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RESEARCH ARTICLE

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Transforming the agri-food sector through eco-innovation: A path to sustainability and technological progress

Nuria Chaparro-Banegas[1] | Mercedes Sánchez-Garcia[2] | Consuelo Calafat-Marzal[1] | Norat Roig-Tierno[1]

[1]Universitat Politècnica de València, València, Spain

[2]Universidad Pública de Navarra, Pamplona, Navarra, Spain

Correspondence
Nuria Chaparro-Banegas, Universitat Politècnica de València, Camí de Vera, s/n, 46022 València, Spain.
Email: nchaban@upv.es

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Abstract

The rapid transformation in the way people live has become a concern for countries around the world. Innovation can offer a strategy to address sustainable development challenges in all areas of society. Traditionally, the agri-food sector has had low levels of innovation and research and development (R&D). Despite its negative environmental effects, its value for society is unquestionable. Therefore, the agri-food sector must not lag behind other sectors in embracing the technological progress that contributes to sustainable development. The scientific literature contains studies of eco-innovation drivers and barriers. Nevertheless, research on low-technology sectors such as the agri-food sector is scarce. To address this research gap, this paper identifies the internal and external factors that are necessary for in-firm eco-innovation and whose absence can constrain or block eco-innovation development. Data were gathered from Spanish agriculture and industrial agri-food firms in 2022 based on primary statistical information collected in a 2022 survey to obtain data on their activity in the period 2017–2021. Necessary condition analysis (NCA) reveals three main findings: (i) internal factors are more relevant than external factors, (ii) the type of firm and the degree of eco-innovation development affect the importance of internal and external factors, and (iii) agricultural and industrial agri-food firms prioritize different stages of eco-innovation development because of the higher complexity and technological progress of industrial firms. These results highlight eco-innovation as a key strategy to enhance the competitiveness and sustainability of the sector. By prioritizing internal factors and fostering eco-innovation through environmental training, green relationships, and support networks, companies can progress toward more sustainable and technologically advanced practices, thus contributing to the overall sustainable development of the sector. This underscores the importance of policies that promote training, investment in R&D, environmental and fiscal

Abbreviations: AKIS, agricultural knowledge and innovation system; CAP, Common Agricultural Policy; EGD, European Green Deal; EU, European Union; F2F, farm to fork; GHG, greenhouse gas; LRM, linear regression models; LTVRA, Long-Term Vision for EU Rural Areas; NCA, necessary condition analysis; NGOs, non-governmental organizations; R&D, research and development; SMEs, small and medium-sized enterprises.

regulation, and collaboration to drive eco-innovation and sustainability in the agri-food sector.

KEYWORDS
agricultural system, agri-food sector, eco-innovation, human capital, R&D, sustainable development

1 | INTRODUCTION

Society exists within a fast-changing and disruptive environment. This environment is characterized by increasing competition driven by technological transformation and stakeholder demand for more environmentally friendly products (García-Sánchez et al., 2021). Concern over the impact of economic activity on sustainability has increased in recent years in light of the growth in natural disasters, rising world temperatures (Donis et al., 2023), and other such factors. Countries, regions, and companies tackle these environmental problems through innovation and environmental technology (García-Sánchez et al., 2021). Given the increasing demand for sustainable development and growing environmental problems, pressure on the agri-food sector to undergo a sustainability transition has grown. Innovation is a key driver of this transformation (Depetris-Chauvin et al., 2023).

Agricultural systems are among the main greenhouse gas (GHG) producers, also contributing to natural resource depletion in terms of, for example, soil and water (Bagagiolo et al., 2023; Gołasa et al., 2021). Other negative effects are related to rural community crises or labor exploitation (Bonanno, 2017). According to Benton et al. (2021), agri-food systems are one of the key factors driving climate change by their significant contribution to greenhouse gas emissions. This negative contribution degrades ecosystems and stimulates species loss, leading to biodiversity loss. The European Green Deal (EGD) aims to achieve a climate-neutral Europe by 2050, focusing on transitioning towards a more sustainable agricultural and food system to mitigate climate change and protect biodiversity. The European Commission targets a 50% to 55% reduction in emissions compared to the 1990s (European Commission, 2024e), with the Farm to Fork (F2F) strategy ensuring that agriculture, fisheries, aquaculture, and the food chain contribute significantly to this goal. In the European Union (EU), the food industry accounts for 64% of pollution generated by European industries (del Carmen Galera-Quiles et al., 2023), transforming it into a more sustainable and climate-friendly system is crucial for achieving the EDG objectives.

In addition to these negative effects, the agri-food system faces difficulties in innovating and developing in a sustainable manner due to numerous challenges. One of the challenges is related to demographic growth and diet changes, leading to an increase in resource pressure (Dury et al., 2019). Consumer preferences can shift to more fresh vegetables and fruits, less meat products (Kabasa et al., 2015), and more organic and ecological products (Díaz-Méndez & Lozano-Cabedo, 2020). Therefore, food demand is increasing (Spielman, 2005), being accentuated by urbanization (Dury et al., 2019). In turn, urbanization contributes to land abandonment (Calafat-Marzal et al., 2023a) and depopulation of rural areas (Kruseman et al., 2020; Swerts et al., 2014). The land abandonment is also intensified by the lack of generational renewal, having severe implications in the agri-food sector (Garcia-Alvarez-Coque & Piñeiro, 2022). According to Chen et al. (2015), the lack of financing constrains technological progress and modernization of the agricultural sector due to limited access to institutional finance or the lack of confidence in commercial banks and other financial organizations. This becomes even harder for smallholders in agriculture.

Agriculture and agri-food systems are at the core of the global sustainable development agenda (FAO, 2016). For example, in China, the agricultural sector provides food to more than 1 billion people, or almost 20% of the world's population (Wang et al., 2019). According to the Food and Agriculture Organization (FAO, 2023), despite the negative health, social, and environmental effects of agri-food systems, their value is unquestionable. They sustain economies, provide nourishment, and shape the cultural identities of the world population. Moreover, agricultural investment and rural development could contribute to sustainable development by ending hunger and poverty. (FAO, 2016) Therefore, it becomes paramount to tackle the challenges agri-food systems face to mitigate the negative effects and stimulate the positive ones. Today's well-being of rural areas requires innovative measures that differ from traditional ones in their ability to take advantage of technological and development opportunities while facing and overcoming complex global challenges (Borrelli et al., 2013; Marinelli et al., 2014). In this way, the agri-food sector would be committed to sustainable development by offering solutions through technology-based and innovative approaches (Panetto et al., 2020). Sustainable agriculture depends on digital innovations (Finger, 2023; Walter et al., 2017). The Common Agricultural Policy (CAP) towards 2020 strategy promoted by the European Commission claims that innovation is key for the agriculture of the future, trying to focus on innovative ideas that unlock rural areas potential through local and business governance (European Commission, 2010; Knickel et al., 2018). In this European context, the multiple CAP reforms in the agri-food sector boost actions that support the sector's economic, social, and environmental sustainability (Calafat-Marzal et al., 2023b).

Alternative agricultural and food production techniques could be combined with technological innovation and eco-friendly practices such as sustainable agriculture, which aims to balance agricultural production with environmental conservation, and organic farming, a specific approach within sustainability that avoids the use of synthetic chemicals. These practices complement each other to promote more sustainable and equitable food systems, next to circular economy principles in agriculture, which focus on minimizing waste and optimizing resource use. The integration of these eco-friendly practices improves the quality of life and protects natural resources (Ben Amara & Chen, 2022). Thus, the implementation of eco-innovation in the agri-food sector could boost its technological progress, while mitigating its negative effects and enhancing its positive influence (Ben Amara & Chen, 2021). Eco-innovation generates positive impacts on the economy, society, and environment. First, this type of innovation improves productivity and financial performance (Depetris-Chauvin et al., 2023), enabling economic growth. Second, eco-innovation improves corporate image given its basis in sustainability values, encourages responsible consumption, emphasizes environmental impact to shareholders and owners, generates new employment opportunities, and raises social sustainability awareness (Marco-Lajara et al., 2023). Finally, from the point of view of the environmental dimension of sustainability, eco-innovation reduces pollution emissions, waste (Ben Amara & Chen, 2021), energy consumption, and the use of raw materials, boosting circular economy practices (Le et al., 2023).

