone una calidad baja o muy baja para su compostaje. De forma general, se puede decir que la calidad de la FORSU ha sido más alta en los 6 primeros meses de estudio (invierno-primavera) que en los 6 últimos (verano-otoño), es decir, con el paso del tiempo ha ido evolucionando negativamente.

Para el periodo de diciembre 2020 a noviembre 2021, la TRD-N media ha sido de 0,027 kg/hab-día. Respecto a su evolución, se observa una clara disminución hasta marzo, lo que indica una bajada de la calidad de la FORSU recogida, ya que en ese mismo periodo la TRD-B aumentó. De forma general, se pude decir que durante los 12 meses del estudio la TRD-N tiene una tendencia descendente.

De media, el distrito donde la FORSU recogida selectivamente tiene mayor calidad para su compostaje es el distrito Oeste. Este distrito es el que cuenta con una media de edad más baja en la ciudad, lo cual puede evidenciar una relación que sea objeto de análisis en posteriores estudios.

Para mejorar estos resultados, serán necesarias acciones de educación y sensibilización ambiental, enfocadas a concienciar a los ciudadanos por ejemplo en el uso de la bolsa adecuada (compostable) ya que es uno de los impropios más comunes en el contenedor de orgánica. Otras medidas de mayor envergadura consistirían en el cambio de modelo de recogida o la implantación de sistemas de identificación del productor.

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Research article

Sustainable selection of waste collection trucks considering feasible future scenarios by applying the stratified best and worst method

Héctor Moreno-Solaz *, Miguel-Ángel Artacho-Ramírez, Pablo Aragonés-Beltrán, Víctor-Andrés Cloquell-Ballester

Project Management, Innovation and Sustainability Research Center (PRINS), Universitat Politècnica de València, 46022 Valencia, Spain

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ABSTRACT

Municipal solid waste (MSW) management is vital in achieving sustainable development goals. It is a complex activity embracing collection, transport, recycling, and disposal; and whose management depends on proper strategic decision-making. The use of decision support methods such as multi-criteria decision-making (MCDM) is widespread in MSW management. However, their application mainly focuses on selecting plant locations and the best technologies for waste treatment. Despite the critical role played by transport in promoting sustainability, MCDM has seldom been applied for the selection of sustainable transport alternatives in the field of MSW management. There are a few MCDM studies about choosing waste collection vehicles, but none that include the most recent green vehicles among the options or consider feasible future scenarios. In this article, different engine technologies for collection trucks (diesel, compressed natural gas (CNG), hybrid CNG-electric, electric, and hydrogen) are evaluated under sustainability criteria in a Spanish city by applying the stratified best and worst method (SBWM). This method enables considering the uncertainty associated with future events to establish various feasible scenarios. The results show that the best-valued options are electric and diesel trucks, in that order, followed by CNG and hybrid CNG-electric, and with hydrogen-powered trucks coming last. The SBWM has proven helpful in defining a comprehensive framework for selecting the most suitable engine technology to support long-term MSW collection. Considering sustainability among the criteria and feasible future scenarios in waste management collection decision-making provides more comprehensive and conclusive results that help managers and policymakers make better informed and more reliable decisions.

1. Introduction

All human activities should care for and preserve the environment by meeting current ecological requirements and standards. Studies and efforts to control the environmental impact of human actions have grown exponentially in recent years [1]. Hence, sustainability is gradually being consolidated as a premise in decision-making processes, especially in those expected to have a

* Corresponding author.
E-mail addresses: hcmoso@aaa.upv.es (H. Moreno-Solaz), miarra@dpi.upv.es (M.-Á. Artacho-Ramírez), aragones@dpi.upv.es (P. Aragonés-Beltrán), vacloque@dpi.upv.es (V.-A. Cloquell-Ballester).

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long-term impact. Municipal solid waste (MSW) management, defined as the management of domestic and commercial garbage generated under the jurisdiction of a municipal body [2] is not an exception. Waste disposal and waste handling are global problems [3] and many countries are implementing mitigation strategies in MSW to reduce greenhouse gas (GHG) emissions [4]. Additionally, MSW management is called to play a relevant role in the circular economy because landfills as end-of-life product receivers could promote remanufacturing and zero-waste implementations. As a result, sustainable waste management is crucial for reaching sustainable development goals and a more sustainable society [5]. For this reason, the collection, transfer, and transport of MSW are some of the most challenging tasks for local municipalities and represent a significant portion of municipal expenditure [6]. To pursue sustainability, MSW management must face complex mobility challenges. A well-designed transport system improves delivery operations and quality of life by reducing costs, resources, and energy consumption [7]. The collection of MSW is carried out by varyingly sized collecting vehicles working within schedules that collect waste from bins in the streets until full. The waste is then transported to treatment plants or intermediate transfer stations using powerful trucks that consume a lot of energy. This energy currently comes mainly from petroleum derivatives, specifically diesel, that produce high levels of GHG emissions and noise [8]. In addition, in recent years, European regulations on selective collection have forced municipalities to increase the number of routes and vehicles to collect five different fractions of waste (glass, paper & cardboard, packaging, biowaste, and mixed waste) [9,10]. Additionally, door-to-door collection is becoming more frequent in many municipalities since this system achieves the best separation ratios [11]. Therefore, the optimal design of routes, the location of transfer plants, and the type of collection truck are vital to obtaining cost-effective and environmentally friendly solutions [12]. However, although current technological alternatives for transport appear to be clean and sustainable, there is much uncertainty about their global ecological fit and long-term deployment [13]. Thus, apart from the interaction of economic, institutional, social, political, and environmental factors, there is uncertainty about regulation, normalization, and deployment of existing green vehicles. These factors and uncertainties make it difficult to find the suitable alternative that best fits real-world conditions.

In this scenario, multi-criteria decision-making (MCDM) methods are appropriate for choosing the best engine technology because they can concurrently synthesize these conflicting criteria and achieve a trade-off among them [14]. MCDA concepts, methods, and applications have been widely studied in the operational research literature [15,16]. Among the better-known models are those based on multiple attribute utility theory (MAUT) [17], analytic hierarchy process (AHP) [18] and analytic network process (ANP) [19], as well as outranking methods such as ELECTRE [20] or PROMETHEE [21] or a technique for order preference by similarity to ideal solution (TOPSIS) [22]. These methods assume that the decision-maker has a certain level of knowledge about the alternatives and the consequences of the choice. When there is vagueness or imprecision in the data or in the judgments in the context of the decision problem, fuzzy MCDM can be used [23].

MCDM has been extensively used for decades in various waste management problems and circumstances. However, its application mainly focuses on selecting suitable locations and waste treatment, disposal, and recycling technologies [24]. To the authors' knowledge, the selection of truck engine technologies, including the most recent green vehicles, has not yet been addressed. Moreover, the most applied MCDM methods in waste management have been AHP (47%), followed by ANP (9%), and VIKOR (7%) [24]. Studies including uncertainty management are less frequent (37%), and only one percent deal with the probability of different scenarios occurring [24]. After making a decision, the decision-maker frequently becomes hesitant about whether the proper weightings were assigned to the criteria, given that various possibilities may occur in the near future [25]. Thus, as a complex system operating in volatile, uncertain, complex, and ambiguous (VUCA) environments, waste management should develop plans to manage uncertainty considering feasible future scenarios.

This paper aims to select the best engine technology for waste collection trucks in the city of Castellon, considering sustainability and feasible future events that could in the long term affect the decision to be made at present. The paper applies a recent MCDM method, the stratified MCDM (SMCDM) [25], which is based on the best and worst method (BWM) [26] and enables computing weightings for criteria for feasible future scenarios. The starting hypothesis is that considering sustainability among criteria and feasible future scenarios in waste management collection decision-making will provide more comprehensive and conclusive results to help managers and policymakers make more informed and reliable decisions.

The remainder of this paper is structured as follows. Section 2 provides a background of previous academic works on MCDM methodologies in the context of waste collection and the research gap of the paper. In Section 3, the methodology of this research is presented, and Section 4 contains the main results of the application of this methodology in the city of Castellon (Spain) for selecting among vehicle motor options. A discussion of the results is then presented in Section 5. Finally, Section 6 provides the conclusions, the limitations of the study, and suggests research work.

2. Background

Multi-criteria decision-making (MCDM) involves a broad range of methods to support decision-making to reach a compromise when there are multiple criteria. The most used methodologies are the analytic hierarchy process (AHP), outranking procedures, and a technique for ordering preferences by similarity to an ideal solution (TOPSIS) [27].

Several studies use MCDM techniques to deal with waste management problems. Many of these studies focus on either locating waste treatment plants [28–31] or on technological decisions within the broad field of waste treatment [14,32–34]. However, most only describe one scenario without considering the impact of future situations and the probabilities of occurrence.

A feasible future scenario is a possible or trending situation that can be imagined or achieved by applying different variables (including political, economic, social, and cultural). In this sense, SMCDM was created to consider feasible future scenarios in the decision-making process.

SMCDM is based on the concept of stratification (CST) introduced by Zadeh [35]. The author considered a series of stratum or multiple levels through which the system transits from the input to a given target state or desired level. The concept has proven helpful in logistic informatics [36], artificial intelligence, natural language processing, big data, and robotics [37]. Asadabadi [25] was the first author to apply the CST in MCDM, and first coined the term SMCDM in the literature by considering future events that might influence decision-making. Single and integrated uses of SMCDM can be found in the literature. It has been applied for humanitarian aid distribution center selection in a post-disaster planning phase [38], for long-term planning in flood risk management [39], for

Table 1
Application of MCDM techniques in waste collection and transportation.

Work	Country	Problem description	Simple MCDM	Hybrid MCDM	Assessed Alternatives	Considering future scenarios
[51]	USA	Rank fuel alternatives for waste collection vehicles	–	TOPSIS, SAW	Waste collection trucks	No
[52]	Turkey	Rank waste collection systems in a smart city	TOPSIS	–	Technologies for smart collection	No
[53]	Tunisia	Route planning with GIS tools	ELECTRE III	–	Route optimization	No
[54]	Serbia	Rank fuels for waste collection	WASPAS	–	Waste collection trucks	No
[55]	Egypt	Optimizing construction and demolition waste transportation	COPRAS OCRA	–	Number and volume of vehicles	No
[56]	India	Evaluate different collection alternatives	Linear optimization model	–	Cost-benefit vs home segregation degree	Yes
[57]	Saudi Arabia	Choose recycling collection method for recovered fiber	–	BWM, TOPSIS	MCDM results comparation	No
[58]	Pakistan	Provide a facilitating framework incorporating circular economy principles	–	SWARA, VIKOR	Critical facilitators for the adoption of smart waste management	No
[59]	Saudi Arabia	Complete solid waste collection system selection	T-SHFS	–	Smart technologies for waste collection	No
[60]	Turkey	Select most appropriate policy for small household appliance collection methods		–	Small household appliance collection systems	No
[61]	Spain	Design methodology to evaluate circularity alternatives for construct and demolition waste	VIKOR	–	Types of recycled concrete, influenced by transport distances	No
[62]	Canada	Design waste collection program	CBA	–	Levels of satisfaction	No
[63]	Bosnia and Herzegovina	Selecting the best municipal solid waste collection scenario	–	AHP, VIKOR	Degrees of waste separation	No
[64]	Iran	Assess environmental problems derived from petroleum products in transportation	PROMETHEE	–	Fuels for light-duty vehicles	Yes
[65]	China	Locate a recyclable waste transportation vehicle parking center	–	DEMATEL, EW, WASPAS	Facility location	No
[66]	Poland	Planning of waste management systems in urban areas	–	Selection compromise programming	Waste management systems and waste fractions	Yes
[67]	Turkey	Analysis of location selection Problem for underground waste containers	–	MAIRCA, MABAC	Waste container location	No
[68]	Iran	Design transportation system in industrial waste management	–	BWM, PROMETHEE	Routes and fleet optimization	No
[69]	Iran	Define new model for urban waste collection and energy generation	–	NSGA-II, MOPSO	Integrated waste management models	No
[70]	Iran	Minimize the transportation cost and maximize the suitability	–	DELPHI, TOPSIS, E-CONSTRAINT	Holistic decision support tool	No
[71]	Malaysia	Define a Route optimization method combinate with GIS	AHP	–	Route optimization	No
[72]	Turkey	Evaluate smart waste collection systems based on internet of things	–	CODAS and IVq-ROFSs	Smart waste collection alternatives	No
[73]	Italy	Minimize operational costs and environmental impact of MSW management (heuristic approaches)	BWM	–	Algorithms for routes optimization	No
[74]	India	Mitigate the interacting barriers to online e-waste collection platforms	DEMATEL	–	Strategies for mitigating existing barriers	No
[75]	Italy	Evaluate smart reverse logistics development scenarios	–	Fuzzy DANP and fuzzy COBRA	Scenarios integrating Industry 4.0 technologies	No
[76]	India	Evaluate different collection alternatives	AHP	–	MSW collection and transportation methods and vehicles	No

implementation of Industry 4.0 in the mobility sector [40], and for selecting sustainable circular suppliers [41].

