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Sustainability in the Portuguese agricultural sector: Assessment and multicriteria approach

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ABSTRACT: Based on data available between 2016 and 2021 from the Portuguese FADN, fifteen sustainable indicators were measured, and a compromise programming model was designed to balance environmental and economic objectives, that reveal a conflict between them. The findings identified solutions dominated by dried fruits, olive trees, sheep and goats, extensive horticulture, and beef cattle for sustainable farming planning at the national level. We conclude that the complementary between these two approaches constitute an important instrument for supporting decision-making and developing public policies focused on current sustainability paradigms.

Sostenibilidad en el sector agrícola portugués: evaluación y enfoque multicriterio

RESUMEN: A partir de los datos disponibles entre 2016 y 2021 de la RICA portuguesa, se midieron quince indicadores sostenibles y se diseñó un modelo de programación compromiso para equilibrar los objetivos medioambientales y económicos, que revelan un conflicto entre ellos. Los resultados identificaron soluciones dominadas por los frutos secos, olivos, ganado ovino y caprino, horticultura extensiva y ganado vacuno de carne para la planificación de la agricultura sostenible a nivel nacional. Concluimos que la complementariedad entre estos dos enfoques constituye un instrumento importante para apoyar la toma de decisiones y desarrollar políticas públicas centradas en los paradigmas actuales de sostenibilidad.

KEYWORDS / PALABRAS CLAVE: Economic and environmental dimensions; sustainability indicators; monitoring; planning; farming systems / Dimensiones económica y medioambiental; indicadores de sostenibilidad; monitorización; planificación; sistemas agrarios.

JEL classification / Clasificación JEL: C61, Q01, Q12

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1. Introduction

The concept of sustainability, despite its established history, continues to occupy a central focus of contemporary interest, attracting attention from both theoretical and technical perspectives. Positioned as the guiding paradigm for territorial planning and economic activities, sustainability transcends mere discourse, necessitating substantive insights to propel transformations in existing production paradigms. To catalyse these shifts effectively, there is an imperative need to develop conceptual frameworks and practical tools capable of translating theoretical ideals into tangible actions on the ground. Sustainability thus arises as a crucial concept for guiding instrumental implementation within the decision-making process.

Central to sustainability lies the effort to align the three dimensions of development –economical, environmental and social–, as outlined by Elkington (1994), thereby enhancing the overall quality of human life. This endeavour presents a significant and complex challenge, especially when incorporating it into the agri-food sector, which serves as a vital intersection in the discourse on sustainability. The adoption of a sustainable approach is increasingly recognized as a fundamental factor in enhancing competitiveness and resilience within the agri-food industry (Flores, 2018; Keichinger & Thiollet-Scholtus, 2017; Marta-Costa *et al*., 2022).

Sustainability assessment methodologies are widely regarded as essential tools in facilitating this transition (Ramos, 2019). They provide a strategic framework for monitoring production processes, thereby enhancing efficiency and optimizing environmental performance (Costa *et al*., 2020; Merli *et al*., 2018). Importantly, these methodologies have far-reaching effects beyond the confines of the industry, impacting local communities, society at large, consumers, workers, and various actors within the value chain (Luzzani *et al*., 2020).

In recent years, there have been significant efforts to adopt comprehensive indicators and indices in sustainability assessment methodologies, encompassing all economical, environmental and social dimensions. These procedures enable the selection and prioritization of alternatives, thereby mitigating the constraints associated with a reductionist approach (Boix-Cots *et al*., 2022). Given the considerable variability and interdependency among the multitude of attributes and indicators of sustainability, it is imperative that sustainability assessments be approached with utmost caution. This entails consistently considering a myriad of criteria structured within the three aforementioned dimensions (Olde *et al*., 2016).

Not only are the dimensions of sustainability crucial, but also the methods chosen to operationalize them play a relevant role in conducting an effective and robust sustainability assessment. The selection of these methods must prioritize global applicability, realism, cost-effectiveness, comparability, and comprehensibility (Hayati, 2017). The heterogeneity of methodologies used is evident, stemming from the complexity and lack of consensus surrounding the concept of sustainability, as well as the multifunctionality inherent in agriculture. Trigo *et al*. (2022) identify several key challenges in assessing the sustainability of farming systems, including the determination of appropriate scales, selection of indicators, establishment of linkages and integration among these indicators, and the practical application of assessment results within agricultural systems.

Sustainability has indeed become an indispensable concept in every decision-making process, leading to the adaptation of a diverse array of decision-making methods to accommodate it (Boix-Cots *et al*., 2022). Within this framework, the integration of sustainability assessment studies with decision support optimization models has been extensively examined in various studies (e.g., Cao *et al*., 2023; Guo *et al*., 2022; Marta-Costa, 2010; Rezaei-Moghaddam & Karami, 2008). This approach holds promise for yielding more suitable solutions to the challenges confronting the sustainability of the agri-food sector. Therefore, there is an emerging imperative to render the sector less environmentally impactful, more economically efficient, and a promoter of social equity.