For years, many eco-innovation scholars have studied which factors or elements stimulate eco-innovation development (Ben Amara & Chen, 2021; Bossle et al., 2016; Del Río et al., 2016; Díaz-García et al., 2015; Hojnik & Ruzzier, 2016; Horbach, 2008; Zubeltzu-Jaka et al., 2018). Nevertheless, they have tended to focus on the eco-innovation drivers of high-technology sectors (e.g., energy-intensive or polluting industries). In contrast, low-technology sectors such as the agri-food industry have received less attention (Cuerva et al., 2014; Triguero et al., 2018). In addition, agri-food firms have less knowledge, know-how, and experience in innovation, and they are more vulnerable to technological processes because of higher barriers (Calafat-Marzal et al., 2023c). According to several authors (e.g., Bossle et al., 2016; Cuerva et al., 2014; Triguero et al., 2018), few studies have examined the factors that influence eco-innovation in the agri-food industry, suggesting the existence of a gap in the literature. Therefore, further research on eco-innovation in the agri-food sector is needed (Ben Amara & Chen, 2021; Bossle et al., 2016) to understand the specific challenges and opportunities faced by agri-food firms in eco-innovation. Addressing these challenges and taking advantage of these opportunities through technological transformation and eco-innovation strategies may create a sustainable food system where human health, global well-being, and food security are preserved.

To address this research gap, this paper identifies the internal and external factors (conditions) that are necessary for the development of eco-innovation in agricultural and industrial agri-food firms. These necessary conditions are considered to have the power to constrain eco-innovation within the firm if they are absent. They are considered barriers, bottlenecks, or obstacles when they are not adequately managed (Dul, 2016b). Necessary condition analysis (NCA) enabled the identification of necessary conditions that are required for the outcome of eco-innovation to occur. The data for the analysis were collected through a questionnaire administered to firms in the Spanish agri-food sector in 2022. This study builds on the literature on eco-innovation drivers to determine which are necessary for fostering eco-innovation activities within agri-food firms (e.g., Ben Amara & Chen, 2021; Bossle et al., 2016; Del Río et al., 2016; Díaz-García et al., 2015; Hojnik & Ruzzier, 2016; Horbach, 2008; Zubeltzu-Jaka et al., 2018). The effect of these drivers on eco-innovation is examined in two separate domains (i.e., agricultural and industrial agri-food firms), trying to capture any differences in how eco-innovation occurs within diverse firm contexts.

Therefore, three main pillars make this scientific contribution unique: (i) it is based on eco-innovation drivers, (ii) it applies the analysis in two different contexts of agri-food firms, and (iii) it relies on necessary causality to identify which drivers would constrain eco-innovation performance when they are absent. This paper contributes to the literature on eco-innovation in the agri-food sector by shedding light on how internal and external factors can drive (or constrain in case they are absent) the development of eco-innovation designed to boost the ecological and technological development of this sector. The European Union has shown its commitment to sustainable agriculture by devoting resources and efforts to create intelligent, resilient, competitive, and sustainable agri-food systems. Given that resources are limited and it is impossible to simultaneously address all eco-innovation drivers and barriers, it becomes paramount to know which factors are more important to promoting sustainable agriculture through eco-innovation strategies. This paper's findings could be used as an information source in European policy to adapt eco-innovation and sustainable agri-food strategies to each type of agri-food firm (agricultural or industrial), guaranteeing strategy success in the global agri-food industry.

The following sections provide the structure for this paper. Section 2 contextualizes the concept of eco-innovation, describing the literature on the types and drivers of eco-innovation reflected in the study questionnaire. The materials used to collect the data for the analysis and the research methodology are explained in Section 3. Section 4 presents the NCA findings. Finally, Section 5 discusses the findings by comparing them with those found in the existing literature. It also presents the conclusions, limitations, and future research avenues.

2 | THEORETICAL FRAMEWORK

Society's values, beliefs, habits, and norms influence individuals' willingness to reduce negative environmental behaviors and activities (Gkargkavouzi et al., 2019; Klöckner, 2013). This idea is relevant to eco-innovation because the adoption of greener lifestyles and technologies is necessary in order to develop more environmentally friendly products that reduce negative environmental behaviors and activities (Jansson et al., 2010). Different agents introduce eco-innovations by developing new ideas, products, processes, and behaviors that contribute to the attainment of goals for sustainable development (Pereira et al., 2020; Rennings, 2000). Nevertheless, scholars disagree on the terminology and definition of sustainability-related innovation. Green innovation, environmental innovation, sustainable innovation, and eco-innovation are four terms employed to refer to such innovation. In the definitions of these terms, the environment is emphasized more than the other two dimensions of sustainability (Chaparro-Banegas et al., 2023b). Although authors argue that the only type of innovation that combines the three dimensions of sustainability (economic, social, and environmental) is sustainable innovation (e.g., Schiederig et al., 2012), this paper uses the definition of eco-innovation provided by Chaparro-Banegas et al. (2023b). This definition includes the other sustainability-related innovation concepts interchangeably. It also implies that eco-innovation fosters sustainable development and thus simultaneously enhances the economic, social, and environmental dimensions of sustainability.

The OECD (2005) classifies eco-innovation according to its area of implementation: product, process, or organizational (Horbach et al., 2012; Triguero et al., 2013). Moreover, eco-innovation can be implemented in companies or other organizations to meet different objectives depending on the intended effect on the environment. Companies can apply eco-innovation to improve resource productivity, thereby increasing economic value while reducing pressure on the environment. For example, **resource efficiency** is increased by improvements in material, water, energy, or greenhouse gas (GHG) emissions productivity (European Commission, 2022). Implementing eco-innovation is sometimes aimed at **reducing environmental impact** by eliminating dangerous products, lowering pollution emissions, preventing climate change, and promoting recycling (Păcesilă & Ciocoiu, 2017). Thus, eco-innovation is crucial to address the most urgent environmental and sustainable development challenges such as natural resource scarcity and biodiversity reduction (Scarpellini et al., 2020).

Advances in technology and innovation can provide solutions that improve health and quality of life by mitigating negative environmental externalities (Horbach, 2016). They can also enhance health and quality of life by providing access to instruments that allow elderly self-management (Omri, 2020), improve communication or access to information and data, and increase efficiency and productivity by automating potentially dangerous routine tasks (Castellacci & Tveito, 2018). Hence, eco-innovation can also **improve the health and security of employees**. According to Bossle et al. (2016), compliance with government and institutional standards strongly influences the commitment to sustainable development. Thus, another motive for companies to introduce eco-innovations may be **compliance with environmental, health, or security regulations**. Governments and public administrations have tightened environmental regulations and have introduced economic, social, and environmental incentives to encourage environmentally friendly business behaviors to meet environmental targets (del Río et al., 2015; Demirel et al., 2018; Demirel & Kesidou, 2019). Sustainable development improvements triggered by government initiatives include reducing the ecological footprint and introducing clean technologies (Mercado-Caruso et al., 2020). Figure 1 summarizes the different types of eco-innovation depending on the firm's implementation objective.

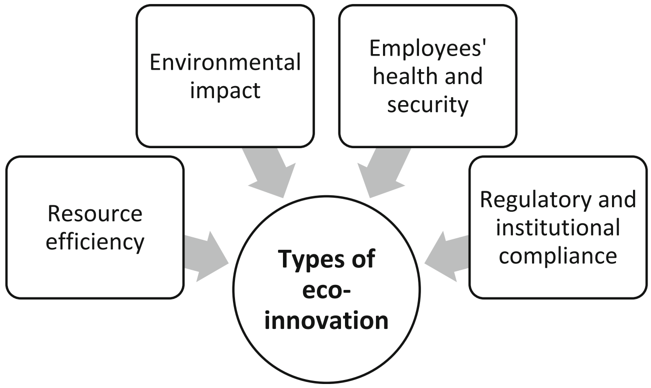

FIGURE 1 Types of eco-innovation by implementation objective.

The literature identifies a myriad of eco-innovation drivers (Horbach, 2008) and classifies them into different groups using a range of criteria. Díaz-García et al. (2015) created a multilevel framework of eco-innovation drivers. Under this framework, these drivers are grouped into macro- (national/regional level), meso- (market level), and micro-level drivers (firm level). Horbach (2008) classified eco-innovation drivers into technological push (supply side), market pull (demand side), and institutional and political influences. Hojnik and Ruzzier (2016) argued that eco-innovation is influenced by internal and external drivers. Internal factors are in-firm conditions or attributes that encourage green innovation changes, whereas external factors are incentives from agents outside the company that lead a firm to react (del Río González, 2009). This classification is the one applied in the present study.