Because of its newness, little research on applying SMCDM can be found for waste management. As stated by Torkayesh et al. [24], only one percent of the existing studies with uncertainty-based MCDM methods in this field use the concept of stratification. As remarkable exceptions, we can find the work of Torkayesh et al. [42], applying SMCDM for waste disposal technology selection, Torkayesh & Simic [43], using the method for recycling facility location and the work of Tirkolaee et al. [44], employing SMCDM for sustainable healthcare landfill location selection. However, a developing trend of using uncertainty-based MCDM methods has arisen [24] because their greater reliability and accuracy ensure more scientifically robust and informed decision-making processes. Specifically, SMCDM enables decision-makers to develop plans considering different scenarios, and uncertainty can be managed to select the option that best fits real-world conditions.

Regarding the choice of vehicles, several MCDM studies compare options for motorizing people transport [45,46]; or more recently, mobility sharing systems [47]. Furthermore, in the last few years, some authors have focused on aspects related to electric vehicles, such as multiple fuel supply systems [48], smart charging scheduling at workplaces [49], or the management of lithium-ion batteries at the end of their lives [50]. However, there is little academic literature on analyzing available technologies for waste collection truck motors using MCDM, and none that considers feasible future scenarios simultaneously.

Table 1 summarizes the literature review on the application of MCDM techniques for the collection and transport of waste. A survey has been carried out on the literature using the following keywords: MCDM; multi-criteria; waste collection; MSW; vehicles; trucks; technologies; fuel; electric; and transport.

As can be seen in Table 1, none of these academic works apply techniques that consider the occurrence of feasible future scenarios using the stratified BWM (SBWM). It is possible using CST to assess each criterion under each foreseen scenario [25]. This approach provides this research with considerable potential because it enables important decisions to be made, such as selecting waste collection trucks by considering feasible future events that will probably affect the final suitability of choice.

2.1. Research gap and contributions

The inclusion of uncertainty management in MCDM applied to waste management is still far from frequent – but the number of examples continue to grow given its reliable results. Using the concept of stratification (CST) and considering future scenarios in the decision-making process is even less frequent and practically residual in MSW [24]. To the authors' knowledge, no MCDM study has included the most recent green vehicles as alternatives for selecting truck engine technologies in MSW management. Thus, the present work tries to fill these gaps in the literature by applying the SMCDM to choose the most suitable engine technology for MSW collection trucks in the city of Castellon. Moreover, with the inclusion of sustainability criteria in the decision-making process, the paper defines a comprehensive framework to select the most suitable engine technology for long-term MSW collection.

3. Methodology

The objective is to select the best engine technology for waste collection trucks considering feasible future events. A MCDM known as the stratified best and worst method (SBWM) has been chosen [42] as it considers feasible future scenarios when prioritizing available alternatives. The SBWM is an extension of the best and worst method (BWM), which is used to assess and compare the criteria chosen in each possible scenario.

3.1. The stratified best and worst method (SBWM)

The best and worst method is a popular multi-criteria decision-making (MCDM) method developed by Rezaei [26] which solves the inconsistency problem generated with AHP [77]. Torkayesh et al. [42] recently extended this method, considering different future scenarios, and developed the SBWB as follows:

Step 1. Determine a set of decision criteria $\{c_1, c_2, .., c_n\}$ that should be used to arrive at a decision.

For example, when choosing a house, the criteria could be C1, size; C2, availability of public transportation; and C3, price.

Step 2. Possible future scenarios are identified because they can change the decision-making process.

Following the example, three scenarios could be S1, current situation; S2, family growth; and S3, workplace change.

Step 3. Probabilities for transitioning between scenarios are assessed to build the transition probability matrix. In other words, experts determine the likelihood of the occurrence of each scenario based on historical data and their expertise.

Simplifying the probabilities could be 50% in the first case, 30% in the second, and 20% in the third. The probability matrix would be (0.5, 0.3, 0.2).

Step 4. Based on expert knowledge, determine the best (e.g., most desirable, most important) and worst (e.g., least desirable, least important) criteria for each scenario. No comparison is made at this stage.

For example, the best criteria in the first scenario could be price, and the worst could be size. This evaluation must be made in each scenario because each can differ.

Step 5. Determine, for each scenario, the preference of the best criterion over other criteria using a number between 1 and 9, according to this scale:

1: equal importance, 2: between equal and moderate, 3: moderately more important than, 4: between moderate and strong, 5: strongly more important than, 6: between strong and very strong, 7: very strongly more important than, 8: between very strong and absolute, 9: absolutely more important than.

The resulting best-to-others vector would be $A_B = (a_{B1}, a_{B2}, \ldots, a_{Bn})$, where a_{Bj} j indicates the preference of the best criterion B over criterion j. It is clear that $a_{BB} = 1$.

Making the pairwise comparison, an example of a best-to-others vector for the first scenario could be (7,3,1). The same is done in each of the three scenarios.

Step 6. Determine, for each scenario, the preference of all the criteria over the worst criterion using a number between 1 and 9, with the scale of step 5. The resulting others-to-worst vector would be $A_W = (a_{1W}, a_{2W}, \ldots, a_{nW})^T$, where a_{jW} indicates the preference of the criterion j over the worst criterion w, and $a_{WW} = 1$.

In the example, the others-to-worst vector in the first scenario could be (1,4,6). The same is done in each of the three scenarios.

Step 7. Find the optimal weights for each scenario $(w_1^*, w_2^*, \ldots, w_n^*)$. The optimal weight for the criteria is the one where, for each pair of w_B/w_j and w_j/w_W, we have $w_B/w_j = a_{Bj}$ and $w_j/w_W = a_{jW}$. To satisfy these conditions for all j, we should find a solution where the maximum absolute differences $\left|\frac{w_B}{w_j} - a_{Bj}\right|$ and $\left|\frac{w_j}{w_W} - a_{jW}\right|$ for all j is minimized. Considering the non-negativity and sum condition for the weights, Eq. (1) results:

$$\min \max_j \left\{ \left|\frac{w_B}{w_j} - a_{Bj}\right|, \left|\frac{w_j}{w_W} - a_{jW}\right| \right\},$$

s.t.

$$\sum_j w_j = 1 \tag{1}$$

$w_j \geq 0$, for all j.

This can be transferred to the Eq. (2):

min ξ.

s.t.

$$\left|\frac{w_B}{w_j} - a_{Bj}\right| \leq \xi, \text{for all } j \tag{2}$$

$\left|\frac{w_j}{w_W} - a_{jW}\right| \leq \xi$, for all j.

$$\sum_j w_j = 1$$

$w_j \geq 0$, for all j.

Optimal weights $(w_1^*, w_2^*, \ldots, w_n^*)$ and ξ^* are then obtained.

Following with the example,

$$\left|\frac{w_3}{w_1} - 7\right| \leq \xi,$$

$$\left|\frac{w_3}{w_2} - 3\right| \leq \xi,$$

$$\left|\frac{w_2}{w_1} - 4\right| \leq \xi,$$

$$w_1 + w_2 + w_3 = 1,$$

$$w_1, w_2, w_3 \geq 0.$$

Table 2
Example of weights of criteria in each scenario.

Criteria	S1	S2	S3
C1	0.0909	0.0600	0.3260
C2	0.2545	0.2560	0.1890
C3	0.6545	0.6840	0.4850

So, the weights in the first scenario would be.

$w_1 = 0.0909, w_2 = 0.2545, w_3 = 0.6545, \xi = 0.4010$

The same procedure must be followed in each scenario to build a matrix criteria/scenario (see Table 2).

Step 8. The consistency ratio "*CR*" provides a measure of the consistency of a comparison. This ratio is calculated in each scenario using (3).

$$Consistency\ ratio\ (CR) = \frac{\xi}{Consistency\ index} \quad (3)$$

In the example, for the consistency ratio, $a_{Bw} = a_{31} = 7$, the consistency index is 3.37 [26] so the $CR = 0.4010/3.37 = 0.1190$, which means good consistency. The same procedure must be repeated in each scenario.

Step 9. Multiply the weightings in the scenarios using the transition probability matrix to obtain the optimal weights of the criteria.

Once we have the weights in each scenario, we build the matrix (Table 2).

We then multiply the matrix by the transition probability matrix (see step 3), resulting in the optimal criteria weights: C1, 0.1287; C2, 0.2419 and C3, 0.6295.

Step 10. Construct an alternative criteria matrix again using SBWM. In this matrix, each option is evaluated with respect to the selection criteria, and a score is computed for each. Applying BWM in each alternative, an example of an alternative normalized decision matrix with two alternatives (house "A" and house "B") is shown in Table 3.

Step 11. Multiply the alternative normalized decision matrix by the optimal weights of the criteria matrix. These will be the final values showing the preference for each technology.

Finally, in the example proposed, we multiply the Table 3 matrix by the optimal criteria weights. By doing this, we obtain the final values of our alternatives: house "A" (0.4613) and house "B" (0.5386).

3.2. Research methodology

Once the chosen method is explained, the methodology phases created for this work are:

Phase I. Description of the problem and the specific case study of the city of Castellon.

Phase II. Selection and description of the decision support experts.

Phase III. Identification of the technologies used in waste collection trucks and the method of choosing them, identifying the main available technologies to be evaluated (the alternatives).

Phase IV. Selection of the criteria for choosing a technology based on an academic review and decision-maker experience.

Phase V. Analysis of the feasible future scenarios that will play a role when prioritizing the alternatives.

Phase VI. Definition of the probability occurrence of these feasible scenarios and assessing each criterion by applying BWM (SBWM).

Phase VII. Determination of the optimal weights for each criterion, multiplying the weights obtained in each scenario by the probability of their occurrence.

Phase VIII. BWM application for assessing each of the evaluated technologies (alternatives) for each criterion and answering the question: which technology is better for each of the chosen criteria?

Phase IX. Ranking the available technologies from highest to lowest according to the scores obtained by multiplying the matrices obtained in phases VII and VIII.

Phase X. Conducting a sensitivity analysis.

Fig. 1 shows a graphical scheme of the methodology followed.

4. Case study: Castellon City Council, Spain

Castellon is a Spanish Mediterranean city (**Phase I**). It is the capital of the province of Castellon and is in the north of the Valencia Region with a population of 172,589 [78]. Waste generation in the city exceeds 405 kg per inhabitant and year [79]. Collection is divided into five fractions according to current regulations [80] with more than 6900 containers – a containerization ratio of 74.7 L per inhabitant. Most collection trucks are diesel or CNG and have been in use for over ten years. For this reason, Castellon City Council is considering replacing the fleet.

Table 3
Example of the alternative normalized decision matrix.

Criteria	House "A"	House "B"
C1	0.4280	0.5720
C2	0.3680	0.6320
C3	0.5040	0.4960

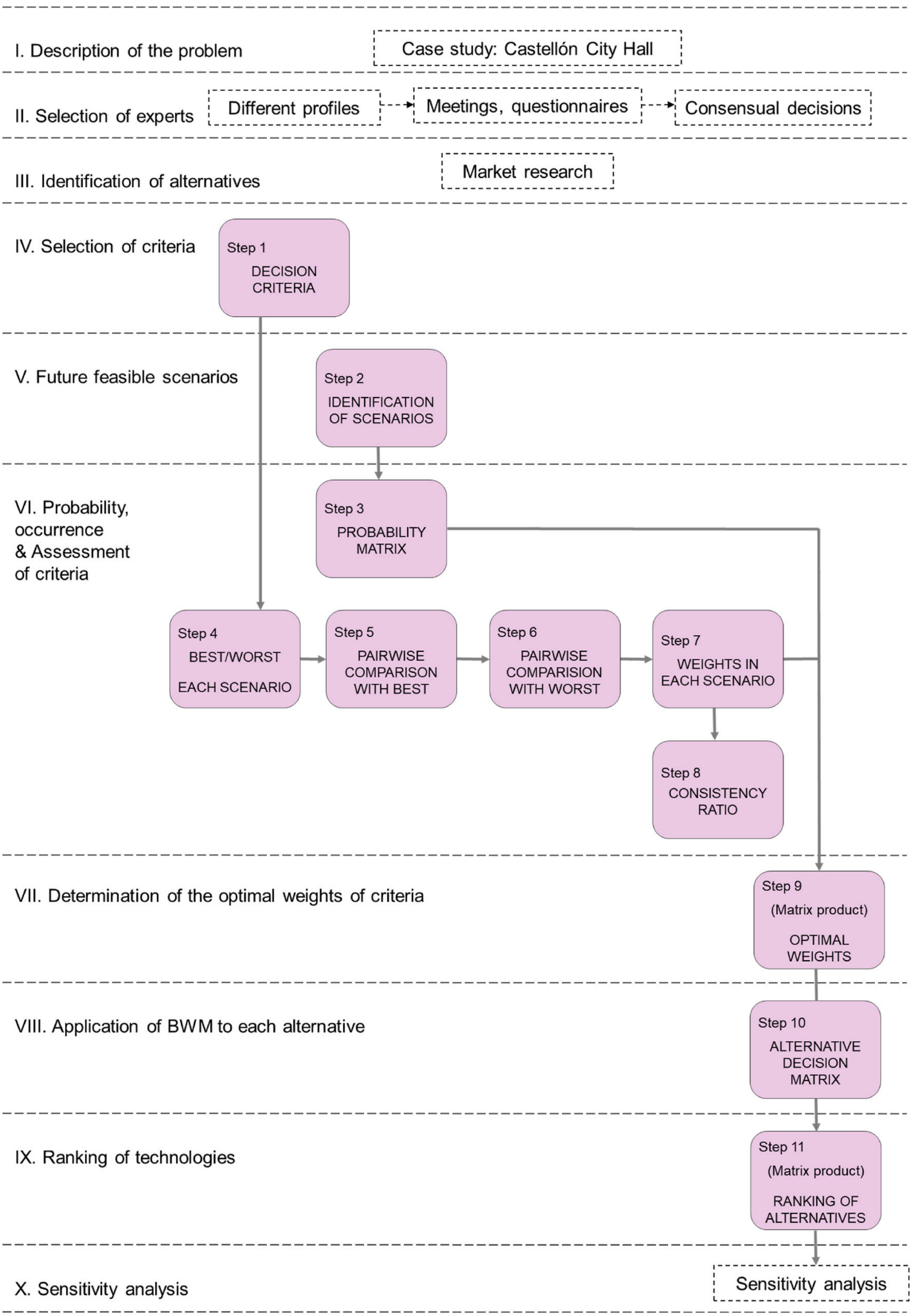

Fig. 1. Phases of the methodology.