The challenges faced by farming systems are inherently interconnected, necessitating a holistic approach to explore the interactions among various factors (Cao *et al*., 2023). This path involves devising suitable technological, managerial, and policy interventions, thereby embodying the principles of Environmental, Social, and Corporate Governance (ESG) responsibility (Gerber *et al*., 2023). Within this framework, indicators and parameters encompassing environmental and economic dimensions have been employed, in conjunction with the technical attributes of the systems (Cao *et al*., 2023; Deo *et al*., 2022; Guo *et al*., 2022).

However, despite the recognized importance of optimization, Guo *et al*. (2022) highlight that its practical implementation remains ambiguous. Deo *et al*. (2022) further note that many existing models are tailored to a fixed set of crops and specific agro-ecological conditions, such as those discussed in the work of Popp *et al*. (2003), or focus solely on one crop per season, failing to capture the complexity of real-world scenarios (e.g., Roy *et al*., 2009). Additionally, Deo *et al*. (2022) stress the necessity of establishing a realistic framework and developing a robust, versatile tool capable of integrating all pertinent system conditions into the decision-making process.

Overall, despite a notable growth in recent years, there is still considerable room for improvement in the utilization of multi-criteria methods for assessing agricultural sustainability (Cicciù *et al*., 2022). Indeed, decision-making based on mathematical models holds significant potential to enhance the sustainable performance of agriculture and the efficiency of resource utilization (Mellaku & Sebsibe, 2022).

In response to these challenges, the primary objective of this study is to assess and compare the sustainability of agricultural systems practiced in Portugal, utilizing the official data provided by the Farm Accountancy Information Network (FADN) spanning from 2016 to 2021. Building upon these findings, the aim is to develop a comprehensive multicriteria model capable of generating solutions to foster more sustainable agricultural planning at the national level. This model will effectively integrate environmental and economic considerations, as these are the most critical in the context being analysed, thereby contributing to a more holistic approach towards sustainable agriculture in Portugal. The insights gleaned from this analysis will not only facilitate the development of agricultural public policies aimed at promoting sustainability but also endeavor to strike a balance between production methods and meeting the population's food and raw material needs.

2. Methods

From the available data of the Portuguese FADN (2016-2021), fifteen sustainability indicators (Table 1) were identified across the three dimensions of economics, social, and environmental, aligning with the principles outlined by Elkington (1994).

The economic indicators are designed to illuminate aspects such as productive efficiency, profitability, competitiveness, and the autonomy of agricultural activities. Within the environmental domain, these indicators aim to elucidate both the potential negative impacts arising from chemical usage and resource depletion, as well as the positive effects on the environment, which may be moderated by subsidies. The social component of sustainability is demonstrated through the professionalization of agricultural activities and their contributions to sustaining local communities and broader society. These indicators were substantiated by relevant literature sources (e.g., Marta-Costa *et al*., 2022; Trigo *et al*., 2021; Trivino-Tarradas *et al*., 2019; Triviño-Tarradas *et al*., 2020) and constrained by the information accessible within the FADN dataset.

The sustainability assessment process was facilitated through the calculation of indicators, selected based on the available information from the FADN dataset. An effort was made to uphold a balanced representation of sustainability dimensions within the established matrix.

The indicators were computed at the farm scale, utilizing the average values obtained for the period from 2016 to 2021. These values were adjusted for inflation according to the INE (2023), with the reference year being 2021, chosen for its recency. This approach aligns with the procedures outlined by Cao *et al*. (2023). Subsequently, these indicators were normalized to a non-dimensional value ranging from 0 to 100, with the highest value obtained for each indicator set as the benchmark at 100. The normalization procedure adheres to economic efficiency techniques within the context of performance evaluation (Santos *et al*., 2020), and aligns with the methodologies outlined in the studies of González-Esquivel *et al*. (2020) and Marta-Costa *et al*. (2022).

TABLE 1

Sustainability indicators identified for the Portuguese farming systems using available FADN data (2016-2021)

Sustainability dimension	Indicators	Formula	Units
Environmental	Pollution by fertilizers	Fertilizers and correctives/ UAA	€/ha
	Pollution by phytopharmaceuticals	Phytopharmaceuticals /UAA	€/ha
	Energy and water consumption	Electricity, fuels and water/UAA	€/ha
	Soil traction	Fuel and lubricants/UAA	€/ha
	Environmental effects	Environmental subsidies/UAA	€/ha
Economic	Technical Efficiency	Agricultural production/ intermediate inputs	-
	Activity Profitability	Business and Family income/UAA	€/ha
	Competitiveness	Investment/UAA	€/ha
	Labor productivity	Gross Value Added/ Labor	€/AWU
	Autonomy	External costs /Real costs	-
Social	Land ownership and transferability	Own-account UAA/Total UAA	%
	Professionalization of the activity	Paid labor/Total labor	%
	Contribution to society	Taxes and fees/UAA	€/ha
	Level of remuneration	Wages paid/Wage-earner labor	€/AWU
	Dependence on subsidies	Subsidies to the activity /Gross Product	-

Legend: UAA - Utilised agricultural area; AWU - annual work unit.