Some of the reasons for companies to introduce eco-innovations are considered external factors because they refer to elements that are outside the boundaries of the company. The **political and regulatory framework** is one of the most influential external drivers of eco-innovation. When public policy is oriented to sustainable development, companies are encouraged to embrace eco-innovation (Mercado-Caruso et al., 2020) regulations prohibit actions that have negative impacts on the environment, for example, pollution. Knowing that these regulations are strict would encourage companies to adopt eco-innovation to avoid fines or sanctions (Tsai & Liao, 2017). **Subsidies and other financial incentives** also drive eco-innovation (Fernández et al., 2021). According to Arranz et al. (2021), financial support accelerates the eco-innovation process, making firms more willing to implement eco-innovations. Subsidies often provide incentives to introduce innovations that decrease environmental effects by reducing costs (Tsai & Liao, 2017).

Market dynamics also influence firms' implementation of eco-innovations because of pressure from both **customers and competitors** (Díaz-García et al., 2015). The increase in demand for and supply of more environmentally friendly products and services pushes many firms to engage in eco-innovation (Hojnik et al., 2022; Hojnik & Ruzzier, 2016). The implication is that environmentally ethical consumption and market pressure lead companies to take corporate social responsibility actions, increasing their commitment (Xin &

Xie, 2023) to sustainable development through eco-innovation. Finally, companies may introduce **voluntary codes of practice or agreements for good environmental practices** related to eco-innovation. For example, managerial support guarantees the success of environmental and sustainability initiatives (Hojnik et al., 2022; Keszey, 2020). Human capital (Zhen, 2011) and collaboration among stakeholders (Díaz-García et al., 2015; Petruzzelli et al., 2011) can also encourage eco-innovation activities and processes within companies. It facilitates the flow of knowledge and information, which are essential to deal with the complexity and uncertainty of eco-innovation (De Marchi, 2012; Hojnik & Ruzzier, 2016). According to Chaparro-Banegas et al. (2023a), eco-innovation requires human capital, which can be promoted through training, education, and new policies. These actions motivate society to support improving quality of life and well-being through sustainability and eco-innovation actions.

In contrast to external drivers, internal drivers are aspects that are under a company's control and that the company considers core objectives that justify the introduction of eco-innovations. Firms with a concern for sustainable development encourage the design and implementation of eco-innovation and sustainability-related activities (Díaz-García et al., 2015). The inclusion of sustainability concerns in business strategies and routines ensures the success of firms' sustainable development behavior (Baumgartner & Ebner, 2010). These strategies may be associated with (i) the design of **environmental and sustainability plans**, which may provide guidelines for future actions, (ii) **environmental objectives** that form the basis of a firm's planning and lines of action, and (iii) measurement of a firm's **environmental impact**, which is crucial for monitoring sustainable performance and taking corrective measures if needed. Zubeltzu-Jaka et al. (2018) reported that environmental concern is one of the most influential drivers of a firm's eco-innovation adoption. Through this concern, companies reflect their environmental orientation and responsibilities regarding the natural environment, expressing their commitment to green principles (Banerjee et al., 2003; Hojnik et al., 2022).

Employee willingness to engage in sustainable development and adoption of environmentally friendly behaviors can also influence eco-innovation. For example, a country's environmental sustainability increases when society is more educated (Park et al., 2007; Reverte, 2022), suggesting that the predisposition of employees toward sustainability is greater when their level of knowledge, experience, and skills is higher. Greater skills, experience, and knowledge can be achieved through training and awareness raising by the company (De Marchi, 2012; Zubeltzu-Jaka et al., 2018). Finally, **R&D expenditure and initiatives** by companies also foster eco-innovation. R&D provides and improves the technological capabilities a firm needs to implement environmental alternatives (Horbach, 2008; Jové-Llopis & Segarra-Blasco, 2018). Costa-Campi et al. (2017) argued that green R&D can reduce a firm's environmental impact by cutting emissions, thus addressing climate change and other sustainable development challenges (Hojnik et al., 2022). This argument reflects the idea that a firm's internal R&D is a catalyst of sustainable development and eco-innovation activities. Table 1 summarizes the external and internal drivers presented in the literature and links them to aspects included in the questionnaire for this study.

3 | DATA AND METHODS

3.1 | Data

This empirical study focused on the agri-food sector in Spain. This sector stands as one of the country's crucial industrial sectors.

TABLE 1 External and internal drivers of eco-innovation in the Agri-food sector.

DRIVER		QUESTIONNAIRE ASPECT	REFERENCES
External drivers	Political and regulatory framework	Current or future environmental regulations or pollution taxes	(Mercado-Caruso et al., 2020; Tsai & Liao, 2017)
	Subsidies and other financial incentives	Availability of grants, subsidies, or other financial incentives for eco-innovation	(Arranz et al., 2021; Fernández et al., 2021; Tsai & Liao, 2017)
	Customer pressure	Current or future customer demand for eco-innovation	(Díaz-García et al., 2015; Hojnik et al., 2022; Hojnik & Ruzzier, 2016)
	Competitor pressure	Pressure from competitor performance forcing the firm to adopt eco-innovation	
	Voluntary agreements	Voluntary codes or agreements for environmental practices	(Díaz-García et al., 2015; Hojnik et al., 2022; Keszey, 2020; Petruzzelli et al., 2011; Zhen, 2011)
Internal drivers	Planning	Environmental and sustainability plans	(Banerjee et al., 2003; Baumgartner & Ebner, 2010; Díaz-García et al., 2015; Hojnik et al., 2022; Zubeltzu-Jaka et al., 2018)
	Goal setting	Environmental objectives	
	Monitoring and evaluation	Environmental impact	
	Human capital	Employee willingness to perform sustainability behaviors	(De Marchi, 2012; Park et al., 2007; Reverte, 2022; Zubeltzu-Jaka et al., 2018)
	R&D	R&D expenditure and initiatives	(Costa-Campi et al., 2017; Hojnik et al., 2022; Horbach, 2008; Jové-Llopis & Segarra-Blasco, 2018)

TABLE 2 Characterization of surveyed companies.

VARIABLE		AGRICULTURE	INDUSTRIAL AGRI-FOOD
Number of questionnaires	Total: 196	99	97
		% units	
Family-run firms		75.76	85.57
Size	Microenterprises (< 10 employees)	32.32	18.56
	Small (10–50 employees)	40.40	57.73
	Medium-sized (50–250 employees)	22.22	22.68
	Large (> 250 employees)	5.05	1.03
Membership of a business group	Yes, national	28.28	28.87
	Yes, multinational	4.04	4.12
	No	67.68	67.01
International sales	None	48.48	31.96
	From 1% to 25% of sales	31.31	37.11
	26% to 50% of sales	8.08	13.40
	More than 50% of sales	12.12	17.53
Digital innovation		59.60	69.07

Following Maudos and Salamanca (2020), Spain represents 10.1% of the EU agri-food industry, behind Italy and France. Participants for the study were companies in the agricultural sector and the agri-food industry. The aim was to reflect the range of sizes of companies present in Spain, where there is a majority of small and medium-sized enterprises (SMEs), mainly with fewer than 50 employees (Gobierno de España, 2024).

The data from Spanish agri-food firms were collected via telephone in March 2022 by a specialized survey company. The survey targeted companies in the agri-food sector in Spain that had conducted R&D activities between 2017 and 2021. The sample error was 7.1% for a 95.5% confidence level (2σ). The sample distribution was proportional to the universe, based on the CNAE[1] code of the companies interviewed. A total of 200 surveys were administered. Finally, 196 were chosen. The selection criterion was companies that had conducted research and development (R&D) between 2017 and 2021. The sample included companies from different regions (*Comunidades Autónomas*) and sectors (agriculture and agri-food industry). The descriptive characteristics of the companies appear in Table 2. Half of the sample consisted of agricultural firms. The other half consisted of industrial agri-food firms. In both cases, the firms, most of which were family-run enterprises, had similar characteristics. Most had fewer than 50 employees, were unaffiliated with any national or multinational corporate group, and had a low export orientation. Regarding digital innovation, more than half of both groups of firms had taken digital innovation actions, although such actions were more prevalent among industrial firms. A 4-point Likert scale ranging from 1 (*Very important*) to 4 (*Not important at all*) was used to collect data on eco-innovation and a Likert 5-point scale to collect the internal and external drivers.

[1]Clasificación Nacional de Actividades Económicas (National Classification of Economic Activities).