A group of experts was created (**Phase II**). This group was constituted of five senior managers, one from each of the five main MSW management companies in Eastern Spain, three municipal engineers, two PhD engineers from the Jaime I University, two PhD engineers from Universitat Politècnica de València, a representative from the local transport association, an executive of the Valencian Energy Association, two local political representatives, and four environmental educators from the provincial MSW management board. It is also important to point out that all the scores introduced in the steps of the multi-criteria method – and the decisions made – were established consensually.

First, an informative meeting was held with the experts to gather the necessary data. The main objective was to obtain an initial proposal of technological alternatives, criteria, and scenarios for the case study. The facilitator then wrote and explained the proposal and sent it by email to the experts. Once this part was confirmed, in a second meeting, a questionnaire was delivered to establish the probability of occurrence of each of the scenarios and the criteria were compared in each. In the questionnaire, the questions for each scenario were phrased in this style:

In your opinion, what is the probability of occurrence for the different events? Which are the most/least important criteria in this scenario? Finally, compare for each scenario and using the following scale, all the rest of the criteria with the best and worst criterion.

In a third meeting, a similar questionnaire was delivered. This time the objective was to establish the expert opinions regarding the chosen technologies, and so the following question was asked for each of the criteria:

In your opinion, which is the best/worst technology for C1? Finally, compare in each criterion, using the following scale, all the other technologies with the best and the worst technology.

The experts then identified several technologies available for truck engines and evaluated the options. Currently, the leading technologies available (**Phase III**) in Europe for garbage trucks are diesel (T1), compressed natural gas – CNG (T2), hybrid electric-CNG (T3), electric (T4), and hydrogen (T5).

A series of relevant criteria (**Phase IV**) were then defined as extracted from the scientific literature and confirmed by expert experience. These criteria, fundamental when selecting an engine technology, are the following:

C1: cost of buying the vehicle [51].

C2: operating cost, that is, the servicing cost of the truck (insurance, tires, fuel, etc.) [81].

C3: polluting atmospheric emissions [82,83].

C4: truck noise [84].

C5: social acceptance of the technology and its use [42].

C6: availability of spare parts [54].

C7: estimated lifetime of the truck. Based on their experience, the group of experts determined that this criterion was crucial for making this kind of decision.

C8 is the ease of refueling (number of service stations, refueling times, etc.) [51,54].

C9 is flexibility in the vehicle's configuration (such as the possibility of mounting several axles, boxes, reduced chassis, and bicompartments) [85].

When setting the feasible scenarios, the choice is not limited to the current scenario and so eight scenarios are considered (**Phase V**) to determine the choice of truck technology by considering the probability of each occurring. To determine these future scenarios, the experts considered those foreseen events with a high probability of occurrence that could have meaningful repercussions on the decision process. To do this, they created a list of trends by analyzing the sector and market situation, current technologies, and legislation. They then observed the evolution of other sectors that have impacted or could directly or indirectly impact on waste management. When determining future expectations, the mentioned eight scenarios were established – from the most conservative scenario to a scenario that presents significant changes. Finally, the time horizon set by the experts was ten years as this is usually the amortization period for machinery in waste management services [86]. The eight scenarios obtained are shown in Fig. 2.

The occurrence probabilities for the scenarios were estimated by the experts consensually and based on their experience and observations of trends in recent years (**Phase VI**). Probabilities of 10%, 60%, 75%, and 80% were established for scenarios S1, S2, S3 and S4, respectively. The scenario with the smallest probability value (10%) is called "pS1". The remaining scenario probabilities are expressed as a function of "pS1". Considering that scenarios are independent situations, the probability of scenarios S5, S6, S7, and S8 is

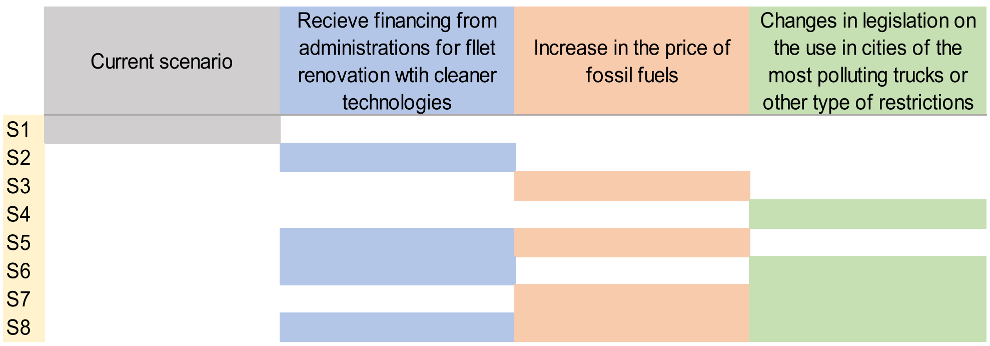

Fig. 2. Definition of scenarios.

obtained as a product of their probabilities.

Finally, considering that the sum of the probabilities of the contemplated scenarios must be equal to 1, the following equation can be created:

$360pS1^3 + 153pS1^2 + 22{,}5pS1 = 1$

where $pS1 = 0.03528$.

Table 4 shows the transition probability between the defined scenarios based on this data.

As shown in Table 4, the experts have determined that the most foreseeable scenario for the next ten years is a series of regulatory changes in the field of waste management (S4). They have also allocated a high probability for increased fossil fuel prices (S3).

Once the transition probability is calculated, the experts determine consensually the score each criterion should have for each scenario (**Phase VI**). The objective in this phase is for the decision-maker to complete Table 5, choosing the best and worst criteria for each scenario and then comparing the rest of the criteria with both in pairs.

After applying the BWM solver, the weights obtained for each scenario are shown in Table 6. The consistency index "*CR*" is close to zero for all of them, which means that the obtained results are robust.

In the S1 current scenario (no change), investment costs achieve the highest weight for the decision-maker. However, in scenarios S2, S3, S4, and S5, operating costs obtain a higher weight in the decision-making process. In the rest of the scenario combinations (S6, S7, and S8), the criterion with the highest weight is atmospheric emissions (C3).

The matrix product in Tables 4 and 6 is then calculated to obtain the optimal weights for each criterion (**Phase VII**). The result is shown in Table 7.

Considering all the scenarios and their transition probabilities, it can be generally observed that the highest optimal weight is obtained by the operating cost criterion (C2).

The next step (**Phase VIII**) establishes which technology (T1, T2, T3, T4, and T5) is best for each criterion. For this, the technical characteristics provided by the truck manufacturers were analyzed, and BWM was again applied to obtain the alternative normalized decision matrix (Table 8).

For the decision-maker, the diesel truck is the most appropriate in four of the nine criteria (C1, C6, C8, and C9), and it stands out in terms of flexibility and ease of refueling. The electric truck obtains the best weights in three categories (C3, C4, and C5) and stands out in social acceptance.

Finally (**Phase IX**), to choose the best technology, the optimal weights of each criterion (Table 7) are multiplied by the alternative normalized decision matrix (Table 8). Fig. 3 shows the ranking of the alternatives.

In light of the results, where the differences between the first alternative and the second are small, a sensitivity analysis is proposed (**Phase X**). The process followed consists of developing an algorithm where the weight of a given criterion is successively modified in several steps, keeping the sum of criteria equal to 1. What is added or subtracted from the weight in each step of the reference criterion, is added or removed to the other criteria according to the initial proportion. At each step, the ranking of alternatives is recalculated, allowing us to observe how the orders are modified when modifying the weight of the reference criterion.

The results show a similar trend for criteria C1, C8, and C9 (see supplementary material). When the weight of these criteria is increased slightly from their original values, the T4 (electric) quickly falls in position, while the T1 (diesel) gains very quickly. In the case of criterion C6, this tendency is also fulfilled, but it is less pronounced than for the previous criteria.

The opposite happens with criteria C2, C4, and C5. When their weight is increased from the original values, technology T4 (electric) increases its ranking quickly while T1 (diesel) decreases.

In the case of C3, the more its weight increases from the original, the more the ranking of T4 (electric) increases. But simultaneously, the ranking of T5 (CNG-electric) increases, and when the weight of C3 reaches approximately 0.65, the alternative T5 takes first place. T1 (diesel) falls to last position in this situation.

In the case of C7, when its weight increases from its original value, the ranking of T4 (electric) drops rapidly, and T1 (diesel) takes the first position when the weight of C7 is approximately 0.15. In this case, T2 (CNG) also increases rapidly, taking the first position when the weight of C7 reaches about 0.38.

Fig. 4 shows the sensitivity analysis of the first criteria (C1, vehicle cost). The rest of the sensitivity analysis figures have been included in the supplementary material.

The following section analyses and discusses the results obtained.

5. Discussion

The criteria chosen by the experts are aligned with those evaluated by other authors for the selection of waste management technologies in MCDM studies, according to the literature review carried out by Torkayesh [24]. That is why they can be grouped, following the dimensions of sustainability, in the categories defined by this author as economic (C1, C2), environmental (C4, C3) and social (C5). In addition, the author recommends other technical criteria specific to each study (C6, C7, C8, and C9 in this study).

Table 4
Transition probability of scenarios.

Scenario	pS1	pS2	pS3	pS4	pS5	pS6	pS7	pS8
Transition probability	0.0353	0.2117	0.2646	0.2822	0.0560	0.0597	0.0747	0.0158

Table 5
SBWM. Scores of each scenario.

States	S1	S2	S3	S4	S5	S6	S7	S8
Best criterion	C1	C2	C2	C3	C2	C3	C3	C3
Worst criterion	C5	C5	C5	C5	C5	C5	C5	C5
Best to others								
C1	1	4	3	1	4	4	2	4
C2	2	1	1	1	1	2	2	2
C3	3	2	2	1	2	1	1	1
C4	3	2	2	2	2	3	3	3
C5	4	3	4	4	3	4	4	4
C6	3	2	3	2	2	2	2	2
C7	3	3	2	2	2	2	2	2
C8	2	2	2	2	2	2	2	2
C9	3	3	3	3	3	3	3	3
Others to the worst								
C1	8	3	8	7	4	4	8	4
C2	8	8	9	7	9	8	8	9
C3	6	7	4	9	6	9	9	9
C4	4	5	3	6	5	5	4	4
C5	1	1	1	1	1	1	1	1
C6	5	6	5	6	6	7	7	7
C7	5	6	6	6	6	6	6	7
C8	4	5	6	5	5	6	6	6
C9	5	5	4	4	4	4	4	3

Table 6
Weights of criteria based on SBWM.

Criteria	S1	S2	S3	S4	S5	S6	S7	S8
C1	0.2019	0.0677	0.0889	0.1440	0.0647	0.0673	0.1261	0.0678
C2	0.1442	0.1805	0.1778	0.1920	0.1727	0.1345	0.1261	0.1355
C3	0.0962	0.1353	0.1333	0.1920	0.1295	0.1883	0.1765	0.1848
C4	0.0962	0.1353	0.1333	0.0960	0.1295	0.0897	0.0840	0.0903
C5	0.0288	0.0301	0.0222	0.0240	0.0288	0.0269	0.0252	0.0246
C6	0.0962	0.1353	0.0889	0.0960	0.1295	0.1345	0.1261	0.1355
C7	0.0962	0.0902	0.1333	0.0960	0.1295	0.1345	0.1261	0.1355
C8	0.1442	0.1353	0.1333	0.0960	0.1295	0.1345	0.1261	0.1355
C9	0.0962	0.0902	0.0889	0.0640	0.0863	0.0897	0.0840	0.0903
CR	0.0865	0.0902	0.0889	0.0480	0.0863	0.0807	0.0756	0.0862

Table 7
Optimal weights of criteria.

Criteria	C1	C2	C3	C4	C5	C6	C7	C8	C9
Weight	0.1037	0.1738	0.1561	0.1147	0.0255	0.1095	0.1117	0.1230	0.0820

Table 8
Alternative normalized decision matrix.

Criteria	T1. Diesel	T2. CNG	T.3 CNG-Electric	T4. Electric	T5. Hydrogen
C1	0.4213	0.2528	0.1011	0.1685	0.0562
C2	0.0800	0.1600	0.2400	0.4000	0.1200
C3	0.0396	0.0808	0.1347	0.3407	0.4041
C4	0.0406	0.1168	0.2335	0.3756	0.2335
C5	0.0374	0.0935	0.2336	0.4019	0.2336
C6	0.3043	0.2174	0.2174	0.2174	0.0435
C7	0.2677	0.3780	0.1890	0.0394	0.1260
C8	0.4757	0.1822	0.1822	0.1093	0.0506
C9	0.5000	0.2055	0.1233	0.1233	0.0479

The results show that the best-valued options are electric and diesel trucks, in this order and with a small margin of difference, followed by CNG and hybrid CNG-electric, and with hydrogen-powered trucks coming last.