Source: Own elaboration.

The value attributed to each dimension was determined by calculating the arithmetic mean of its respective indicators, while the overall sustainability index resulted from the mean of all dimensions. A similar methodology was employed in the studies conducted by Marta-Costa *et al*. (2022) and Trivino-Tarradas *et al*. (2019).

Based on the sustainability indexes, a multicriteria model was constructed (Equation 1), employing compromise programming to reconcile the pursuit of economic (Z_1) and environmental (Z_2) objectives. Owing to the limited variability observed in the identified indicators and constrained by the information available from the FADN dataset, the social dimension was not included in the analysis. Furthermore, due to the predominant absence of conflicting effects with the economic objectives, the exclusion of the social dimension did not compromise the integrity of the analysis.

The constraints delineate the set *F*, which was determined based on the production factors including Utilized Agricultural Area (UAA), labour, and stocking density used in each region. Additionally, restrictions were imposed to guarantee the minimum production of each agricultural product in accordance with the average levels observed in the FADN dataset (2016-2021). Finally, non-negativity constraints were incorporated to ensure that all variables remain positive.

$$1)\ Max\ Z_1 = \sum_i \sum_j c\_ec_{ij}\, x_{ij} \qquad [1]$$

or

$$1)\ Max\ Z_2 = \sum_i \sum_j c\_en_{ij}\, x_{ij}$$

Subjecto to:

$$2)\ \sum_i \sum_m a_{ijm}\, x_{ij} \leq b_{mj}$$

$$3)\ \sum_i \sum_n a_{ijn}\, x_{ij} \geq b_{ni}$$

$$4)\ x_{ij} \geq 0$$

The sustainability indexes of the economic and environmental dimensions are represented by c_ec_{ij} and c_en_{ij}, respectively. The decision variables, denoted by x_{ij}, correspond to the farming systems in hectares developed in each NUT II region of Portugal. Here, *i* ranges from 1 to 17, representing various farming systems (arable crops, rice, extensive horticulture and other extensive crops, intensive horticulture, quality wines, other wines, fresh fruits, dried fruits, olive trees, dairy cattle, beef cattle, sheep and goats, pigs, poultry, mixed cropping, mixed livestock, and mixed crops and livestock, respectively), and *j* ranges from 1 to 7, representing the NUT II regions: NRT (North), CTR (Center), LVT (Lisbon and Tagus Valley), ALE (Alentejo), ALG (Algarve), MAD (Madeira), and AZO (Azores), respectively.

The coefficients a_{ijm} and b_{mj} correspond to the existing needs and availabilities of the production factors used respectively. The index *m* represents the production factors and ranges from 1 to 3. Additionally, a_{ijn} and b_{ni} represent the yields obtained from each crop, livestock, and miscellaneous activity and the minimum yield to be achieved, corresponding to the average yield obtained over the previous six years according to the FADN data (2016-2021), and ranges from 1 to 3.

The compromise technique is grounded in the concept of distance (d) between (possible) solutions and the ideal point, utilizing the Lp family of metric distances. When both objectives are equally important (unitary weights, W_j), the compromise set is defined for the L_1 and L_∞ metrics, corresponding to p values of 1 and ∞, respectively (Romero & Rehman, 2003). Intermediate compromise solutions ($1 < p < \infty$) lie between these boundary solutions (Romero & Rehman, 2003). Consequently, solving two linear programming problems is adequate, aimed at minimizing the metrics L_1 and L_∞.

For the metric L_1 (i.e. $p = 1$), the optimal compromise solution, or the solution closest to the ideal point, is derived by solving Equation 2.

$$MinL_1(W) = \sum_{j=1}^{n} W_j \left| \frac{Z_j^* - Z_j(x)}{Z_j^* - Z_{*j}} \right| \quad [2]$$

Subjecto to:

$$x \in F$$

The set F comprises the constraints initially imposed on the model (Equation 1).