3.2 | Method

3.2.1 | Overview of NCA

To identify the necessary conditions (internal and external factors) that can lead to the development of eco-innovation in agricultural and industrial agri-food companies, necessary condition analysis (NCA) was conducted (Dul, 2016b; Dul et al., 2020, 2023; Hauff et al., 2021). In traditional methodologies such as regression or correlation analyses, it is assumed that each factor is sufficient to explain an outcome. If a factor has a low or zero value, the increase in the value of other factors would compensate for this small or non-existent effect. Unlike this traditional additive assumption, necessary causality is a multiplicative phenomenon where the presence of necessary conditions is essential for an outcome to occur. The absence of a necessary condition would mean that the outcome would not occur because the other conditions would be unable to compensate for the absence of the effect of this necessary condition (Dul, 2016b). Therefore, the presence of a necessary condition triggers the outcome, whereas its absence prevents the occurrence of the outcome (Dul et al., 2020). NCA identifies the necessary conditions that result in a particular outcome by analyzing the average impact of various explanatory conditions. A necessary condition is a critical factor that leads to a certain outcome level. This necessary condition blocks or constrains the occurrence of the outcome (Hauff et al., 2021). Although the outcome of interest is achieved when necessary conditions are met, other necessary conditions may also have to be present for the outcome to occur. This idea suggests that conditions may be necessary but not sufficient to trigger an outcome. NCA examines necessary conditions in kind and in degree. In-kind necessity refers to the fact that a specific condition is necessary for a particular outcome to occur. In contrast, in-degree necessity describes the condition level necessary to achieve a specific outcome level (Dul, 2016b), reflecting the required condition levels (Li & Che, 2024).

3.2.2 | Drawing ceiling lines

In NCA, XY scatter plots are essential graphical tools. The empty spaces found in the upper left corners of these plots reflect the presence of necessary conditions (Dul et al., 2023). The size of these empty spaces indicates how tightly the necessary condition constrains the outcome in case the necessary condition is absent (Dul, 2016b). In XY scatter plots, a ceiling line is drawn to separate zones with and without observations (Dul et al., 2023). The two approaches used for drawing ceiling lines in NCA are ceiling envelopment with free disposal hull (CE-FDH) and ceiling regression with free disposal hull (CR-FDH). CE-FDH is a piecewise linear function applied with discrete data with few condition levels (ERIM, 2023). In contrast, CR-FDH is an ordinary least squares (OLS) regression line applied to continuous and discrete data with many condition levels (Hauff et al., 2021).

3.2.3 | Accuracy and effect size

NCA validity is evaluated through accuracy and effect size. Accuracy reflects the number of cases found above the ceiling line in percentage terms (Dul, 2016b), whereas effect size ($d = C/S$) indicates the ratio between the empty space (ceiling zone, C) above the ceiling line and the total observation space (scope, S) in the analysis (Linder et al., 2022). Researchers must assess whether the effect size is theoretically and empirically significant depending on the context under study (ERIM, 2023). According to Dul (2016a), the necessary condition's effect size varies between 0 and 1. This effect size is classified into small (lower than 0.1), medium (between 0.1 and 0.3), large (between 0.3 and 0.5), and very large (greater than 0.5). A necessary condition has a meaningful effect size when the threshold of 0.1 is surpassed (Ding, 2022; Dul et al., 2020).

3.2.4 | Data calibration

NCA can use raw or calibrated data in terms of set membership scores (Dul, 2016a). The techniques applied by Ragin (2014) were followed to calibrate the data in terms of set membership. Therefore, the raw data were transformed to fuzzy data between 0 and 1, with 0 full non-membership and 1 full membership to the feature. The outcome eco-innovation was calculated as the average of the four types of eco-innovation by implementation objective (resource efficiency, environmental impact, employees' health and security, and regulatory and institutional compliance. The fuzzy values were established as follows: 0 equals not eco-innovative, 0.6 equals moderately eco-innovation, 0.8 equals eco-innovation, and 1 equals highly eco-innovative. The rest of the conditions (internal and external variables) were assigned fuzzy scores between 0 and 1, with 0 total absence and 1 total presence of the condition. For example, a value of 0.8 in the condition "political and regulatory framework" indicates high importance for the regulatory factor.

4 | RESULTS

This section presents the findings of the NCA considering two separate outcomes. The analysis examined the necessary internal and external factors that may explain eco-innovation in (i) agricultural and (ii) industrial agri-food firms. The absence of these necessary factors would constrain eco-innovation development. Therefore, two separate outcomes were considered: (i) eco-innovation in agricultural firms and (ii) eco-innovation in industrial agri-food firms. Figure 2 presents 10 scatterplots with the ceiling lines corresponding to each relationship between **agricultural firms' eco-innovation** and the internal drivers (planning, goal setting, human capital, R&D, and monitoring and evaluation) and external drivers (political and regulatory framework, subsidies and other financial incentives, competitor pressure, customer pressure, and voluntary agreements). Empty spaces in the upper left corner of the scatterplot indicate the presence of a necessary condition (Dul, 2016b). In the case of eco-innovation in agricultural firms, only the analysis of all internal factors revealed empty spaces. The external factor political and regulatory framework also shows an empty space in the upper left corner. Table 3 corroborates these findings.

Under CE-FDH (Ding, 2022; Rey-Martí et al., 2023), the effect sizes were less than 0.1 for all external factors except for the political and regulatory framework condition. This finding indicated that their effect on boosting eco-innovation in agricultural firms was null and non-significant. The political and regulatory framework condition had a small effect on the outcome because its effect size was between 0 and 0.1 (0.01). This finding is contrary to those reported by Donis et al. (2023)), who argued that the institutional environment and judicial system where companies operate affect eco-innovation creation.

In contrast, the internal factors had significant effects on agricultural firms' eco-innovation. Both findings were confirmed by Figure 3. Valero-Gil et al. (2023) presented a similar argument, claiming that internal motivations have a greater influence on eco-innovation than external pressures. The conditions of human capital, monitoring and evaluation, and goal setting had effect sizes of 0.1, 0.2, and 0.28, respectively. The effect of these three conditions on stimulating eco-innovation in agricultural firms was medium. Therefore, having employees who are committed to sustainability behaviors and who design and implement actions considering environmental objectives and their subsequent impact was found to be important for eco-innovation development. Eco-innovation is promoted through training and education to improve employees' environmental abilities, skills, and knowledge, which, in turn, increase human capital awareness