The competitive advantage of alternative 1, electric truck (24.53%), is determined by its specific weight in the criteria of operating

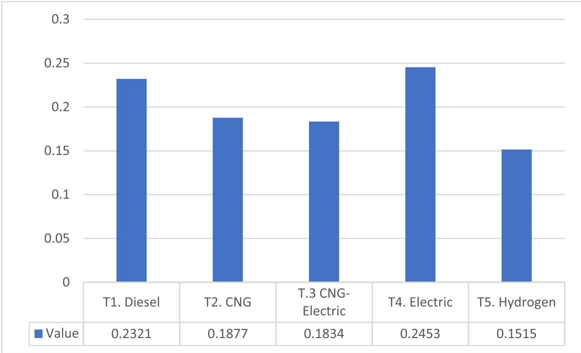

Fig. 3. Ranking of alternatives.

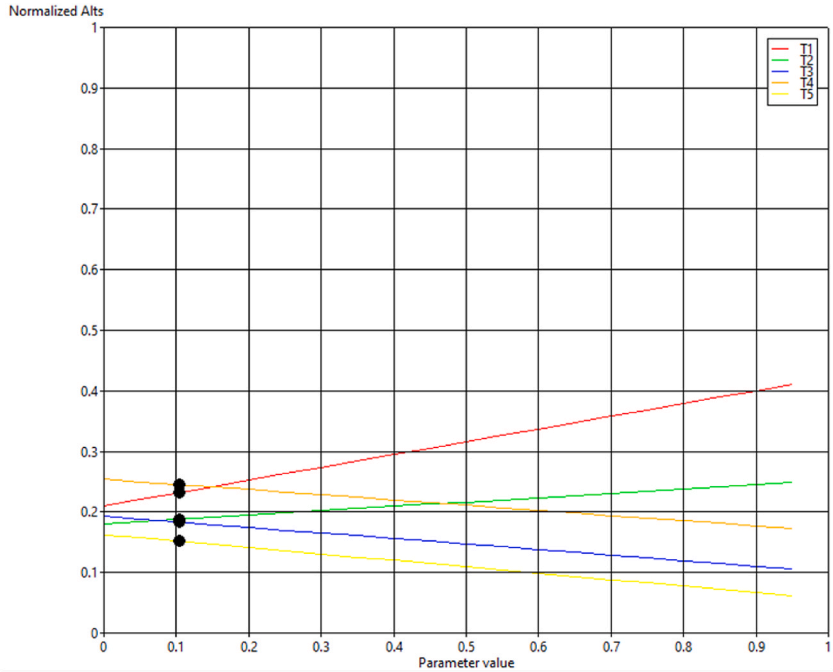

Fig. 4. Sensitivity analysis of criteria C1.

costs, atmospheric emissions, quieter operation, and social acceptance, with values between 34.1% and 40.2%. This result aligns with findings by other authors [12,87]. It should be noted that operating costs and atmospheric emissions represent 32.99% of the specific weight of the nine defined criteria. Despite the moderate and low ranking results presented by electric trucks in criteria such as configuration flexibility, ease of refueling (due to long recharge times), and lifetime (conditioned by the usually daily frequency of charging cycles for this type of vehicle), the results of the four criteria indicated above, combined with moderate specific weights in the criteria of investment costs and availability of spare parts, enable electric trucks to remain in first position.

The good results for diesel trucks, which are in second position and 1.31% behind electric vehicles (with a total 23.21%), are based precisely on their clear advantage in the rest of the criteria analyzed – with specific weights ranging between 26.8% and 50.0%. Diesel waste collection vehicles are highly developed, and their well-established position in the market (with a high level of competition) has produced machinery and spare parts at accessible prices. Almost any configuration is available, and the refueling methodology quickly recovers 100% of autonomy.

After these two alternatives, with very similar results, trucks powered by compressed natural gas (CNG) (18.77%) and hybrid CNG-electric (18.34%) are the third and fourth rankings (although based on different criteria). CNG-powered trucks have been progressively introduced in the Spanish market [88] and an increasingly wide range of configurations is available. At the same time, an increasing number of manufacturers have developed CNG vehicles and this has increased price competition – a criterion in which it obtains more specific weight than trucks that combine CNG with electric traction. The hybrid CNG-electric alternative, which uses fossil fuel to charge the batteries and electric motors for traction, shows better scores in the criteria related to environmental and social aspects and slightly better operating costs due to an optimization of the combustion engine operating regime. However, along with efficiency increments, hybrids come with other environmental impacts; for instance, they need more accessory materials per vehicle – including batteries [50,89].

It should be noted that compressed natural gas (CNG) (mainly methane) can also have a renewable origin, for example, from anaerobic digestion waste treatments. In this case, the assessments made by the experts would indeed have been different, as fuel generation would come from waste treatment processes that contribute to the circular economy. Liquefied biogas is a potentially important substitute for fossil fuels for heavy trucks [90] that has received little attention until now [91] and the results of a recent well-to-wheel assessment show that, compared to conventional fuels, in transport applications and for all vehicle classes (including heavy-duty vehicles), the use of compressed and liquefied renewable natural gas shows an 81% greenhouse gas emission reduction per kilometer traveled [92].

Finally, with a result of 15.15%, are hydrogen-powered trucks. This type of vehicle achieves the best results for atmospheric emissions [93] and relatively good specific weights for noise and social acceptance; however, its contribution to reducing greenhouse emissions depends on the energy mix used for its production [94]. Its low valuation in the rest of the criteria determines a lower valuation in global terms. It is a technology with little current implementation and an uncertain future [95] so both the offer and the variety of configurations is limited. Furthermore, this limited offer has reduced competition and so investment costs and options for spare parts are determined by a limited number of suppliers – meaning that this alternative is relegated to last place. Finally, high hydrogen production costs, a limited supply network, and inefficiencies in conversion to and from electricity [96], make this option the least attractive for the decision-maker.

Therefore, electric trucks are positioned as the best current alternative despite limitations in battery life, vehicle autonomy, and recharging times [97]. In agreement with other authors [47,48], electric vehicles can improve urban air quality, lessen climate change and reduce total energy usage. Diesel and compressed natural gas trucks are positioned as strong options [98] with superior evaluations in criteria such as investment costs, configuration versatility, ease of refueling, and lifetime – but fail to gain the top position due to lower social acceptance, noise, emissions [99], and operating costs (especially in the current context of rising fossil fuel prices). The hybrid combination of compressed natural gas and electric technologies is positioned close behind, as it is cleaner than pure combustion options [100]. However, it shows limitations due to the sum of the conditioning factors of compressed natural gas (supply points for refueling) and electric trucks (lifetime) and limits on possible configurations (higher weight due to CNG tanks and batteries). Finally, hydrogen trucks appear as the lowest-ranked alternative. Despite offering the lowest degree of atmospheric emissions [101] they are considered the least viable option due to their limited development, lack of competitiveness in the acquisition and aftersales market, and limited supply network.

If CST had not been used and only the current scenario (S1) had been considered, the ranking of alternatives would have been different (the diesel truck would be chosen with a considerable advantage over electric vehicles and compressed natural gas). This fact aligns with other SMCDM studies [25,38,102] and reveals the importance of considering the different feasible future scenarios when making decisions [24,39].

6. Conclusions

MCDM methods have often been used to deal with problems arising from MSW management, but they are usually focused on evaluating the best alternatives for waste treatment and disposal. However, from a sustainable and circular economy perspective, improving treatment techniques is insufficient, and waste collection and transport processes must also be reinforced. Municipalities are increasing MSW separation at source, and consequently, the collection routes grow in number (sometimes becoming door-to-door collections). Some MCDM studies have been made about choosing waste collection vehicles, but none that include the most recent green vehicles among the alternatives or consider feasible future scenarios.

This paper analyzes the five main vehicle motorizations in waste collection trucks (diesel, CNG, hybrid CNG-electric, electric, and hydrogen), considering sustainability criteria and using SBWM as a novel decision support model. SBWM is a multi-criteria method that combines two recently developed techniques: BWM and SMCDM. This method incorporates the probability of occurrence of feasible future scenarios in the decision-making process, which empowers decision-makers to express their judgments considering the uncertainty associated with decisions with long-term impact.

The results show that, despite their high price, electric trucks are already the best option for decision-makers, as they stand out in environmental criteria (emissions and noise) and social perception. However, the second ranked alternative, very close to the first, was diesel because of the ease of refueling, flexible configurations, and the fact that it offered the lowest investment costs.

SBWM offered reliable results and allowed dealing with uncertainty by considering different scenarios and enabling decision-makers to assign a likelihood of occurrence to possible future events. As sustainability criteria have been considered in evaluating alternatives, it can be concluded that SBWM has helped choose the best option to promote waste management sustainability by reducing the long-term impacts of mobility.

6.1. Limitations, recommendations, and future directions

This study has a few limitations that can be addressed in future works. One limitation is that only a few sustainability criteria were considered, especially for the social pillar. More balanced sustainability criteria, both qualitative and quantitative, should be considered in future works. Another limitation is that the criteria were assumed independent, which may not be the case. Future studies should address this issue using some methods that allow modelling the criteria interdependencies: ANP, DEMATEL, or interpretative structural modelling (ISM), to name a few. Moreover, to deal with uncertainty in criteria weights, decision-makers should be allowed to assign rating ranges or a value more an error instead of a single number when comparing criteria. Applying such a robust BWM in the future, we will add uncertainty to pairwise comparisons, making the decision-making process more realistic in current complex and ever-changing environments. Another limitation is that the proposed probabilities of occurrence assigned to the feasible futures may significantly affect the results obtained. Future studies should better inform decisions makers about future trends and relevant drivers of the most remarkable decision-making factors to allow more informed forecasting decisions about possible scenarios.

Regarding the case study, the findings may be somewhat limited by the application in a flat medium-sized city with a specific population density. The generalizability of the results will require collecting more experts' opinions in different urban configurations and population distributions.

Finally, as future development, applying the stratification concept with other MCDM will allow comparing the results considering the consistency ratio. Comparing the results to other CST and MCDM combinations will improve the method's validation and test its applicability and usefulness.

Author contribution statement

Héctor Moreno-Solaz: Concieved and designed the experiments; Performed the experiments; Analyzed and interpreted the data; Wrote the paper.

Miguel-Ángel Artacho-Ramírez: Performed the experiments; Analyzed and interpret the data; Wrote the paper.

Pablo Aragonés-Beltrán and Víctor-Andrés Cloquell-Ballester: Contributed reagents, materials, analysis tools or data.

Data availability statement

Data will be made available on request.

Declaration of competing interest

The authors declare no competing interests.

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Prioritizing action plans to save resources and better achieve municipal solid waste management KPIs: an urban case study

Héctor Moreno Solaz[a], Miguel-Ángel Artacho-Ramírez[a], Víctor-Andrés Cloquell-Ballester[a], and Cristóbal Badenes Catalán[b]

[a]Project Management, Innovation and Sustainability Research Center (PRINS), Universitat Politècnica de València, Valencia, Spain; [b]Dirección de Servicios Urbanos, Ayuntamiento de Castelló de la Plana, Castelló de la Plana, Spain

ABSTRACT

The management of municipal solid waste (MSW) in cities is one of the most complex tasks facing local administrations. For this reason, waste management performance measurement structures are increasingly implemented at local and national levels. These performance structures usually contain strategic objectives and associated action plans, as well as key performance indicators (KPIs) for organizations investing their resources in action plans. This study presents the results of applying a methodology to find a quantitative-based prioritization of MSW action plans for the City Council of Castelló de la Plana in Spain. In doing so, cause-effect relationships between the KPIs have been identified by applying the principal component analysis technique, and from these relationships it was possible to identify those action plans which should be addressed first to manage public services more efficiently. This study can be useful as a tool for local administrations when addressing the actions included in their local waste plans as it can lead to financial savings.

Implication: This paper introduces and implements a methodology that uses principal component analysis to analyze real data from waste management KPIs and provide municipal solid waste managers with a decision-making tool for prioritizing action plans. The methodology saves financial resources and time, as well as reinforcing the probability of reaching the meta values of the main performance system KPIs.

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Introduction

The increasing amount of food waste generated as a direct consequence of excessive production, mismanagement, and wasteful behavior is a challenge when promoting resource efficiency (Facchini et al. 2018). One of the objectives of European policy on waste is to move toward a circular economy (Ferronato et al. 2019). Since the publication of the community waste management strategy in 1989, the implementation of principles for material circularity and waste management has been intensifying (Singh and Ordoñez 2016). Furthermore, governments around the world have long been committed to developing plans for the sustainable use of resources by strategies that affect waste management (Wilson, McDougall, and Willmore 2001).

In Spain, these directives have had a direct impact on municipalities, and they have been required to develop local waste management plans and programs (Spain 2022). These plans establish the conditions and means to manage the waste produced by the activities of a city – with priority on source reduction. These plans and programs are well monitored and managed when an adequate key performance indicator (KPI) grid for assessing, controlling, and improving effectiveness is defined (de Pascale et al. 2021). Additionally, the KPIs are an element of a performance measurement structure that usually includes both objectives and action plans.