For the metric L_∞ ($p = \infty$), where the maximum individual deviation is minimized, the optimal compromise solution can be obtained by solving the linear programming model represented by Equation 3.

$$Min\ d_\infty = d \quad [3]$$

Subjecto to:

$$W_1 \frac{Z_1^* - Z_1(x)}{Z_1^* - Z_{*1}} \leq d$$

$$W_n \frac{Z_n^* - Z_{n1}(x)}{Z_n^* - Z_{*n}} \leq d$$

$$x \in F$$

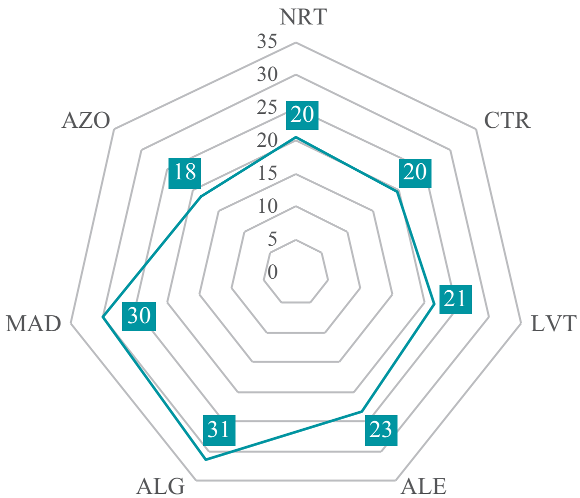
Here, W_j represents the preference weights assigned to each objective, which are considered to be of equal importance in this case (unitary weights, W_j); Z_j^* denotes the ideal point, while Z_{*j} represents the anti-ideal point.

3. Results

The results obtained from measuring the sustainability indicators outlined (Table 1) illustrate the regions that promote the most sustainable agricultural and livestock activities (Figures 1 and 2), as well as the farming systems that demonstrate the highest potential for improving sustainability (Figures 3 and 4), within the Portuguese context. These data provide insights into the distribution of the weight of each evaluation dimension in each of the indicated regions and farming systems.

FIGURE 1

Sustainability indexes achieved by the farming systems implemented in each of Portugal's NUTS II regions (%)



Legend: NRT – North; CTR – Center; LVT – Lisbon and Tagus Valley; ALE – Alentejo; ALG – Algarve; MAD – Madeira; AZO – Azores.

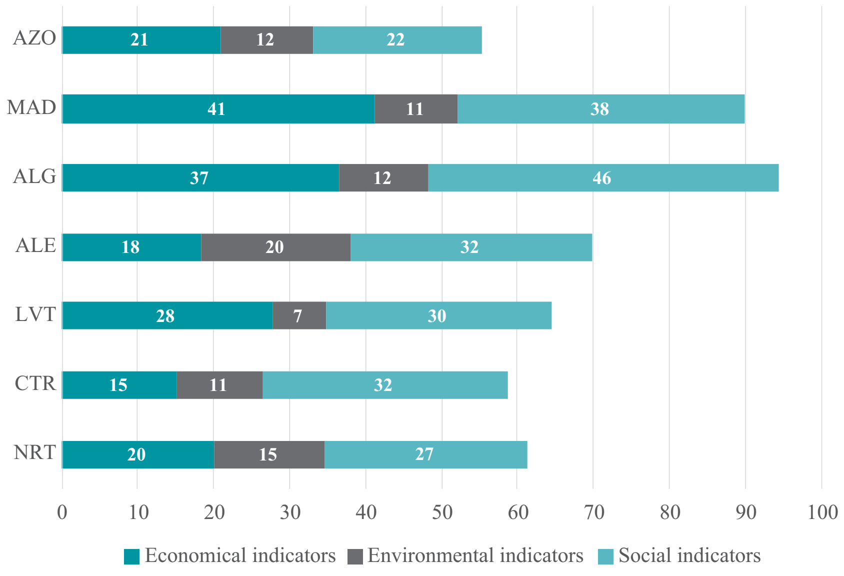
Source: Own elaboration based on FADN data (2016-2021).

The sustainability indexes obtained are generally low, with the highest recorded in the Algarve region (31, Figure 1), particularly within intensive horticulture systems (40.61). This is attributed to the substantial contribution of the economic dimension, primarily driven by indicators of labour productivity and efficiency, alongside the weight of indicators related to land ownership, transferability, and levels of remuneration corresponding to the social dimension. However, it is noteworthy that despite the relatively high sustainability index in this region and activity, the environmental dimension shows the poorest contribution (0.72).

The traditionally rural regions of Portugal, including the North, Center, Alentejo, and Azores, exhibit the lowest overall sustainability indexes (Figure 1), indicating the vulnerability of their production systems primarily due to the modest contribution of the economic dimension when compared to the remaining regions (Figure 2). However, despite the low values also observed in the environmental dimension in these more rural regions, it can be seen that they exhibit superior environmental performance nationwide and demonstrate a more balanced approach across all three dimensions of sustainability. Conversely, the Algarve and Madeira regions display the most significant disparities, but also the best in terms of the economic and social dimensions.

FIGURE 2

Sustainability dimensions achieved by the farming systems implemented in each of Portugal's NUTS II regions (%)



Legend: NRT – North; CTR – Center; LVT – Lisbon and Tagus Valley; ALE – Alentejo; ALG – Algarve; MAD – Madeira; AZO – Azores.