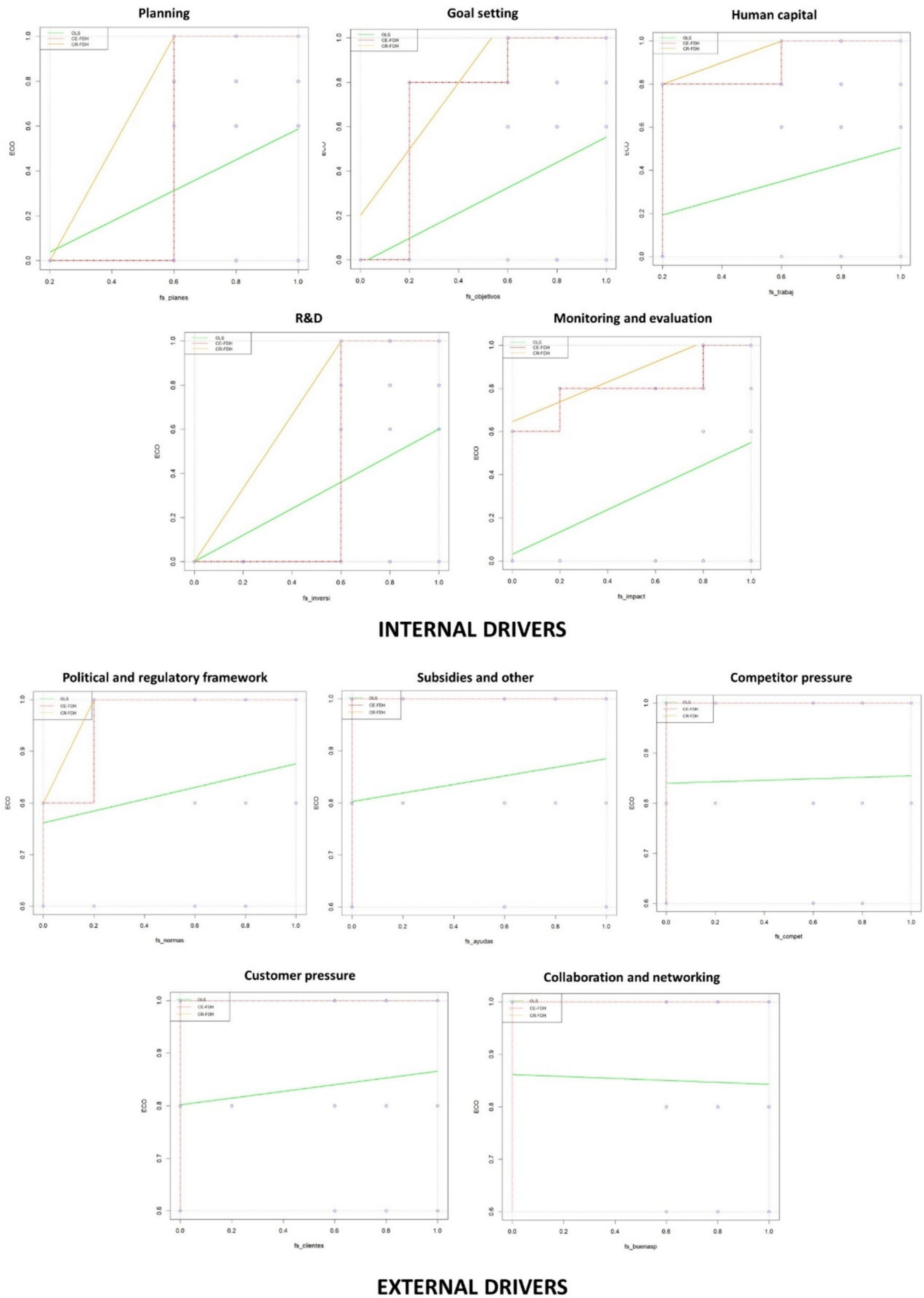

FIGURE 2 Ceiling lines for eco-innovation in agricultural firms and internal and external factors.

(Keshminder & del Río, 2019; Rhaiem & Doloreux, 2022). Finally, planning and R&D had very large effects (greater than or equal to 0.5) on eco-innovation in agricultural firms. This finding suggests that eco-innovation succeeds when agricultural firms create environmental and sustainability plans financed by R&D expenditure and initiatives. This finding contradicts those of Triguero et al. (2018), who showed that

TABLE 3 Effect sizes and descriptive statistics of conditions by type of ceiling line for agricultural firms.

					Descriptive statistics		
DRIVERS		CE-FDH	CR-FDH	*p*-value	Max	Min	Average (SD)
Internal	Planning	0.5	0.25	0.01	1	0	0.802 (0.212)
	Goal setting	0.28	0.21	0.16	1	0	0.824 (0.227)
	Human capital	0.1	0.05	0.42	1	0	0.863 (0.196)
	R&D	0.6	0.3	0.00	1	0	0.755 (0.250)
	Monitoring and evaluation	0.2	0.14	0.21	1	0	0.820 (0.248)
External	Political and regulatory framework	0.01	0.05	0.09	1	0	0.732 (0.319)
	Subsidies and other financial incentives	0	0	1	1	0	0.517 (0.373)
	Competitor pressure	0	0	1	1	0	0.362 (0.342)
	Customer pressure	0	0	1	1	0	0.683 (0.347)
	Voluntary agreements	0	0	1	1	0	0.864 (0.187)

Note: Sample size for agricultural firms' internal drivers = 99; Sample size for agricultural firms' external drivers = 53.

eco-innovation adoption is not related to internal R&D (Rhaiem & Doloreux, 2022).

The *p*-value of the effect size represents the likelihood that the observed sample's effect size is greater than or equal to a random sample's effect size. The observed sample is unlikely to be explained by a random process involving unrelated variables when the *p*-value is less than 0.05 (Dul et al., 2020). A condition can be considered necessary only when it has an effect size greater than 0.1 and a *p*-value less than 0.05. Therefore, only planning and R&D were found to be necessary conditions of eco-innovation in agricultural firms because they were the only conditions to meet both requirements.

Bottleneck tables aid the interpretation of the NCA findings because the same outcome may be explained by multiple necessary conditions (see Table 4). The bottleneck table illustrates the upper limit. This upper limit is the ceiling line of one or more necessary conditions, revealing which level of necessary conditions are required to attain a particular outcome level (Hauff et al., 2021; Li & Che, 2024). Whereas outcome levels are shown in percentage units, conditions are represented in actual values (Dul, 2016b; Rey-Martí et al., 2023). Table 4 corroborates the findings shown in Figure 3 and Table 3. Planning and R&D were necessary conditions for achieving 10% eco-innovation in agricultural firms. The absence of planning and R&D investment and initiatives constrained the development of eco-innovation in these firms by creating a bottleneck. In this case, agricultural firms would not achieve 10% eco-innovation development or higher percentages of eco-innovation unless they first had a minimum level of planning and R&D of 5 and 6, respectively. For an eco-innovation level of 30%, agricultural firms would need to undertake planning, goal setting, and R&D to levels of 15, 6.7, and 18, respectively. This finding reflects the idea that agricultural firms must design and implement environmental and sustainability plans and goals supported by R&D to succeed in eco-innovation to a level of 30%. The absence of these three necessary conditions would constrain eco-innovation development in agricultural firms. According to Han et al. (2023), managers must adopt a clear environmental vision of information technologies to create value through eco-innovation.

Higher levels of these three conditions would be required for an agricultural firm to progress in eco-innovation up to a 60% eco-innovation level. In this case, a new necessary condition should be added to the combination of factors required for eco-innovation. For 60% of eco-innovation, values of 30, 26.7, 36, and 4 of planning, goal setting, R&D, and political and regulatory framework are needed. For 70% eco-innovation, agricultural firms must attain planning, goal setting, R&D, monitoring, and political and regulatory framework levels of 35, 33.3, 42, 11.7, and 8, respectively. For 90% eco-innovation, respective values of 45, 46.7, 25, 54, 55, and 16 of planning, goal setting, human capital, R&D, monitoring, and the political and regulatory framework would be required. Finally, for 100% eco-innovation, agricultural firms would need levels of 50, 53.3, 50, 60, 76.7, and 20 of planning, goal setting, human capital, R&D, monitoring, and the political and regulatory framework, respectively. The highest eco-innovation levels would require all internal drivers but only one external driver (political and regulatory framework). Moreover, monitoring and evaluation would require the highest minimum values to achieve 100% agricultural business eco-innovation, even though it would be a constraining condition from 70% levels. This finding suggests that,