When looking at performance measurement (PM) theory and, more specifically, at the best-known and applied PM framework, the Balanced Scorecard (Kaplan and Norton 1992), organizations interpret their strategic definition (mission, vision, and values) to firstly define their strategic objectives (what to reach) and then define action plans (how the strategic objective will be reached) and KPIs (to indicate whether the strategic objective is being reached). However, public administrations do not usually follow this performance measurement structure. These organizations manage their performance only using KPIs, and when they define the whole measurement structure, they do not apply the tools available to improve effectiveness.

There are many academic works focused on assessing sustainability KPIs (Hristov and Chirico 2019; Kylili, Fokaides, and Lopez Jimenez 2016; Pinna et al. 2018;

CONTACT Héctor Moreno Solaz hcmoso@gmail.com Project Management, Innovation and Sustainability Research Center (PRINS), Universitat Politècnica de València, Camí de Vera, s/n, Valencia 46022, Spain

Valencia, Qiu, and Chang 2022) including waste management KPIs (Ferreira et al. 2020). However, these works usually only address the tasks of definition and historical data collection for KPIs, and do not carry out a sound analysis of the evolution of the values of the KPIs, nor apply appropriate mathematical techniques to identify additional information for making better decisions. These practices are therefore far from being the most efficient way to proceed. In most cases, the KPIs are usually related (Carlucci 2010), which means that changes in the values of some KPIs produce changes in the values of other KPIs – and so change the performance of the system. Further, the identification of cause-and-effect relationships between the KPIs makes it possible to prioritize actions plans and improve the effectiveness of the whole performance system structure – as decision-makers can apply actions that enable reaching associated strategic objectives, as well as other resource-saving objectives.

This work refers to a case study in the city of Castelló de la Plana (Spain), and its main contributions are the following: a) it identifies and classifies the principal KPIs for municipal solid waste (MSW) management at the local level in the three dimensions of sustainability; b) it identifies, by applying the historical data collected by the KPI statistical techniques, the main intra and extra dimensional cause-effect relationships between KPIs; c) it prioritizes the action plans, based on these cause-effect relationships, which help optimize municipal resources since it may not be necessary to activate every action plan to reach the KPI targets – and thereby improving the efficiency of local MSW management.

The remainder of this paper is structured as follows: Section 2 provides a background of previous academic works on waste management and performance measurement. The research approach is presented in Section 3, and Section 4 shows and discusses the main results of applying such a methodology to the city of Castelló de la Plana (Spain). Finally, Section 5 provides the main conclusions, describes the limitations of the study, and suggests further research work.

Background

Planning in the provision of public services is becoming increasingly frequent, and so the use of indicators to measure performance has also become widely used in the local sphere. Studies have been made on using KPIs in urban design (Mosca and Perini 2022), transport (Grote, Waterson, and Rudolph 2021), communications (Imoize et al. 2022), wastewater treatment (van Schaik et al. 2021), air quality (Malm et al. 2018) and MSW management (Ferreira et al. 2020).

Focusing on the latter issue, during the last five years there have been more than 3,000 references to KPIs dealing with MSW management. Some of these works focus on a specific perspective of the problem, such as the social (Ibáñez-Forés et al. 2019), the economic (Zhou et al. 2022), or the fractions that have been increasing most rapidly in recent years (Brouwer et al. 2019); while others evaluate the overall efficiency of the system (Amaral et al. 2022). There are also studies that summarize the literature about MSW KPIs and establish commonalities between different countries and years (Deus, Bezerra, and Battistelle 2019; Olay-Romero et al. 2020). Some go even further and use literature from other subjects for the development of communication campaigns (de Feo et al. 2019) or educational applications (Pappas et al. 2021).

However, only a few studies (Nemmour et al. 2022) analyze the relationship between indicators for waste management. Although these KPIs are often related, it is important to understand these relationships for efficient decision-making processes (AlHumid et al. 2019; Loizia et al. 2021) as well as in the management of available resources (Stricker et al. 2017).

Several studies can be found that apply statistical techniques to identify KPI cause-effect relationships in MSW management. For instance (Hatik and Gatina 2017), used principal component analysis (PCA) to identify similarities between local administrative areas for comparing waste composition (Callas et al. 2012); defined an indicator of solid waste generation potential in the USA using principal component analysis and geographic information systems (Liu et al. 2023); assessed soil pollution and identified potential sources of heavy metals with a combination of a spatial distribution and the principal component analysis model. Other studies about waste management use correlation analysis (Barbudo et al. 2012), for example, assessed the correlation between sulfate content and leaching of sulfates in recycled aggregates from construction and demolition wastes; and (Birgen et al. 2021) developed a data analysis method based on correlations applied to waste-to-energy plants; and (Zhang et al. 2023) recently used correlational analysis to observe how digestion temperature affects the anaerobic digestion of food waste.

Finally, although there are several studies about how to undertake action plans in local waste management plans or programs, most are limited to a descriptive analysis (Asibey et al. 2021) or, at best, they use multicriteria techniques (Andrade Arteaga et al. 2020; Coban, Ertis, and Cavdaroglu 2018; Habibollahzade and Houshfar 2020) that are limited to expert opinions (instead of real data collected by KPIs) and are therefore completely subjective.

Some academic works from other disciplines have discussed identifying and quantifying KPI cause-effect relationships with statistical techniques to improve decision-making processes. For instance (Rodríguez-Rodríguez, Alfaro-Saiz, and Carot 2020a), applied PCA and partial least squares models to draw a KPI cause-effect map for supply chains to improve operational efficiency (Sanchez-Marquez et al. 2018); used KPI relationships to deal with data uncertainty (Cai et al. 2009); identified KPI relationships to improve supply chain performance by analyzing iterative KPI accomplishment.

In the context of MSW management, there are no academic works that have applied statistical techniques to historical KPI datasets to identify cause-effect relationships – and then used this information to prioritize action plans within a performance measurement structure. Once this research gap has been highlighted, the next point presents the research approach followed.

Research approach

Research methodology and objectives

This research identifies the main cause-effect relationships among sustainability KPIs by analyzing the evolution of the historical data. Once the meaningful relationships have been indicated, they are projected to the action plan level, and it is then possible to rank these plans and establish which should be activated first to achieve the main KPIs.

The main research objectives are: 1) analyze the historical data collected by a set of sustainability KPIs and find sound cause-effect relationships; 2) establish which are the most important KPIs to be achieved (effect KPIs) within the KPI set; 3) establish the cause KPIs that strongly affect the effect KPIs; 4) identify the action plans that should be activated first to ensure that the effect KPIs are achieved and so save resources.

The adopted research methodology is the case study, which is adequate for the decision-making involved in this research as it can provide answers to “why” and “how” (Yin 2014). Additionally, as mentioned in other academic works (Lancaster 2007; Leon et al. 2020), the quantitative approach taken in this research is adequate as it: 1) focuses on establishing causal relationships among variables (KPIs); 2) and presents a study based on the application of statistical techniques (PCA) to find meaningful relationships among KPIs.

Methodology

Figure 1 shows the methodology developed for this research; the main steps are the following:

- Expert group definition.
- KPIs and action plan selection.
- Data matrix.
- Data analysis.
- Results discussion.

This is a sequential methodology, where the outputs of one phase are the inputs of the following phase (as presented below).

Phase 1. Expert group definition

An expert group is formed of the decision-makers who conduct the phases of the next methodology. The expert group should be both multi-disciplinary and experienced in waste management and performance measurement, mainly dealing with the definition of strategic objectives, KPIs, and action plans.

Phase 2. KPIs and action plan selection

The expert group selects the KPIs and action plans of the performance structure to be included within the study. The selected KPIs must: 1) have collected historical data during some of the previous time periods; 2) be linked to strategic objectives; 3) be grouped into the three dimensions of sustainability: economic (E), social (S), and environmental (ENV).

Phase 3. Data matrix

The data matrix includes the study variables (KPIs) in columns and observations in rows. Each intersection of this matrix contains the historical value of the KPI, which was collected within the period of observation. Additionally, since it is highly likely that KPIs have different collection frequencies, it is necessary to choose

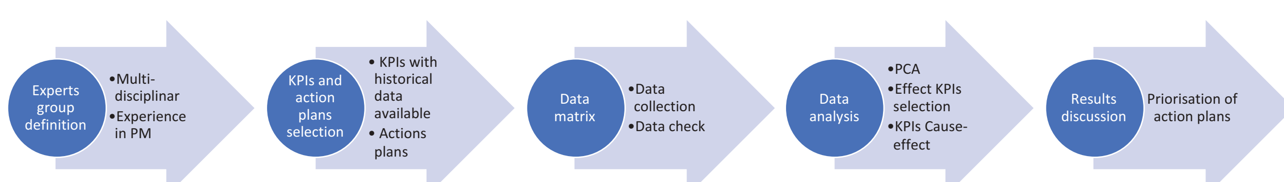

Figure 1. Research methodology.

a common frequency and bring all the values to that frequency. For instance, the data coming from the KPIs in an annual analysis will be homogenized to an annual frequency, and it is necessary to apply different operations to the data of each KPI (for instance, the simple average) when its frequency is other than annual. The resulting frequency standardized matrix is then used for data analysis. Additionally, decision-makers will assess this data matrix from a global standpoint and may exclude some KPIs that do not have enough recent historical data or present irregularities.

Phase 4. Data analysis

Once that the frequency standardized matrix has been calculated, it is possible to apply a statistic technique to identify relationships between the variables (KPIs in our case). Principal component analysis (PCA) is then applied to identify the main cause-effect among the data matrix KPIs. This technique has already proven its efficiency in analyzing the conjoint evolution of variables (KPIs) and the identification of meaningful cause-effect relationships in the context of this research – such as: the relative lack of historical observations of the variables compared with the number of variables; missing data in some of the time periods; and various measurement units of variables such as monetary (euros), time (minutes, hours, days, etc.) or rates (percentages) (Jackson 2003; Rodríguez-Rodríguez, Alfaro-Saiz, and Carot 2020a; Wold et al. 2001). From the application of the PCA, the expert group will be able to identify the KPIs that are maintaining meaningful cause-effect relationships over time; in other words, changes in the values of some KPIs lead to changes in the values of other KPIs. Once the correlated KPIs have been identified, the decision-makers in the expert group choose which of these KPIs are the most important (effect KPIs) from an organizational point of view (sustainability in this research) and then identify the main cause KPIs associated with these effect KPIs. The main steps to apply are:

- Take the initial frequency standardized matrix (study variables, KPIs, in columns and observations in rows).
- Apply statistical software that supports PCA analysis.
- Decide, regarding the data variability explained, how many principal components to retain for the study.
- Identify the KPIs that are forming each of the retained principal components.
- Define the most important KPIs to be reached (the effect KPIs).
- Identify which are the KPIs (called cause KPIs) that most influence these effect KPIs.

Phase 5. Results discussion

Based on the results achieved in the previous phase, decision-makers will be able to identify the action plans that are associated with the strategic objectives linked to both the cause-and-effect KPIs. They can then establish an activation prioritization of such action plans: firstly, the action plans associated with the strategic objectives linked to the KPIs that have more impacts on the most important effect KPIs; secondly, the action plans associated with the strategic objectives linked to the most important effect KPIs; and thirdly, the remaining action plans associated with the strategic objectives linked to other KPIs. By carrying out this activation prioritization of the action plans, decision-makers will improve the probability of achieving the values of the most important effect KPIs, as well as saving organizational resources when achieving the strategic objectives.

Case study

Case study description

The case study was developed at Castelló de la Plana City Council which had just approved its local waste management plan. Castelló de la Plana is a Spanish Mediterranean city, capital of the province of Castellón, in the north of the Valencia Region, and has a population of 172,589 (INE 2021). Waste generation in the city exceeds 1.25 kg per resident/day and waste collection is divided into five fractions (glass, packaging, paper & cardboard, biowaste, and mixed MSW) according to current regulations (Spain 2022). The city also has a network of recycling centers, both fixed and mobile, for depositing specific waste either because of its volume (e.g., household appliances) or its hazardous nature (e. g., engine oils, solvents, X-ray sheets). Finally, it has a small number of specific bins for the collection of cooking oil, textiles, and batteries, respectively. With all these resources, the current separation rate at source is 15.30% by weight of the MSW managed.

Mixed MSW is the majority fraction by weight and is deposited in "all-in-one" containers. These are collected with a rear-loading and side-loading collection service structured in 14 daily routes. Selective biowaste collection is carried out through six routes, with alternative frequencies, and contributes 3.66% of the total municipal weight. For the selective collection of paper & cardboard, which represents 3.59% of the total by weight, the service has three top-loading and one side-loading collection trucks, as is the case with the selective collection of packaging, which contributes 2.36% of the total municipal waste weight. The average collection frequency is three days a week. The fraction with the lowest percentage by weight of the total is glass (2.27%), whose collection is carried out with top-loading collection trucks once a fortnight.

Regarding the main MSW fractions treatment: packaging, paper & cardboard, and glass are deposited directly at the facilities of the recyclers for sorting. Mixed MSW and biowaste collected in the city are deposited at the transfer plant of a provincial public company that manages the treatment and valorization of these fractions (covering 63% of the province's population). In this plant, bulky and improperly disposed of waste in containers is separated and the rest is compacted for transport to a composting plant. Once the waste arrives in the composting plant, the usual mechanical and biological treatments are carried out. MSW is subjected to various mechanical treatments for the recovery of metals, plastics, paper, etc. The remaining organic matter and biowaste that are collected selectively are aerobically processed through fermentation, maturation, and refining. Due to the age of the facilities, the current rejection rate is near 75% (Reciplasa, 2023) and the final destination is a controlled landfill.