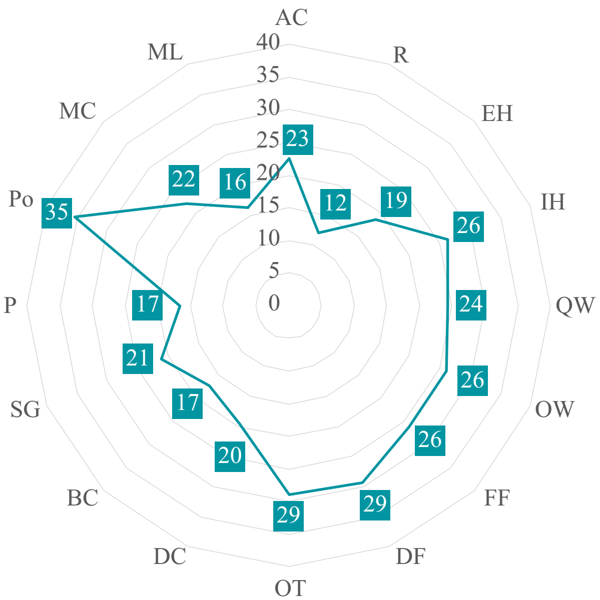
Source: Own elaboration based on FADN data (2016-2021).

In the North region, higher sustainability indexes are observed for dried fruits (29.41) and olive groves (29.03), closely followed by quality wines (25.31). Poultry stands out in the Centre region (35.34), while other wines lead in Lisbon and the Tagus Valley (26.05). In the Alentejo, olive groves record a sustainability index of 28.68. Intensive horticulture dominates in the Algarve (40.61) and Madeira (37.25), with fresh fruit, including citrus fruits, following closely in both cases. Beef cattle leads in the Azores with a sustainability index of 19.25.

Observation of production systems reveals that poultry production has attained a favorable position (Figure 3, 35), mainly attributed to its social component (Figure 4). Indeed, this ranking is largely influenced by the predominance of one sustainability dimension in most cases, rather than reflecting the desired balance across all three components as stipulated by the sustainability concept.

FIGURE 3

Sustainability indexes achieved by the farming systems implemented in Portugal (%)



Legend: AR – Arable Crops; R – Rice; EH – Extensive horticulture and other crops; IH – Intensive horticulture; QW – Quality wines; OW – Other Wines; FF – Fresh fruits; DF – Dried fruits; OT – Olive trees; DC – Dairy cattle; BC – Beef cattle; SG – Sheep and goats; P – Pigs; Po – Poultry; MC – Mixed cropping; ML – Mixed livestock; MCL – Mixed crops and livestock.

Source: Own elaboration based on FADN data (2016-2021).

However, the subsequent systems in the ranking –dried fruits and olive trees, both scoring 29 (Figure 2)– despite demonstrating a robust environmental dimension

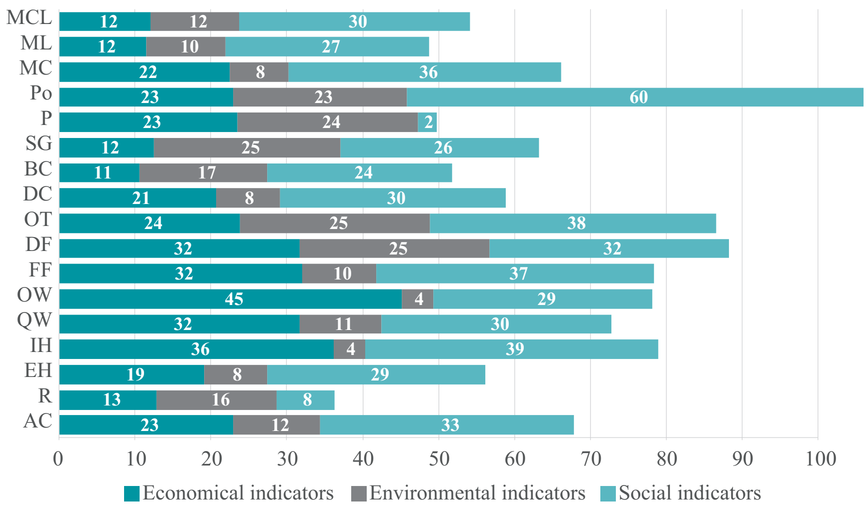
(Figure 3) compared to others, also exhibit a balanced position across various sustainability dimensions.

Building upon the results of the previous phase, a model was formulated to achieve a compromise between the economic and environmental dimensions. This model considered the sustainability indexes achieved and the data provided by the FADN (2016-2021) regarding the availability and requirements of each region for the production factors considered in the equation represented as Equation 1.

The algorithm (Equation 1) initiates with the optimization of each objective individually, yet subject to the same constraints set (F). The resulting values of each objective in the two extreme optimal solutions are depicted in the pay-off matrix shown in Table 2. These values indicate a significant level of conflict between the two objectives under consideration, highlighting a trade-off between economic profit and environmental sustainability. Specifically, maximizing the environmental dimension leads to the attainment of the ideal point (Z_j^*), while the economic objective reaches its lowest value or anti-ideal point (Z_{*j}), and viceversa.