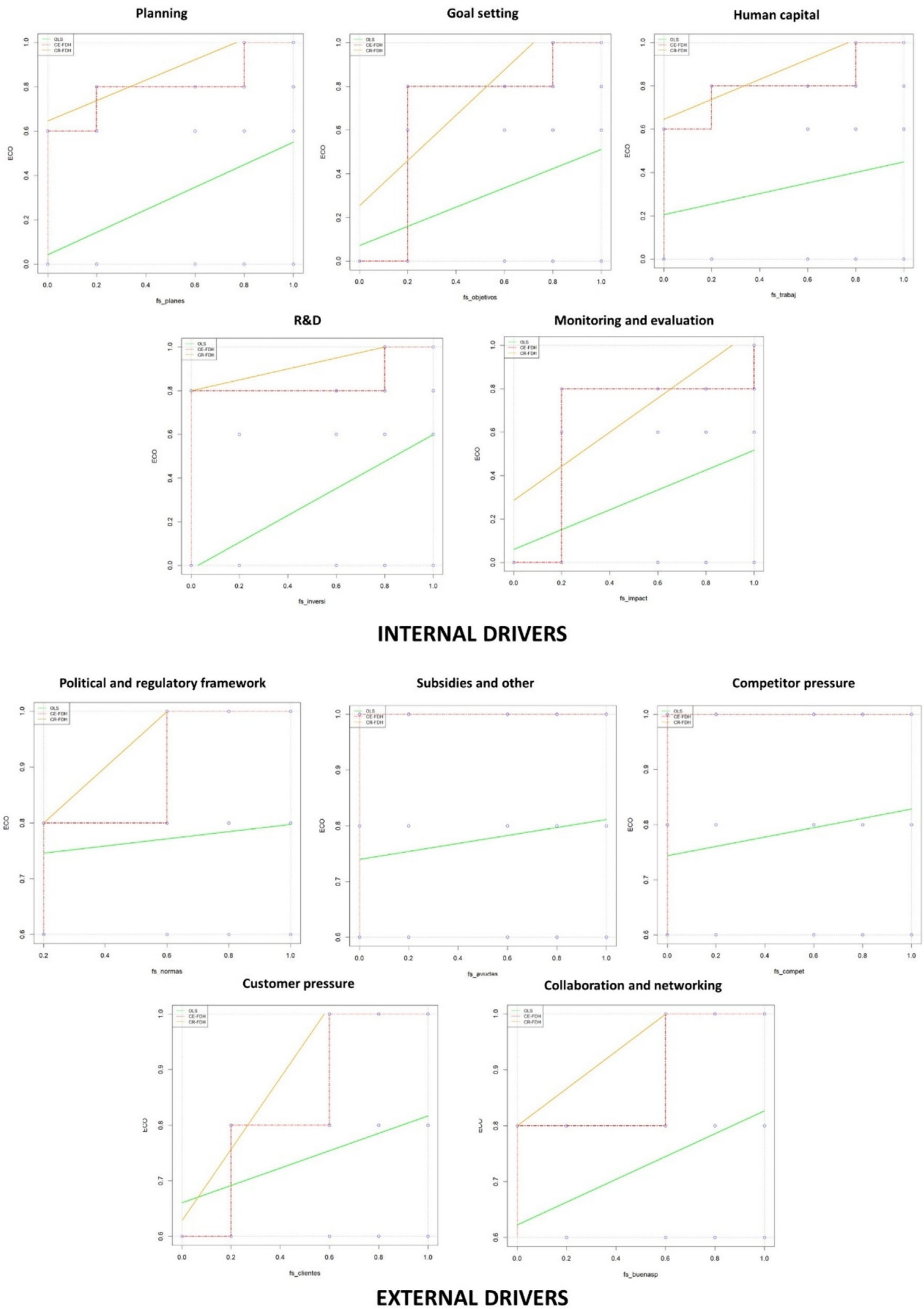

FIGURE 3 Ceiling lines for eco-innovation in industrial agri-food firms and internal and external factors.

although other necessary conditions such as planning, goal setting, and R&D limit eco-innovation development at lower eco-innovation levels, monitoring the environmental impact of eco-innovation activities can ensure full eco-innovation success.

Considering the second outcome, Figure 3 shows the relationship between **eco-innovation in industrial agri-food firms** and internal and external drivers through 10 scatterplots with their respective ceiling lines. As in the case of eco-innovation in agricultural firms, there are

TABLE 4 Bottleneck table for internal and external drivers (necessary conditions or constraints in case of their absence) of eco-innovation in agricultural firms.

	INTERNAL DRIVERS					EXTERNAL DRIVERS				
Eco-i (Y)	Plan	Setting	HC	R&D	Monit.	Pol. and rules	Subs. and other	Comp.	Cust.	Volunt. agreem.
0	NN	NN	NN	NN	NN	NN	NN	NN	NN	NN
10	5	NN	NN	6	NN	NN	NN	NN	NN	NN
20	10	NN	NN	12	NN	NN	NN	NN	NN	NN
30	15	6.7	NN	18	NN	NN	NN	NN	NN	NN
40	20	13.3	NN	24	NN	NN	NN	NN	NN	NN
50	25	20.0	NN	30	NN	NN	NN	NN	NN	NN
60	30	26.7	NN	36	NN	4	NN	NN	NN	NN
70	35	33.3	NN	42	11.7	8	NN	NN	NN	NN
80	40.0	40.0	NN	48	33.3	12	NN	NN	NN	NN
90	45.0	46.7	25	54	55	16	NN	NN	NN	NN
100	50.0	53.3	50	60	76.7	20	NN	NN	NN	NN

Note: Eco-i = eco-innovation (outcome); Plan = planning; Setting = goal setting; HC = human capital; R&D = research and development expenditure and initiatives; Monitor = monitoring and evaluation; Pol. and rules = political and regulatory framework; Subs. and other = subsidies and other financial incentives; Comp. = competitor pressure; Cust. = customer pressure; Volunt. agreem. = voluntary agreements.

TABLE 5 Effect sizes and descriptive statistics of conditions by type of ceiling line for industrial Agri-food firms.

					Descriptive statistics		
DRIVERS		CE-FDH	CR-FDH	*p* value	Max	Min	Average (SD)
Internal	Planning	0.2	0.14	0.02	1	0	0.707 (0.278)
	Goal setting	0.32	0.27	0.01	1	0	0.751 (0.260)
	Human capital	0.2	0.14	0.09	1	0	0.808 (0.255)
	R&D	0.16	0.08	0.047	1	0	0.680 (0.254)
	Monitoring and evaluation	0.36	0.32	0.00	1	0	0.748 (0.280)
External	Political and regulatory framework	0.25	0.13	0.209	1	0.2	0.732 (0.234)
	Subsidies and other financial incentives	0	0	1	1	0	0.564 (0.372)
	Competitor pressure	0	0	1	1	0	0.428 (0.350)
	Customer pressure	0.4	0.27	0.106	1	0	0.764 (0.251)
	Voluntary agreements	0.3	0.15	0.284	1	0	0.772 (0.239)

Note: Sample size for industrial agri-food firms internal drivers = 97; Sample size for industrial agri-food firms external drivers = 50.

empty spaces in the upper left corner of the scatterplots for internal factors. For some external factors (political and regulatory framework, customer pressure, and voluntary agreements), there are also empty spaces in the upper left corner. This finding is also confirmed by Table 5.

As shown in Table 5, the external factors of subsidies and other financial incentives and competitor pressure had a zero-effect size. Therefore, they did not significantly influence eco-innovation in industrial agri-food firms. This finding contradicts those of other studies showing that public incentives (Han et al., 2023) and green finance, which refers to financing that contributes to reducing pollution, environmental degradation, and so on (Sadiq et al., 2023), can stimulate funding related to eco-innovation initiatives. The political and regulatory framework, customer pressure, and voluntary agreements

TABLE 6 Bottleneck table for internal and external drivers (necessary conditions or constraints in case of their absence) of eco-innovation in industrial agri-food firms.

	INTERNAL DRIVERS					EXTERNAL DRIVERS				
Eco-i (Y)	Plan	Setting	HC	R&D	Monit.	Pol. and rules	Subs. and other	Comp.	Cust.	Volunt. agreem.
0	NN	NN	NN	NN	NN	NN	NN	NN	NN	NN
10	NN	NN	NN	NN	NN	NN	NN	NN	1.8	NN
20	NN	NN	NN	NN	NN	NN	NN	NN	8	NN
30	NN	4.4	NN	NN	1.8	NN	NN	NN	14.2	NN
40	NN	14.1	NN	NN	14.5	NN	NN	NN	20.4	NN
50	NN	23.7	NN	NN	27.3	NN	NN	NN	26.8	NN
60	NN	33.3	NN	NN	40	10	NN	NN	32.9	12
70	11.7	43	11.7	NN	52.7	20	NN	NN	39.1	24
80	33.3	52.6	33.3	NN	65.5	30	NN	NN	45.3	36
90	55	62.2	55	40	78.2	40	NN	NN	51.6	48
100	76.7	71.9	76.7	80	90.9	50	NN	NN	57.8	60

Note: Eco-i = eco-innovation (outcome); Plan = planning; Setting = goal setting; HC = human capital; R&D = research and development expenditure and initiatives; Monitor = monitoring and evaluation; Pol. and rules = political and regulatory framework; Subs. and other = subsidies and other financial incentives; Comp. = competitor pressure; Cust. = customer pressure; Volunt. agreem. = voluntary agreements.

conditions had effect sizes of 0.25, 0.4, and 0.3, respectively, indicating that they had a small effect on the outcome because their effect sizes were between the threshold of 0.1 and 0.3. Therefore, the innovation framework (i.e., the innovation system) where the eco-innovation process takes place is also crucial. Agents such as consumers, institutions, and infrastructures, as well as their relationships, drive eco-innovation (Cillo et al., 2019; Donis et al., 2023).

The internal factors of R&D, human capital, and planning also had small effects on eco-innovation in these firms. Their effect sizes were 0.16, 0.2, and 0.2, respectively. Finally, goal setting and monitoring and evaluation had effect sizes of 0.32 and 0.36, respectively, indicating that they had large effects on the outcome (between 0.3 and 0.5). However, only planning, goal setting, R&D, and monitoring were necessary conditions to explain eco-innovation in industrial agri-food firms because they exceeded the minimum effect size and had a *p*-value of less than 0.05. These findings suggest that the success of eco-innovation in industrial agri-food firms is ensured by the design of environmental and sustainability plans and goals, the implementation of R&D, and the monitoring of the environmental actions undertaken by the firm. This finding reflects the importance of a firm's organizational context, which can provide favorable conditions to improve environmental skills and capabilities to create eco-friendly initiatives (De Marchi, 2012; Horbach, 2008; Valero-Gil et al., 2023).