Case study development

Phase 1. Expert group definition

To apply the methodology, a group of experts was created that included: three senior managers (one from each of the three main MSW management companies in Eastern Spain); two municipal engineers; a PhD engineer from the Universitat Jaume I; two PhDs engineers from the Universitat Politècnica de València; two local political representatives; and four environmental educators from the provincial MSW management board. All decisions were made consensually.

The expert group had four face-to-face meetings within a period of three months.

Phase 2. KPIs and action plan selection

From a performance measurement perspective, the Castelló de la Plana City Council had defined the following elements in its 2022 local waste management plan (Ajuntament de Castelló, 2022):

- 36 strategic objectives.
- 98 action plans
- 36 KPIs.

An informative meeting was first held with the experts to gather data. The main objective was to obtain initial proposals for KPIs and group them into the three dimensions of sustainability. Such a proposal was written and explained by the facilitator and then emailed to the experts. Table 1 presents the description of the 36 KPIs classified into three sustainability dimensions.

Table 2 describes the 36 strategic objectives and their 98 associated action plans, as well as their link to the KPIs.

The KPIs were then linked with the objectives and associated action plans shown in Table 2.

Phase 3. Data matrix

In this phase, annual data for the 36 KPIs was collected and the resulting data matrix is presented in Table 3, where it is possible to observe the 36 KPIs of the study in rows, observations in columns, and the historical value of these KPI for the years 2017–2022.

The historical data is a highly compact data matrix, where most the KPIs have historical data for all six years of the study. The exceptions are S5 and ENV16 – which although included in the 2022 planning, were only measured in 2017, and so the expert group decided to exclude them from the next phase of data analysis.

Phase 4. Data analysis

The PCA technique was applied to the data matrix, using SPSS v16.0 and following a rotation method of Varimax normalization and Kaiser criterion. Two principal components were then retained for the study as they explained 99% of the data variability – as shown in Table 4.

The two principal components retained for the study are formed by the KPIs, and it is possible to identify which of these two principal components contribute most by making a graphical analysis of the orthogonal situation of the KPIs within the two principal components (see Figure 2).

By considering the 45º line from the origin (in green in Figure 2), it is possible to classify an orthogonal distribution of the KPIs into one of the two principal components depending on which principal component is closest. Figure 2 shows how the variables (KPIs) are graphically situated within two principal components: PC1 on the x-axis and PC2 on the y-axis. Each KPI contributes to the formation of the principal components, but they can be classified as more related to one of the principal components than to another depending on the graphical proximity. Two green lines have been added to the graph to make it easier to understand to which principal component each KPI is closest:

Table 1. KPIs description.

Indicator	Description	Indicator	Description
E1	Cost of the biowaste collection service per resident and year (€/res.)	S6	Number of public contracts that incorporate sustainability criteria in waste management (unit)
E2	Cost of the container collection service per resident and year (€/res.)	S7	Average time for resolution of complaints in a year (days)
E3	Cost of the paper & cardboard collection service per resident and year (€/res.)	ENV1	Collection service emissions per year (kg CO2/res.)
E4	Cost of the mixed waste collection service per resident and year (€/res.)	ENV2	Annual water footprint of the waste collection service (liters/res.)
E5	Cost of the glass waste collection service per resident and year (€/res.)	ENV3	Selective collection of biowaste percentage with respect to total household waste (%)
E6	Cost of the mixed waste disposal service per resident and year (€/res.)	ENV4	Selective collection of packaging percentage with respect to total household waste (%)
E7	Cost of the mixed waste transfer service per resident and year (€/res.)	ENV5	Selective collection of paper & cardboard percentage with respect to total household waste (%)
E8	Annual cost of maintenance and cleaning of packaging containers per resident and year (€/res.)	ENV6	Selective collection of glass percentage with respect to total household waste (%)
E9	Annual cost of maintenance and cleaning of paper & cardboard containers per resident and year (€/res.)	ENV7	Percentage of waste collected selectively in the recycling center, compared to the city total (%)
E10	Annual cost of maintenance and cleaning of glass containers per resident and year (€/res.)	ENV8	Emissions from recovery and elimination of biowaste (kg CO2/res)
E11	Annual cost of maintenance and cleaning of mixed waste containers per resident and year (€/res.)	ENV9	Emissions from recovery and disposal of packaging waste (kg CO2/res.)
E12	Annual investments for waste management improvement projects per resident and year (€/res.)	ENV10	Emissions from recovery and elimination of paper & cardboard waste (kg CO2/res.)
E13	Annual investment in awareness campaigns per resident and year (€/res.)	ENV11	Emissions from recovery and disposal of glass waste (kg CO2/res.)
S1	Number of people participating in campaigns per year (unit)	ENV12	Number of batteries collected selectively per year (kgs/res.)
S2	Number of sanctions applied per year (unit)	ENV13	Amount of vegetable oil collected selectively per year (gr./res.)
S3	Number of complaints received per year (unit)	ENV14	Percentage of complete contribution areas with all the fractions with respect to the total number of collection areas (%)
S4	Number of interactions due to the impact of communication campaigns in social media (unit)	ENV15	Amount of textile waste collected per year (kgs/res.)
S5	Number of adapted containers available for residents with functional diversity per year (unit)	ENV16	Number of uncontrolled waste dumping points in the city

- Principal component 1 (x-axis): E2, E3, E4, E5, E8, E9, E10, E11, S2, S3, S4, ENV5, ENV9, ENV10, ENV11, ENV13, ENV14, ENV15.
- Principal component 2 (y-axis): E1, E6, E7, E12, E13, S1, S6, S7, ENV1, ENV2, ENV3, ENV4, ENV6, ENV7, ENV8, ENV12.

The expert group used its experience and knowledge of the organization's waste management process (past and present) to identify which of the effect KPIs are most important:

• E6: This KPI represents the cost of the mixed waste disposal service per resident and year expressed in €/res. These costs include labor, materials, machinery, and indirect costs of the disposal plant for one year. Once the total cost has been obtained, it is divided by the population registered in the municipality for the year of measurement.

• S1: This KPI represents the number of people participating in each of the environmental awareness campaigns carried out in the city during a year.

• S3: This KPI measures the annual number of complaints received by the council regarding waste management (location, quantity, cleanliness and maintenance of containers, transit of the vehicle fleet, uncontrolled dumping, recycling center services, etc.).

• ENV1: This KPI represents the annual amount of CO^2 emissions (kgs) emitted by the collection services per resident. It is calculated from the sum of emissions (produced by the fractions of mixed waste, biowaste, packaging, paper & cardboard, and glass) and divided by the total population.

• ENV2: This KPI refers to the total volume of fresh clean water used by the waste collection service for cleaning containers and vehicles.

• ENV3: This KPI is the ratio obtained by dividing the annual amount of biowaste collected by the total annual amount of containerized waste collected (mixed waste, biowaste, packaging, paper & cardboard and glass).

Table 2. KPIs, objectives, and associated action plans.

Indicator	Objective	Action plans
E1	In five years, do not exceed a 15% increase in the annual cost of collecting this fraction in 2022	1. Study the implementation of new collection systems for which better separation ratios were verified 2. Promote and subsidize home and community composting. 3. Support the financing of a new specific transfer plant for biowaste.
E2	In five years, do not exceed a 25% increase in the annual cost of collecting this fraction in 2022	1. Increase the number of packaging containers and reach the average number for the region. 2. Install a monitoring system for packaging containers by installing fill-level sensors. 3. Promote the use of reusable packaging and bulk products.
E3	In five years, do not exceed a 25five% increase in the annual cost of collecting this fraction in 2022	1. Expand the supply of paper & cardboard containers until reaching the average supply of the region. 2. Install a monitoring system for paper & cardboard containers by installing fill-level sensors. 3. Expand commercial participation in door-to-door collection systems.
E4	In five years, reduce the costs of collecting the mixed fraction by 20%	1. Reduce the number of mixed waste containers to promote the use of separative containers. 2. Homogenize containerization to optimize collection routes. 3. Implementation of payment for the generation of mixed waste.
E5	In five years, do not exceed a 25% increase in the annual cost of collecting this fraction in 2022	1. Expand the supply of glass containers to reach the average supply of the region. 2. Install a monitoring system for glass containers by installing fill-level sensors. 3. Optimization of routes and frequencies of collection of this waste.
E6	In five years, do not exceed the annual cost of disposing this fraction in 2022	1. Implement an electronic container closure and user identification system in certain areas. 2. Optimize the warning system and programming of scheduled and unscheduled bulky waste collection routes. 3. Promote the reduction of waste generation through campaigns and incentives.
E7	In five years, do not exceed the annual cost of collecting this fraction in 2022	1. Optimize the distribution, routes, and collection frequencies of this fraction to conduct the collections when containers are full. 2. Modernize the waste management process at the transfer plant to optimize the system and improve its performance. 3. Study and project an optimal location for a new transfer plant.
E8	In five years, do not exceed a 15% increase in the annual cost of maintenance and cleaning of containers for this fraction in 2022	1. Reduce water consumption by cleaning packaging containers using machinery with water-saving technological solutions. 2. Implement an inspection system for light packaging containers that makes it possible to establish optimal cleaning frequencies. 3. Install an internal temperature monitoring system for packaging containers and an accelerometer to prevent failures.
E9	In five years, do not exceed a 15% increase in the annual cost of maintenance and cleaning of containers for this fraction in 2022	1. Reduce water consumption for cleaning paper & cardboard containers by using machinery with water-saving technological solutions. 2. Implement an inspection system for paper & cardboard containers that makes it possible to establish optimal cleaning frequencies. 3. Install an internal temperature monitoring system for packaging containers and an accelerometer to prevent failures.
E10	In five years, do not exceed the annual cost of maintenance and cleaning of containers for this fraction in 2022	1. Reduce water consumption for cleaning glass containers by using machinery with water-saving technological solutions. 2. Implement an inspection system for glass containers that makes it possible to establish optimal cleaning frequencies. 3. Install an internal temperature monitoring system for packaging containers and an accelerometer to prevent failures.
E11	In five years, do not exceed the annual cost of maintenance and cleaning of containers for this fraction in 2022	1. Reduce water consumption for cleaning biowaste containers by using machinery with water-saving technological solutions. 2. Conduct awareness campaigns on the use of closed bags for the deposit of waste in the container. 3. Introduce container model with fewer mobile elements.
E12	In five years, increase by 10% the resources allocated to investments in I+D+I projects	1. Install door-to-door systems in certain areas of the city for the fractions of biowaste, packaging, paper & cardboard, and mixed waste. 2. Implement positioning and control tools in the vehicle fleet. 3. Plan for the creation of complete collecting areas in industrial areas.
E13	In five years, reach an expense per resident and year of 0.5 euros	1. Carry out at least four campaigns a year on the prevention and separation of waste. 2. Carry out a pilot campaign on the collection of medical waste. 3. Modernization of municipal websites and social networks.
S1	In five years, reach 20,000 annual participants	1. Distribution of materials to promote separation at source. 2. Maintain an environmental education team made up of five members. 3. Improve dissemination of positive results and legal waste obligations.

(*Continued*)

Table 2. (Continued).

Indicator	Objective	Action plans
S2	In five years, do not having exceeded the number of sanctions applied during the year 2022	1. Implement a control system for uncontrolled dumping points (reinforcement with drones). 2. Develop a disciplinary procedure in the new ordinance on waste management. 3. Educate on waste management.
S3	In five years, not having exceeded an increase of more than 10% in complaints received during the year 2022	1. Teach collection drivers about more efficient driving that reduces noise pollution. 2. Conduct campaigns that promote the use of the recycling center against the uncontrolled dumping of large volume waste. 3. Avoid container overflow with adequate containerization and collection frequencies.
S4	In five years, increase citizen participation in social media to 4,000 interactions per year	1. Design a social media communication plan that publishes information on the prevention and separation of waste with a suitable frequency. 2. Update the corresponding sections of the city council website that include information on waste management.
S5	In five years, having adapted 200 containers for people with functional diversity compared to those existing in 2022	1. Detect the locations where there is a need to have adapted containers. 2. Adapt and install at least 200 selective containers for packaging, paper & cardboard, and glass. 3. Improve container renewal frequency.
S6	In five years, reach 30 contracts per year that include sustainability criteria	1. Teach sustainability waste criteria to city council technicians who conduct public bidding processes 2. Design and publish a practical guide on sustainability criteria. 3. Promote sustainability criteria to construction contracts especially focused on waste separation.
S7	In five years, improve the citizen support systems to resolve every complaint within 15 days	1. Implement a procedure for handling complaints and provide the corresponding training to personnel assigned to these tasks. 2. Strengthen coordination between the service concession company and the city council by installing standardized procedures and geolocalization.
ENV1	In five years, not having exceeded a 5% increase in emissions compared to those of 2022	1. Replace 50% of the fleet of diesel and/or gas vehicles with other less polluting technologies. 2. Teach collection drivers efficient driving that reduces emissions. 3. Conduct proper vehicle maintenance and a renovation plan.
ENV2	In five years, have half the annual consumption of drinking water compared to 2022	1. Use of reclaimed water in areas of the city where this network exists. 2. Teach workers water-saving techniques. 3. Optimize cleaning frequencies so that they are carried out only when strictly necessary.
ENV3	In five years, increase the percentage of collection of this fraction by 10% compared to 2022	1. Install an electronic closure system for biowaste containers and user identification in certain areas. 2. Carry out a study on the characterization of biowaste for one year. 3. Design a campaign adapted to the need to reduce improper detections, if necessary.
ENV4	In five years, increase the collection percentage of this fraction by 10% compared to 2022	1. Install at least three mobile platforms in the city center area to deposit the separative fractions. 2. Promote selective collection at events by placing containers and their subsequent collection. 3. Carry out communication and environmental education campaigns for the correct separation of packaging waste.
ENV5	In five years, increase the collection percentage of this fraction by 10% compared to 2022	1. Expand the paper and cardboard waste door-to-door collection system to the entire downtown district, as well as the central area. 2. Strengthen the collection during the annual periods of greatest production by increasing the paper & cardboard fraction collection frequencies. 3. Carry out communication and environmental education campaigns for the correct separation of paper & cardboard waste.
ENV6	In five years, increase the collection percentage of this fraction by 10% compared to 2022	1. Implement a door-to-door glass collection system for hotels and restaurants that generate more than 25 kgs per week. 2. Glass waste separation plan at events through the temporary relocation of containers adapted to large producers. 3. Carry out communication and environmental education campaigns for the correct separation of glass waste.
ENV7	In five years, increase the collection percentage in the recycling center by 15% compared to 2022	1. Information campaign on the different locations and hours of the recycling centers through signposting of the locations, billboards, publications on social media and street action. 2. Carry out a campaign on pruning waste that encourages the use of the recycling center for this type of waste. 3. Install a computerized user identification system in the recycling center, which complies with the legislation regarding the collection of home appliances.