FIGURE 4

Sustainability dimensions achieved by the farming systems implemented in Portugal (%)



Legend: AR – Arable Crops; R – Rice; EH – Extensive horticulture and other crops; IH – Intensive horticulture; QW – Quality wines; OW – Other Wines; FF – Fresh fruits; DF – Dried fruits; OT – Olive trees; DC – Dairy cattle; BC – Beef cattle; SG – Sheep and goats; P – Pigs; Po – Poultry; MC – Mixed cropping; ML – Mixed livestock; MCL – Mixed crops and livestock.

Source: Own elaboration based on FADN data (2016-2021).

Two compromise solutions (L_1 and L_∞) were obtained for the designed multicriteria model, through Equations 2 and 3, respectively. The model selected twenty-nine production systems out of a universe of 48 decision variables (Table 3).

In the North region, the model predominantly selects production systems associated with olive growing (L_1) or dried fruits (L_∞), occupying 65 % and 51 % of the available area considered for the region, respectively (equivalent to the sum of the production units included in the FADN data from 2016 to 2021). These two activities exhibit the best environmental and economic impact, respectively.

TABLE 2

Pay-off matrix

	Economic objective	Environmental objective
MAX Z_1	17,990.79	14,677.72
MAX Z_2	11,298.07	20,909.60

Source: Own elaboration.

However, this pattern is not consistent across all regions. In the Center region, the dominant farming system is associated with sheep and goats, while horticulture and other extensive crops prevail in Lisbon and the Tagus Valley. In the Alentejo, the selected systems correspond to beef cattle and small ruminants, whereas polyculture dominates in the Algarve. In Madeira, intensive horticulture (82 %) and quality wines (18 %) are recommended to occupy the available area, whereas in the Azores, based on available information, the system associated with beef cattle should be predominant.

Overall, a variety of production systems are selected across the national territory, but there is a noticeable prevalence of livestock farming in the Alentejo, Center, Azores, and even in the North.

Intensive horticulture, despite demonstrating itself to be the most sustainable option in the southern regions of Portugal, appears to be overshadowed by other activities, possibly due to the necessity of meeting minimum thresholds imposed by selecting the same activity in other regions of the country. Additionally, this could be influenced by constraints related to the availability of production factors in the region.