Table 6 shows the constraining conditions that limit the full achievement of eco-innovation within industrial agri-food firms when they are absent. The first necessary condition required for eco-innovation success is customer pressure. Industrial agri-food firms need a level 1.8 of customer pressure to achieve 10% of eco-innovation. At a level of 30%, the absence of goal setting, monitoring, and customer pressure constrains eco-innovation. These necessary conditions required levels of 4.4, 1.8, and 14.2, respectively, to allow eco-innovation development within industrial agri-food firms. These three conditions required higher levels to reach up to 50% eco-innovation. From 60% onward, additional necessary conditions were needed. For a 60% outcome level, industrial agri-food firms needed values of 33.3, 40, 10, 32.9, and 12 of goal setting, monitoring, political and regulatory framework, customer pressure, and voluntary agreements required values.

For 70%, planning, goal setting, human capital, monitoring, political and regulatory framework, customer pressure, and voluntary agreements required values of 11.7, 43, 11.7, 52.7, 20, 39.1, and 24, respectively. For 80%, these values had to increase to higher levels. For an eco-innovation level of 90%, R&D was also a necessary condition, with a level of 40 required. Finally, industrial agri-food firms could ensure 100% eco-innovation if they achieved levels for planning, goal setting, human capital, R&D, monitoring, the political and regulatory framework, customer pressure, and voluntary agreements of 76.7, 71.9, 76.7, 80, 90.9, 50, 57.8, and 60, respectively. A key implication of these findings is that in the early stage of eco-innovation, the absence of goal setting, monitoring, and customer pressure appears to constrain eco-innovation success. However, in the later stages of eco-innovation, firms seem to require high values for all internal and three external factors. The role of R&D investment and initiatives is notable, given that R&D was observed to start limiting the occurrence of eco-innovation at the 90% level and was the second highest necessary condition at the 100% level. Authors such as Demirel and Kesidou (2019) and Rhaiem and Doloreux (2022) have also underlined the key role of R&D investment in the eco-innovation process.

Table 7 summarizes the findings discussed in this section by comparing the effect sizes of conditions and the necessary conditions of agricultural and industrial firms. Focusing on conditions with higher effect sizes shows that whereas agricultural firms emphasize the role of planning and R&D, industrial agri-food firms prioritize goal setting,

TABLE 7 Differences between agricultural and industrial firms in terms of effect size and necessary conditions.

EFFECT SIZE OF CONDITIONS	AGRICULTURAL FIRMS	INDUSTRIAL AGRI-FOOD FIRMS
Small	Political and regulatory framework (E)	None
Medium	Goal setting (I) Human capital (I) Monitoring and evaluation (E)	Planning (I) Human capital (I) R&D (I) Political and regulatory framework (E)
Large	None	Goal setting (I) Monitoring and evaluation (I) Customer pressure (E) Voluntary agreements (E)
Very large	Planning (I) R&D (I)	None
NECESSARY CONDITIONS*	Planning (I) R&D (I)	Planning (I) Goal setting (I) R&D (I) Monitoring and evaluation (I)

Note: *meeting requirements for effect size and *p*-value. (E) = external; (I) = internal.

monitoring, customer pressure, and voluntary agreements. This difference suggests that agricultural firms attach more importance to the early stage of eco-innovation, where a firm plans its future environmental and sustainable activities and sets the budget for R&D investment and the implementation of eco-innovation. In contrast, goal setting, monitoring, customer pressure, and voluntary agreements appear to be more relevant for industrial agri-food firms. This indicates that well-established environmental objectives and the subsequent assessment of eco-innovation activities may guarantee eco-innovation success. In this eco-innovation process, customer opinion and the collaboration among agents of the eco-innovation systems (voluntary agreements) also influence its success. Thus, industrial agri-food firms focus their eco-innovation efforts more on the intermediate and final stages, also considering the environment where the economic activity is developed, which adds complexity to the eco-innovation process.

Regarding the necessary conditions that meet both NCA requirements (effect size and *p*-value), planning and R&D investment and initiatives are necessary conditions for both types of firms. However, in industrial agri-food firms, goal setting and monitoring are also necessary conditions. This difference may be explained by the fact that industrial agri-food firms are usually more technological than agricultural firms. They therefore have more processes to set and assess objectives to ensure the success of eco-innovation. In other words, they are more complex. To provide a holistic view of the results, Appendix A incorporates four linear regression models (LRM). The four LRM are applied for (i) internal and (ii) external drivers for agricultural firms and (iii) internal and (iv) external drivers for industrial agri-food firms. These results are aligned with the ones shown in the NCA analysis.

5 | DISCUSSION

Agri-food and agricultural companies greatly affect the environment because of the amount of food, packaging, water, and energy resources they use. Although eco-innovation could mitigate this negative effect (Ben Amara & Chen, 2022), recent eco-innovation research has focused on high-technology sectors. Traditional low-technology sectors such as the agri-food sector (Triguero et al., 2018) have been overlooked, despite their relevance in people's daily lives (Garcia Martinez & Briz, 2000; García-Sánchez et al., 2021).

European policies have been applied to support sustainable transitions in different sectors. Sustainable food systems and agriculture are promoted through several strategies and policies. The European Green Deal (EGD) supports the sustainable transition of the agri-food sector to protect biodiversity and mitigate climate change. According to Boix-Fayos and de Vente (2023), the EGD reinforces sustainable agriculture through several approaches. These approaches include the Farm to Fork (F2F), Biodiversity, Soil, and Long-Term Vision for EU Rural Areas (LTVRA) strategies, which aim to protect food systems, biodiversity, use of soils, and rural areas through healthy, fair, and environmentally friendly practices. The new CAP encourages an intelligent, resilient, competitive, and diversified agricultural sector to guarantee global long-term food security (European Commission, 2023). It aims to align agricultural policies with the objectives of the EGD, focusing on sustainability, climate action, and environmental protection (Boix-Fayos & de Vente, 2023), basing agri-food sector's development on technological, knowledge, and innovation practices (European Commission, 2023).

Three main conclusions can be drawn from this paper. First, internal factors are more important than external factors in driving business eco-innovation in both agricultural and industrial agri-food firms. Eco-innovation is promoted through knowledge acquired from a firm's capabilities, skills, and resources (Segarra-Oña et al., 2013; Triguero et al., 2018). According to Ben Amara and Chen (2021), the eco-innovation transformation within the agri-food sector is encouraged by managers and employees who are willing to enhance their education, monitoring, commitment, reviewing, and participation in sustainable development practices. Authors have argued that the transformation of this sector requires personal changes, encouraged by environmental training, green relationships, and supporting networks. This transformation is related to three internal actions taken by firms (planning, goal setting, and monitoring and evaluation) and the development of human capital. All of these conditions are considered in this paper. Ben Amara and Chen (2022) showed that agri-food and agricultural firms that seek to adopt environmental certifications, establish environmental management systems, and invest in R&D engage more in eco-innovation strategies and practices.

Although internal factors are more important than external factors for agricultural and industrial agri-food firms, these two types of firms differ in terms of the role of external factors. The political and regulatory framework influences eco-innovation in both types of firms. Their environmental responsibility is increased by regulations and tax incentives because adopting environmentally friendly technologies can provide greater benefits (Triguero et al., 2018). Environmental legislation can increase business competitiveness while decreasing pollution, which creates benefits and value for all stakeholders, stimulating overall innovation (Díaz-García et al., 2015). Nevertheless, industrial agri-food firms are affected by more external factors than agricultural firms. Customer pressure and voluntary agreements also influence eco-innovation in industrial agri-food firms. Adopting eco-innovation strategies can help companies meet consumer demands and create relationships with stakeholders while contributing to sustainable development achievement (Ben Amara & Chen, 2022).