(*Continued*)

Table 2. (Continued).

Indicator	Objective	Action plans
ENV8	In five years, do not exceed a 20% increase in emissions compared to those of 2022	1. Implement self-composting in at least 50% of urban gardens, infant and primary schools. 2. Implement self-composting in at least 25% of single-family homes. 3. Develop campaigns to avoid food waste that involve the reduction of biowaste management.
ENV9	In five years, do not exceed a 20% increase in emissions compared to those of 2022	1. Implement the container return system in certain areas of the city. 2. Carry out information campaigns that reduce the number of improper materials collected in packaging containers. 3. Encourage the use of glass packaging.
ENV10	In five years, do not exceed a 20% increase in emissions compared to those of 2022	1. Install cardboard compactors in high production areas of this waste such as industrial estates or shopping streets. 2. Inform large paper & cardboard producers of the schedules and collection points that were defined to optimize collection routes. 3. Establish a circuit between commerce and cardboard manufacturers to promote the circular economy.
ENV11	In five years, do not exceed a 20% increase in emissions compared to those of 2022	1. Optimize the distribution, routes, and collection frequencies of this fraction to carry out collections when the container is full. 2. Promote the refund and return system in hotels and restaurants to optimize the return rate through information campaigns and delivery of materials.
ENV12	In five years, reach an annual amount collected from this fraction of 1kg/res/year	1. Carry out an information campaign through street actions to publicize the locations and importance of separating batteries. 2. Implement a bonus system for the delivery of batteries in the recycling centers.
ENV13	In five years, reach an annual amount collected from this fraction of 200 g/res in a year	1. Study the distribution of oil containers and relocate, if necessary, to reach a coverage of 100% of the city. 2. Carry out an information campaign that includes the delivery of funnels to reach at least 13,000 households. 3. Reinforce the mobile recycling center services.
ENV14	In five years, at least 21% of the locations where there is a biowaste container will be full collection areas	1. Move the necessary containers of packaging, paper & cardboard, glass and mixed waste to create at least 230 complete contribution areas from the locations of the biowaste containers. 2. Implement closed contribution areas with access control for five fractions of waste in residential estates (mixed waste, biowaste, packaging, paper & cardboard and glass). 3. Reduce the number of containers for the mixed fraction.
ENV15	In five years, reach an annual amount collected from this fraction of 4.3kg/res in a year	1. Increase the number of containers until it reaches the average for the region. 2. Design a campaign to promote the use of textile containers for companies that produce this type of waste. 3. Conduct communication and environmental education campaigns for the separation of textiles.
ENV16	In five years, reduce 30% the number of illegal dumping points	1. Increase surveillance through police collaboration. 2. Removal of containers where this problem exists. 3. Promotion of the use of recycling centers.

- ENV14: This KPI is the ratio obtained from the number of complete (all waste fractions) containerized areas with respect to the total number of points on the public road with single containers (biowaste, packaging, paper & cardboard, and glass).

Once this is done, it is time to identify the main cause KPIs associated with the effect KPIs. Figure 2 shows the symmetric position of the KPIs with respect to the axes and so reveals the groups of KPIs with a higher cause-effect correlation (Jackson 2003). For the effect KPIs, Table 5 shows the meaningful relationships between KPIs (in columns) and the seven identified effect KPIs and the main cause KPIs (in rows). This Table has been derived by following analytical procedures. Based on the results shown in the previous figure, and following the PCA basis, it is possible to identify the variables that are maintaining some meaningful relationships over time. These variables are those that are grouped around a principal component standing directly together and symmetrically. For instance, regarding the KPI E6 (column "Effect KPI E6" in Table 5), which is defined as one of the most important KPIs, the KPIs that are closest graphically are:

- Directly: E1, E7, E8, E12, E13, S1, S6, ENV1, ENV2, ENV3 and ENV4.
- Symmetrically: S7 and ENV12.

The relationships established above show that E8 is the KPI cause with the greatest influence (influencing all seven effect KPIs). After this, the following KPI causes stand out: E1, E7, E12, E13, S6, S7, ENV3 and ENV12, as well as those which influence five effect KPIs (E6, S1, ENV1, ENV2, ENV3). There is a group of KPIs (E6, S1, ENV1, ENV2, ENV4) that influences four effect KPIs

Table 3. Historical values KPIs.

Indicator	Description	2017	2018	2019	2020	2021	2022
E1	Cost of the biowaste collection service per resident and year (€/res.)	-	-	-	1.77	5.38	5.38
E2	Cost of the container collection service per resident and year (€/res.)	2.48	2.49	2.51	2.71	3.34	4.29
E3	Cost of the paper & cardboard collection service per resident and year (€/res.)	3.22	3.24	3.25	3.15	3.16	3.76
E4	Cost of the mixed waste collection service per resident and year (€/res.)	31.55	31.70	31.86	30.32	29.33	34.71
E5	Cost of the glass waste collection service per resident and year (€/res.)	0.65	0.65	0.66	0.64	0.64	0.75
E6	Cost of the mixed waste disposal service per resident and year (€/res.)	32.00	32.40	33.46	33.17	36.57	38.87
E7	Cost of the mixed waste transfer service per resident and year (€/res.)	5.65	5.72	5.90	5.85	6.45	6.86
E8	Annual cost of maintenance and cleaning of packaging containers per resident and year (€/res.)	0.52	0.52	0.53	0.59	0.77	1.01
E9	Annual cost of maintenance and cleaning of paper & cardboard containers per resident and year (€/res.)	0.52	0.52	0.53	0.51	0.52	0.64
E10	Annual cost of maintenance and cleaning of glass containers per resident and year (€/res.)	0.52	0.52	0.53	0.51	0.51	0.60
E11	Annual cost of maintenance and cleaning of mixed waste containers per resident and year (€/res.)	4.67	4.69	4.72	4.57	4.58	5.42
E12	Annual investments for waste management improvement projects per resident and year (€/res.)	0.63	0.63	0.62	0.62	0.62	0.62
E13	Annual investment in awareness campaigns per resident and year (€/res.)	0.37	0.37	0.37	0.36	0.37	0.37
S1	Number of people participating in campaigns per year (unit)	7651	2704	28,400	663	16,630	17,720
S2	Number of sanctions applied per year (unit)	2	2	0	1	3	15
S3	Number of complaints received per year (unit)	4182	6606	7013	8331	8833	9996
S4	Number of interactions due to the impact of communication campaigns in social media (unit)	38	27	52	2799	2968	2035
S5	Number of adapted containers available for people with functional diversity per year (unit)	25					
S6	Number of public contracts that incorporate sustainability criteria in waste management (unit)	1	3	5	6	11	12
S7	Average time for resolution of complaints in a year (days)	26.5	23.3	25.2	21.7	18.9	17.6
ENV1	Collection service emissions per year (kg CO2/res.)	7.54	7.89	8.20	8.52	9.14	9.18
ENV2	Annual water footprint of the waste collection service (liters/res.)	22.35	22.17	22.06	23.28	26.43	26.67
ENV3	Selective collection of biowaste percentage with respect to total household waste (%)	0.00	0.00	0.09	1.26	4.11	4.27
ENV4	Selective collection of packaging percentage with respect to total household waste (%)	1.75	1.96	2.16	2.69	2.74	2.74
ENV5	Selective collection of paper & cardboard percentage with respect to total household waste (%)	3.27	3.62	4.06	4.37	4.32	4.15
ENV6	Selective collection of glass percentage with respect to total household waste (%)	2.01	2.06	2.18	2.65	2.37	2.60
ENV7	Percentage of waste collected selectively in the recycling center, compared to the city total (%)	7.55	9.92	9.74	9.37	10.71	9.59
ENV8	Emissions from recovery and elimination of biowaste (kg CO2/res)	0.00	0.00	0.12	1,64	5.72	4.94
ENV9	Emissions from recovery and disposal of packaging waste (kg CO2/res.)	0.81	0.92	1.04	1.20	1.31	1.09
ENV10	Emissions from recovery and elimination of paper & cardboard waste (kg CO2/res.)	0.71	0.80	0.91	0.92	0.97	0.77
ENV11	Emissions from recovery and disposal of glass waste (kg CO2/res.)	0.24	0.25	0.27	0.30	0.29	0.26
ENV12	Number of batteries collected selectively per year (kgs/res.)	0.08	0.07	0.08	0.06	0.04	0.04
ENV13	Amount of vegetable oil collected selectively per year (gr./res.)	8.26	38.04	101.28	113.06	112.32	86.08
ENV14	Percentage of complete contribution areas with all the fractions with respect to the total number of collection areas (%)	0.00	0.00	0.00	13.48	14.73	18.07
ENV15	Amount of textile waste collected per year (kgs/res.)	2.50	2.53	2.45	2.68	2.98	2.30
ENV16	Number of uncontrolled waste dumping points in the city	25					

Table 4. Data variability explained by the principal components.

	Eigenvalues		
Components	Total	% of the variance	% Acumulated
1	25,102	73,830	73,830
2	8,898	26,170	100,000
3	1,365E−15	4,016E−15	100,000
4	8,567E−16	2,520E−15	100,000
5	7,750E−16	2,279E−15	100,000
6	6,812E−16	2,003E−15	100,000
7	5,596E−16	1,646E−15	100,000
8	5,157E−16	1,517E−15	100,000
9	4,019E−16	1,182E−15	100,000
10	3,779E−16	1,111E−15	100,000
11	3,145E−16	9,249E−16	100,000
12	2,998E−16	8,817E−16	100,000
13	2,388E−16	7,023E−16	100,000
14	1,992E−16	5,860E−16	100,000
15	1,734E−16	5,100E−16	100,000
16	1,392E−16	4,094E−16	100,000
17	7,346E−17	2,161E−16	100,000
18	5,322E−17	1,565E−16	100,000
19	1,958E−17	5,759E−17	100,000
20	−3,657E−17	−1,075E−16	100,000
21	−4,082E−17	−1,201E−16	100,000
22	−9,379E−17	−2,758E−16	100,000
23	−1,627E−16	−4,786E−16	100,000
24	−1,779E−16	−5,232E−16	100,000
25	−2,016E−16	−5,928E−16	100,000
26	−2,404E−16	−7,070E−16	100,000
27	−3,268E−16	−9,613E−16	100,000
28	−3,514E−16	−1,033E−15	100,000
29	−4,047E−16	−1,190E−15	100,000
30	−4,462E−16	−1,312E−15	100,000
31	−5,073E−16	−1,492E−15	100,000
32	−6,138E−16	−1,805E−15	100,000
33	−7,634E−16	−2,245E−15	100,000
34	−1,352E−15	−3,977E−15	100,000