TABLE 3

Outputs of the multicriteria model

Region	Activity	Unity	Variable	Sustainability index (%)	Economic dimension (%)	Environmental dimension (%)	Social dimension (%)	Solution L_1	Solution L_∞
NRT	Extensive horticulture and others crops	(Ha)	XA_{31}	17,71	16,70	9,71	26,72	0,00	0,00
	Intensive horticulture	(Ha)	XA_{41}	21,76	27,63	3,40	34,24	7,16	4,19
	Quality wines	(Ha)	XA_{51}	25,31	27,78	9,96	38,19	0,00	0,00
	Fresh fruits	(Ha)	XA_{71}	19,97	23,40	8,49	28,01	0,00	0,00
	Dried fruits	(Ha)	XA_{81}	29,41	31,72	24,98	31,54	12,43	75,28
	Olive trees	(Ha)	XA_{91}	29,03	19,32	35,51	32,24	94,96	42,83
	Dairy cattle	(Ha)	XA_{101}	23,39	23,61	9,30	37,26	17,88	18,64
	Beef cattle	(Ha)	XA_{111}	13,60	9,24	12,45	19,13	8,52	0,00
	Sheep and goats	(Ha)	XA_{121}	17,16	11,23	17,65	22,59	0,00	0,00
	Pigs	(Ha)	$XA1_{31}$	16,57	23,48	23,85	2,39	4,36	4,36
	Mixed cropping	(Ha)	XA_{151}	20,39	17,75	10,37	33,04	0,00	0,00
	Poly-livestock	(Ha)	XA_{161}	12,87	13,50	11,62	13,49	0,00	0,00
	Mixed crops and livestocks	(Ha)	XA_{171}	18,52	15,62	11,43	28,51	0,00	0,00
CTR	Rice	(Ha)	XA_{21}	12,11	12,88	15,82	7,63	20,06	20,06
	Extensive horticulture and others crops	(Ha)	XA_{32}	16,82	13,59	8,54	28,33	12,76	15,97
	Intensive horticulture	(Ha)	XA_{42}	16,78	19,49	2,47	28,39	0,00	0,00
	Quality wines	(Ha)	XA_{52}	19,48	23,63	9,28	25,51	28,99	21,53
	Fresh fruits	(Ha)	XA_{72}	22,79	19,44	9,47	39,46	0,00	0,00
	Dairy cattle	(Ha)	XA_{102}	18,49	16,57	9,01	29,90	23,03	21,91
	Beef cattle	(Ha)	XA_{112}	17,82	8,07	13,10	32,31	44,71	19,80
	Sheep and goats	(Ha)	XA_{122}	19,78	13,71	15,28	30,36	55,50	85,79
	Poultry	(Ha)	XA_{141}	35,34	22,95	22,85	60,22	1,92	1,92
	Mixed cropping	(Ha)	XA_{152}	19,36	13,77	8,82	35,51	0,00	0,00
	Poly-livestock	(Ha)	XA_{162}	19,66	9,51	9,13	40,35	0,00	0,00
	Mixed crops and livestocks	(Ha)	XA_{172}	16,11	9,15	10,35	28,82	0,00	0,00
LVT	Arable crops	(Ha)	XA_{11}	22,60	22,90	11,50	33,39	21,78	21,78
	Extensive horticulture and others crops	(Ha)	XA_{33}	21,66	27,03	6,71	31,25	33,17	31,26
	Intensive horticulture	(Ha)	XA_{43}	22,33	31,93	3,53	31,52	0,00	7,19
	Other wines	(Ha)	XA_{61}	26,05	45,13	4,24	28,80	8,39	8,39
	Fresh fruits	(Ha)	XA_{73}	23,31	34,10	8,65	27,17	15,15	12,46
	Beef cattle	(Ha)	XA_{113}	12,42	10,69	11,43	15,12	11,52	8,93
	Mixed cropping	(Ha)	XA_{153}	21,98	21,85	3,94	40,16	0,00	0,00
ALE	Quality wines	(Ha)	XA_{53}	21,99	32,46	10,12	23,40	22,97	35,68
	Olive trees	(Ha)	XA_{92}	28,68	28,35	14,54	43,16	5,97	35,77
	Beef cattle	(Ha)	XA_{114}	23,30	14,98	21,52	33,41	162,34	254,56
	Sheep and goats	(Ha)	XA_{123}	22,95	5,12	38,32	25,41	160,05	25,32
	Mixed crops and livestocks	(Ha)	XA_{173}	19,50	11,41	13,06	34,03	0,00	0,00
ALG	Intensive horticulture	(Ha)	XA_{44}	40,61	51,77	0,72	69,34	2,18	1,58
	Fresh fruits	(Ha)	XA_{74}	33,88	43,55	7,99	50,10	9,49	11,42
	Sheep and goats	(Ha)	XA_{124}	24,39	19,66	27,15	26,37	3,29	3,29
	Mixed cropping	(Ha)	XA_{154}	27,03	31,45	10,48	39,16	18,18	16,85
MAD	Intensive horticulture	(Ha)	XA_{45}	37,25	55,29	10,73	45,71	2,26	2,26
	Quality wines	(Ha)	XA_{54}	30,31	42,73	13,72	34,50	0,50	0,50
	Fresh fruits	(Ha)	XA_{75}	30,75	39,38	14,30	38,58	0,00	0,00
	Mixed cropping	(Ha)	XA_{155}	21,53	27,49	5,05	32,04	0,00	0,00
AZO	Intensive horticulture	(Ha)	XA_{46}	19,15	31,25	3,45	22,73	0,00	3,18
	Dairy cattle	(Ha)	XA_{103}	16,94	21,79	7,00	22,03	0,00	0,00
	Beef cattle	(Ha)	XA_{115}	19,25	9,66	25,97	22,11	52,82	49,64

Legend: NRT – North; CTR – Center; LVT – Lisbon and Tagus Valley; ALE – Alentejo; ALG – Algarve; MAD – Madeira; AZO – Azores.

Source: Own elaboration based on FADN data (2016-2021) and LINGO 20.0 software.

4. Discussion and conclusions

The methodologies employed in this study highlight the potential for monitoring the sustainability and planning of various farming systems in Portugal, using the data provided by FADN. A multi-year analysis spanning from 2016 to 2021 was conducted to capture real-time dynamics and mitigate weaknesses found in the original databases, such as the lack of data for farming systems in certain regions and interruptions in data collection for some farming systems.

The results of the sustainability assessment provide valuable insights into identifying the most sustainable activities and pinpointing areas where sustainable practices are most effectively implemented. However, it is noteworthy that these activities exhibit very low sustainability indexes, just above 41 %. These levels indicate a critical degree of sustainability, falling within the range defined as above 33 and less than or equal to 67, established by Triviño-Tarradas *et al*. (2020). It is essential to recognize that despite being identified as relatively more sustainable, these activities have room for improvement to achieve higher sustainability standards. Additionally, the remaining systems under study are deemed unacceptable (equal to or less than 33, according to Triviño-Tarradas *et al*., 2020), further underscoring the need for comprehensive sustainability efforts across agricultural practices. These results are consistent with the work of Grigoroudis *et al*. (2024), who found farming to be largely unsustainable globally, with median scores near 0.5 (on a 0-1 scale). Portugal scored 0.5976, ranking 19th out of 148 countries.