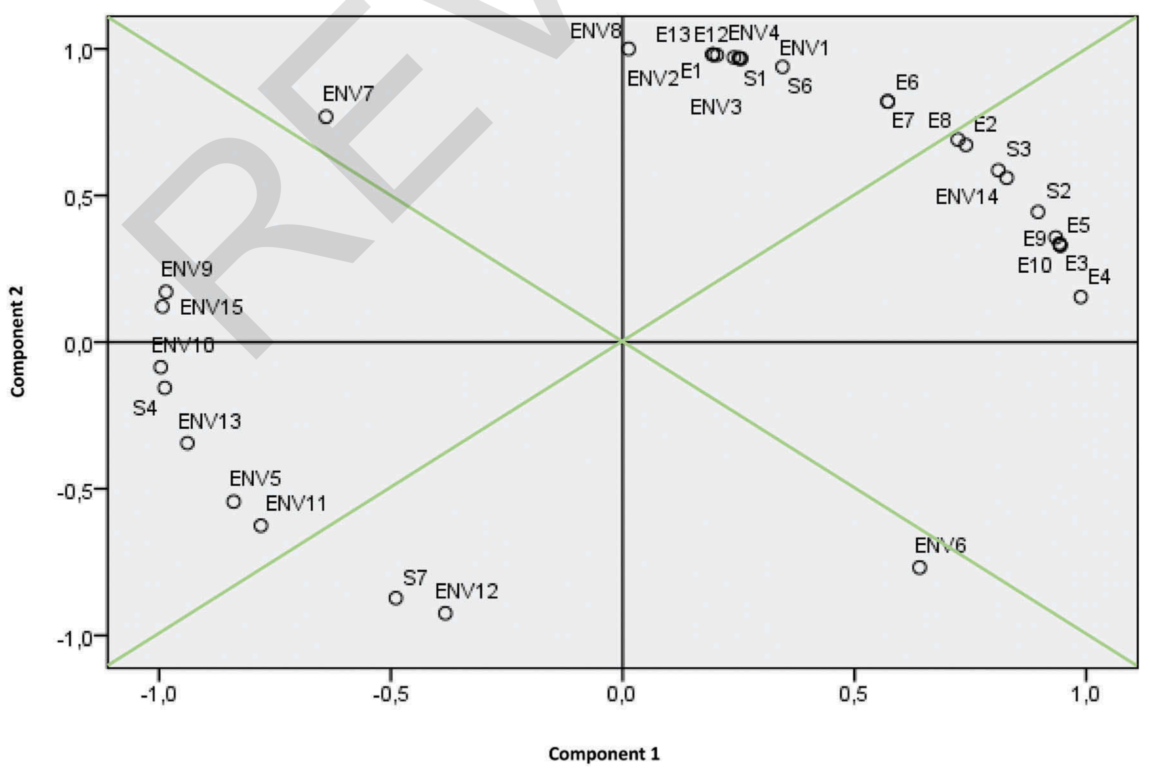

Figure 2. Graphic shows the KPI orthogonal situation within the principal components.

Table 5. Cause-effect relationships between KPIs.

Cause KPI	Effect KPI E6	Effect KPI S1	Effect KPI S3	Effect KPI ENV1	Effect KPI ENV2	Effect KPI ENV3	Effect KPI ENV14
E1	X	X		X	X	X	
E2			X				X
E3			X				X
E4			X				X
E5			X				X
E6		X		X	X	X	
E7	X	X		X	X	X	
E8	X	X	X	X	X	X	X
E9			X				X
E10			X				X
E12	X	X		X	X	X	
E13	X	X		X	X	X	
S1	X			X	X	X	
S2			X				X
S3							X
S4			X				X
S6	X	X		X	X	X	
S7	X	X		X	X	X	
ENV1	X	X			X	X	
ENV2	X	X		X		X	
ENV3	X	X		X	X	X	
ENV4	X	X		X	X		
ENV5			X				X
ENV10			X				X
ENV11			X				X
ENV12	X	X		X	X	X	
ENV13			X				X
ENV14			X				

and another group of KPIs (E2, E3, E4, E5, E9, E10, S2, S4, ENV5, ENV10, ENV11, ENV13) that influence two effect KPIs. The following phase establishes specific organizational recommendations that arise from this data analysis.

Phase 5. Results discussion

Based on the results achieved in the previous phase, decision-makers were able to identify the action plans that are associated with the strategic objectives linked to both the cause-and-effect KPIs. From analyzing the results of Table 5, the cause KPIs are ranked from more to less influence (measuring this influence as the number of effect KPIs they influence). E8 is the most influential cause KPI, as it influences all seven effect KPIs. This means that the three action plans that are associated with the strategic objective that E8 is measuring (namely, "do not exceed in five years a 15% increase in the annual cost of maintenance and cleaning of containers for this fraction in 2022") should be activated first, as these action plans will contribute to reaching the strategic objective – as well as those associated with the effect KPIs that E8 is directly affecting:

- E6: cost of the mixed waste disposal service per resident and year.
- S1: number of people participating in campaigns per year.
- S3: number of complaints received per year.
- ENV1: collection service emissions per year.
- ENV2: annual water footprint of the waste collection service.
- ENV3: selective collection of biowaste percentage with respect to total household waste.
- ENV14: percentage of complete contribution areas with all the fractions with respect to the total number of collection areas.

Table 6 shows the action plan prioritization produced when carrying out this analysis for all the identified cause KPIs. Table 6 also shows the main KPI causes identified (E8, E1, E7, E12, E13, S6, S7, ENV3 and ENV12), the KPIs they affect (from the seven identified in the previous phase as the most important to be achieved), and the 25 action plans associated with the strategic objectives of the cause KPIs. These plans are then prioritized in the order of activation.

Decision-makers will then have available a prioritization of action plans for the whole performance system that have practical and theoretical implications.

Practical implications

The main aim of any performance measurement system is to ensure that the defined strategic objectives are reached in the most efficient way. The proposed methodology provides a novel and efficient approach for MSW decision-makers because it identifies – with the application of objective rather than subjective analytical

Table 6. Action plan prioritization.

KPI cause	KPI effect	Action plan prioritization
E8	E6, S1, S3, ENV1, ENV2, ENV3, ENV14	1. Reduce water use for cleaning packaging containers by using machinery with water-saving technological solutions. 2. Implement an inspection system for light packaging containers that enables optimal cleaning frequencies. 3. Install an internal temperature monitoring system for packaging containers and an accelerometer to prevent failures.
E1	E6, S1, ENV1, ENV2, ENV3	1. Study new collection systems for better separation ratios. 2. Promote and subsidize home and community composting. 3. Support the financing of a new specific transfer plant for biowaste.
E7	E6, S1, ENV1, ENV2, ENV3	1. Optimize the distribution, routes, and collection frequencies of this fraction to conduct collections when the containers are full. 2. Modernize the waste management process at the transfer plant to optimize the system and improve performance. 3. Study and project an optimal location for a new transfer plant.
E12	E6, S1, ENV1, ENV2, ENV3	1. Install door-to-door systems in certain areas of the city for the fractions of biowaste, packaging, paper & cardboard, and mixed waste. 2. Implement positioning and control tools in vehicle fleet. 3. Plan for the creation of complete collecting areas in industrial areas.
E13	E6, S1, ENV1, ENV2, ENV3	1. Conduct at least four campaigns a year on the prevention and separation of waste. 2. Carry out a pilot campaign on collection of medical waste. 3. Modernization of municipal websites and social networks.
S6	E6, S1, ENV1, ENV2, ENV3	1. Teach city council technicians who conduct public bidding processes about sustainability waste criteria. 2. Design and publish a practical guide on sustainability criteria. 3. Promote sustainability criteria to construction contracts especially focused on waste separation.
S7	E6, S1, ENV1, ENV2, ENV3	1. Implement a procedure for handling complaints and provide the corresponding training to personnel assigned to these tasks. 2. Strengthen coordination between the service concession company and the city council by installing standardized procedures and geo-localization.
ENV3	E6, S1, ENV1, ENV2, ENV3	1. Install electronic closure systems for biowaste containers and user identification in certain areas. 2. Carry out a study on the characterization of biowaste for one year. 3. Design a campaign adapted to the need to reduce improper detections, if necessary.
ENV12	E6, S1, ENV1, ENV2, ENV3	1. Conduct an information campaign through street actions to publicize the locations and importance of separating batteries. 2. Implement a bonus system for delivery of batteries in recycling centers.

procedures – the order of activation for action plans associated with strategic objectives. It enables reaching all the defined strategic objectives by activating some of the action plans in the performance measurement system and this can provide the organization with notable resource savings. However, like all performance measurement systems, this approach must consider some specific points from a practical point of view:

- Exogeneous variables/events and how they affect the performance measurement system in the present and future. There are some interesting academic works discussing this point but the approaches are always subjective, as we do not know the future and to what extent external changes will affect future developments/performance.
- As a result of the application of this methodology, some actions plan may not be activated. This will result in cost-savings for the organization, but it is necessary to ensure that all the defined strategic objectives for the period (usually one year) are reached despite the activation of fewer action plans. Otherwise, the application of this methodology will mean that an organization achieves short-term cost savings, but compromises the achievement of other sustainability strategic objectives.
- Additionally, it is necessary to keep in mind that an effective follow-up should be carried out in the short-term to ensure that the activation of these analytically chosen action plans is truly helping achieve all the defined strategic objectives of the performance measurement system.

The application of this methodology provided the Castelló de la Plana city council with an order of activation for its 98 action plans. The council was recommended to first activate the 25 action plans associated with the strategic objectives of the cause KPIs. This will make it possible to achieve the meta values of the cause KPIs they are associated with for strategic objectives – as well as those associated with the effect KPIs. With the initial activation of these 25 action plans, the city council can later check whether it is achieving the meta values of both cause-and-effect KPIs. If so, it would not need to activate the action plans associated with the strategic objectives of the effect KPIs (whose estimated cost is €3.2 m for 2022) and the funds could be used elsewhere within the city council. If it is necessary to activate some of the action plans associated with the strategic objectives of the effect KPIs, the council would still save some money if it does not need to activate all of the plans. Therefore, the activation times of the action plans should follow Table 6 and have control and check points.

Theoretical implications

It is well known that numerous aspects (operational, economic, environmental, and social) should be considered for the optimization of MSW systems from collection to ultimate disposal (Teixeira et al. 2014). KPIs are an important tool for evaluating performance, but they provide only partial productivity measurements. Without an appropriate aggregation metric, an analysis of KPIs may result in misleading conclusions about MSW service performance (Ferreira et al. 2020). For this reason, standardized methods – such as life cycle assessment (Feiz et al. 2020), life cycle costing, cost-benefit analysis, risk assessment, eco-efficiency analysis, and social life cycle cost (Allesch and Brunner 2014) – have frequently been used. In addition to these standardized methods, multi-criteria analysis has become increasingly used in recent years (Andrade Arteaga et al. 2020; Coban, Ertis, and Cavdaroglu 2018; Habibollahzade and Houshfar 2020) for finding relationships between performance elements. However, multiple-criteria decision analysis always harbors doubts about the subjectivity of expert opinions or about the selection of KPIs (Amaral et al. 2022).

This case study has presented the results of applying a methodology for prioritizing waste management action plans which has proven effective in similar approaches found in the literature (Cai et al. 2009; Rodríguez-Rodríguez, Alfaro-Saiz, and Carot 2020b; Sanchez-Marquez et al. 2018) and could become an efficient tool for MSW management. The methodology enables objectifying decision-making since it is based on employing historical data from a wide variety of parameters to establish cause-effect relationships using statistical analysis. Combining KPIs further removes bias in evaluation (De La Barrera, Reyes-Paecke, and Banzhaf 2016), especially when appropriate correlations have been defined for contributing to synergistic decision-making (Papamichael et al. 2022).

The potential limitations of this study are mainly that it is applied to just one waste management organization, and that the results of following the suggested action plan order of activation are unavailable (which would have shown to what extent the intended resource savings are produced). This is relevant because the MSW performance measurement system is multi-dimensional and, as was observed by (Parekh et al. 2015): "the performance of some indicators is influenced by the performance of other indicators, similarly to how the cost of transportation does not only depend on manpower, machinery, spare vehicles but also depends on distance to landfill site, mode of operation i.e., departmental, contractual or public private partnership mode". This means that the recommended actions must always be followed up.

Conclusions, limitations, and future research work

This paper has presented the results of applying a methodology to prioritize the waste management action plans of the Castelló de la Plana City Council in Spain. Such a methodology is based on the performance structure of strategic objectives, action plans, and KPIs – and their structural relationships. For the study, 36 KPIs were classified into three sustainability dimensions and six years of historical values were gathered. The main cause-effect KPI relationships were identified by applying principal component analysis, and once the most important effect KPIs were identified, the main cause KPIs were indicated. Finally, a prioritized list of 25 action plans (linked to the cause KPIs via the strategic objectives) that should be activated first (from a total of 98 action plans) was produced. Activating these plans first will ensure that their values are reached, as well as the values of the chosen effect KPIs. Following this order of activation enables the city council to save resources, as the values of the effect KPIs can be achieved without activating some (or all) of the action plans linked via the strategic objectives.

Future work could include the application of other statistical techniques to find KPI cause and effects (such as factor analysis or partial least squares) and other implementations of the methodology to improve and generalize its use for any MWS organization

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About the authors

Héctor Moreno Solaz is a PhD student at the Project Management, Innovation and Sustainability Research Center (PRINS) of the Polytechnic University of Valencia (UPV), Spain.

Miguel Ángel Artacho Ramírez is PhD, lecturer at the Polytechnic University of Valencia (UPV), Spain, and Director of the Project Management, Innovation and Sustainability Research Center (PRINS).

Víctor Andrés Cloquell Ballester is PhD, Associate Professor at the Polytechnic University of Valencia (UPV), Spain, and head of sustainability in the Project Management, Innovation and Sustainability Research Center (PRINS).

Cristóbal Badenes Catalán is a senior engineer, Director of Infrastructures, Public Services and Environment at the City Council of Castelló de la Plana, Spain.

ORCID

Héctor Moreno Solaz http://orcid.org/0000-0002-7750-5512

Data availability statement

The data that supports the findings of this study are available from the corresponding author [H.M.-S.] on request.

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