However, the observations conducted per sustainability dimension do not always align with the selection of activities that achieve the best overall sustainability value. This discrepancy may be attributed to conflicts among the three assessment areas (environmental, economic, and social). For instance, one of the farming systems with the highest economic dimension score is intensive horticulture in the Algarve (51.77), which coincides with the worst environmental impact (0.72). Conversely, farming systems associated with small ruminants in the Alentejo exhibit the highest environmental ranking (38.32) but the lowest economic ranking (5.12). The conflicting relationship identified between the economic and environmental dimensions corroborates the findings of models by Guo *et al*. (2022). However, this contradicts the results obtained by Drofenik *et al*. (2023), who, through nine sustainability indicators across the three dimensions, mention clear trade-offs between environmental and social indicators, but suggest that the trade-offs between ecological and economic indicators are not as apparent.

It is important to highlight that the optimal balance across the three dimensions is frequently achieved in Portugal's predominantly rural regions, spanning from the North to the Centre, encompassing the Alentejo and Azores. These areas exhibit a remarkable prevalence of product recognition for their origin, intricately linked with the cultural traditions of the local communities (Pato & Duque, 2023). This not only contributes to the economic vitality of these regions but also generates employment opportunities. From an environmental perspective, Milano & Cazella (2021) have demonstrated that the production systems associated with these traditional products display a harmonious relationship with various environmental attributes. This reveals a heightened level of adaptation to the conditions of the territory, emphasizing their crucial role in promoting sustainable agricultural practices.

This study adopts a holistic view of sustainability, encompassing all three dimensions proposed by Elkington (1994), as discussed by Trivino-Tarradas *et al*. (2019). However, within the context of Portuguese agriculture, environmental and economic factors emerged as the most critical and potentially conflicting aspects. Reflecting this, Grigoroudis *et al*. (2024) reported strong social performance (0.665) in Portuguese agriculture. Consequently, to address the relative weaknesses in environmental and economic sustainability, a multicriteria model was developed to balance these two dimensions. The studies by Marta-Costa (2010) and Marta-Costa *et al*. (2013) also considered both pillars, although limited to analyzing only one economic variable (added value) and one environmental variable (energy costs). Additionally, they were focused solely on animal production systems.

The designed model identified approximately 60 % of the proposed systems as viable options, which is consistent with the findings of Deo *et al*. (2022). Their model also generated fewer options for cultivation plans compared to the one outlined in its construction, prioritizing crops with high water productivity over those with high profitability and lower risk. This highlights the importance of considering various factors, including environmental sustainability and economic viability, in agricultural decision-making processes. By adopting a multicriteria approach, it becomes possible to achieve a balance between these dimensions, ultimately leading to more sustainable agricultural practices.

Our proposed solutions highlight the potential of specific farming systems, notably olive cultivation, dried fruits production, beef cattle, sheep and goat farming, and extensive horticulture. These activities are deemed as the most effective avenues towards fostering a deeper commitment to environmental and economic sustainability within the observed scenarios. This selection considers the inherent constraints within the country, as implied by the data from FADN.

However, the limitation of data availability confined to the NUT II regions resulted in each region being treated as a spatially homogenous area in the model. This constraint is also acknowledged in the work of Cao *et al*. (2023). Future studies could benefit from incorporating and combining more specific information to allow for the representation of spatial and productive heterogeneity in the integrated model. This approach aligns with the suggestions of Guo *et al*. (2022) and Kokemohr *et al*. (2022), which advocate for capturing the performance of the system under changing conditions. By addressing these limitations and incorporating more nuanced data, future research endeavours can enhance the accuracy and applicability of integrated models, thereby enabling more informed decision-making in sustainable agriculture.

Therefore, the integration of sustainability indicators with multicriteria theory represents a valuable tool for guiding new public policies toward contemporary sustainability paradigms. These models enable the identification of acceptable compromises between conflicting objectives, allowing farmers to optimize performance across multiple dimensions simultaneously. Moreover, they provide a systematic framework for evaluating and comparing various farm management strategies, considering diverse objectives such as productivity, resource efficiency, environmental sustainability, and social welfare. This empowers decision-makers to pinpoint solutions that best align with the specific needs and priorities of a given region or farming system, thereby fostering more sustainable agricultural practices and policies.

Furthermore, these models offer an effective means of tackling emerging challenges such as climate change, water scarcity (e.g., Cao *et al*., 2023; Deo *et al*., 2022), and the growing social demands for sustainable agricultural practices and food supply chain (e.g., Drofenik *et al*., 2023). Their flexibility and adaptability enable the incorporation of new information, evolving environmental and social conditions, and emerging sustainability goals. Consequently, they serve as dynamic tools for steering agricultural policies and practices towards greater sustainability in a constantly changing landscape.

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