Second, the bottleneck tables present valuable findings regarding agricultural and agri-food industrial firms. Agricultural firms must channel their efforts and resources toward planning and R&D investment to guarantee eco-innovation success in the early stage of development. However, monitoring and evaluation have a greater impact on achieving full eco-innovation development. In contrast, industrial agri-food firms should emphasize the role of customer pressure, goal setting, and monitoring early in the eco-innovation process and the role of all internal and three external factors (i.e., customer pressure, political and regulatory framework, and voluntary agreements) at the later development stage. For instance, the adoption of greener processes or production would be accompanied by organizational and marketing eco-innovation, with integration in areas such as products, planning, R&D, and technology proving crucial (Antonelli et al., 2020; del Carmen Galera-Quiles et al., 2023). According to Cheng et al. (2014), applying administrative support procedures and programs within firms is essential to improve technology-related aspects of eco-design and eco-innovation because these support activities ensure eco-innovation effectiveness (García-Sánchez et al., 2021).

Finally, this paper highlights some differences between agricultural and agri-food firms in terms of the necessary conditions that drive eco-innovation development. The comparison of the necessary conditions of these two types of firms shows that agricultural firms prioritize the early stage of eco-innovation through planning and R&D investment. In contrast, industrial agri-food firms focus on all stages of eco-innovation development (early, intermediate, and final) because of the necessary conditions for R&D and planning, goal setting, and monitoring. This difference could be explained by differences between the products of each type of firm. Agricultural firms participate in a perfectly competitive market, where products are commoditized and do not necessarily imply a transformation of the final product. In contrast, industrial agri-food firms perform more complex activities and processes, where issues related to technology and innovation are essential.

According to these findings and the European agricultural policy framework, policies and instruments can be designed and implemented to guarantee the sustainable development of food systems and rural areas, protecting in this way biodiversity. Three different approaches could define these policies: strengthening internal capacity for eco-innovation, encouraging technological and innovation investments, and enhancing monitoring and evaluation mechanisms. The approach to **strengthening internal capacity for eco-innovation** includes human capital and collaboration actions. Environmental **training and education** programs for managers and employees can foster a sustainability culture within agri-food firms. Some examples may include partnerships with education institutions, workshops, or recognized certifications. This approach also includes **knowledge-sharing platforms**, where firms and other economic agents can share best practices, innovations, and experiences related to sustainability and eco-innovation. These platforms, such as online forums, conferences, and collaborative research initiatives, may be online or in-person. The internal capacity for eco-innovation could also be strengthened through **support networks** that support green relationships among firms, research institutions, and non-governmental organizations (NGOs) to enhance cooperation and knowledge transfer.

These actions and approaches are aligned with the European CAP Network, which aims to enhance the communication of agricultural and rural policy within the EU. One of its main action areas is innovation in agriculture, boosted by information and knowledge exchange among agents participating in agri-food systems (European Commission, 2024a). This is promoted through the "Support Facility for Innovation and Knowledge," which facilitates collaboration among agents interested in exchanging knowledge, expertise, digitalization, and innovation ideas for sustainable farming, forestry, and agriculture in rural communities. This collaboration among agents is built on multi-actor projects, contributing to the strengthening of the agricultural knowledge and innovation system (AKIS) based on intelligent, resilient, and joint efforts towards the sustainable development of rural areas and agriculture (European Commission, 2024d).

Technological and innovation investments can be encouraged by R&D grants and subsidies and public-private partnerships. **R&D subsidies** (e.g., grants, tax reductions, low-interest loans, etc.) provide financial incentives for research and development activities focused on sustainable agricultural practices and technologies. Moreover, **public-private partnerships** encourage collaboration between the public and private sectors to drive technological advancements in sustainable agriculture, leveraging resources, expertise, and infrastructure. In this context of early-stage technological and innovation development, **planning** becomes paramount, suggesting that knowledge of the environment and market characteristics could help design and implement innovation strategies. This could provide insights into competitors or consumers' demands. Finally, eco-innovation in the agri-food sector could be enhanced through **monitoring and evaluation mechanisms**. For example, **digital tools and data analytics** could facilitate the creation of platforms to monitor and evaluate the environmental impact of agricultural practices based on data collected from satellite imaging, IoT sensors, and blockchain for traceability. In addition, **regular**

reporting on sustainability metrics from agricultural and industrial agri-food firms can help track progress toward environmental goals and inform policy adjustments, ensuring transparency and accountability. In this sense, Domínguez et al. (2024) claim that natural language processing techniques and sentiment analysis applied to collecting social media data can be used to assess rural and agricultural policies.

Agriculture has continuously operated in a dynamic environment, which has been converted into a more complex context during the last decades characterized by environmental regulations and economic conditions that lead to risks and opportunities. Rural innovation may be essential for preventing economic and social marginalization, reducing geographical isolation, and fostering green and inclusive economic growth (European Commission, 2024b). Successful innovation in rural areas highly depends on social and human capital. According to the (European Commission, 2024c), strengthening social and human capital and knowledge and innovation systems should be placed in the spotlight of the political agenda. This priority seeks to encourage sustainable development in rural communities by encouraging innovation built on an innovation and environment ecosystem that stimulates system and participatory approaches.

6 | CONCLUSIONS AND IMPLICATIONS

This paper identifies the internal and external factors whose absence constrain the development of eco-innovation within agricultural and industrial agri-food firms and that are thus necessary for this process. The findings complement the scarce literature that explores the relationship between eco-innovation and the agri-food sector (e.g., Rabadán et al., 2020). Internal factors have a major role in firm eco-innovation in agri-food firms, both industrial and agricultural. Agricultural firms should manage their resources and efforts towards planning and R&D investment at the early stages of eco-innovation. As the company progresses in eco-innovation, monitoring and evaluation will become increasingly important. In contrast, industrial agri-food firms should prioritize customer pressure, goal setting, and monitoring at the beginning of the eco-innovation process and all internal and three external factors (i.e., customer pressure, political and regulatory framework, and voluntary agreements) in later stages. The necessary conditions for eco-innovation development differ between these firms due to the nature of their products, with agricultural firms emphasizing early-stage investments and industrial agri-food firms addressing all stages comprehensively.

The social importance of the agri-food and agricultural industry is reflected by improvements in human health, well-being, and food security, emphasizing the need to build a sustainable food system based on a sustainable shift (Depetris-Chauvin et al., 2023) and technological transformation of the industry. Policymakers should consider the agri-food sector because of its contribution to the national innovation ecosystem by adopting technologies developed in other sectors (e.g., healthcare, nutrition, and biotechnology) in the agri-food value chain (Kastelli et al., 2018; Triguero et al., 2018). This idea is related to the concept of the agricultural innovation system, according to which innovation diffusion drivers within the agricultural sector are understood in terms of the interaction and joint efforts of private companies, government, research institutions, and civil society (Blasi et al., 2015; Scott, 2008). Therefore, the connection between agricultural innovation systems and eco-innovation systems may be essential to develop innovation within the agricultural system that positively contributes to the attainment of sustainable development. Further research on both topics could promote eco-innovation activities within agricultural and agri-food firms by providing crucial insights that facilitate sustainability and technological development and thus enable the progress of this traditional sector.

The European Union has introduced different strategies and programs for addressing the current needs of the agri-food sector, but also considering the demands of current and future society and the different stakeholders that participate and could be affected by agri-food policies. The new CAP, the EDG, and the strategies included in this deal evidence the European commitment to sustainable agriculture, devoting resources (e.g., human, financial, technological, etc.) and efforts to create intelligent, resilient, competitive, and sustainable agri-food systems. However, resources are limited, making it impossible to simultaneously address all drivers and barriers to eco-innovation and sustainable practices. This paper's findings provide fundamental insights into implementing policies and strategies that consider the factors that should be prioritized or stimulated to achieve sustainable development in the agri-food sector and rural areas. This enables decision-makers to adapt agri-food policy to the characteristics of different agri-food firms (agricultural and industrial). Policies related to environmental training, investment in R&D, green relationships, and collaboration support networks can strengthen the internal capacity for eco-innovation. In this way, firms can progress towards more sustainable and technologically advanced practices by emphasizing internal factors and encouraging eco-innovation. This progress on sustainability requires information and knowledge on the practices and performances of different firms that are applying eco-innovation or sustainable practices. Collecting and analyzing this information depends on monitoring and evaluation mechanisms. Therefore, policymakers, managers, and scholars could prioritize eco-innovation factors, leading to smart policies and actions that guarantee their strategies' success in the global agri-food industry. These smart and green policies could foster sustainable innovation, mitigating adverse environmental and social issues, such as reducing resource consumption, technological gaps, lack of financing, or demand pressures.

Not all contexts and circumstances are identical, considering that the specific characteristics of firms or regions could influence eco-innovation and sustainability performances. Therefore, this study provides crucial information on which internal and external factors may block eco-innovation activities when they are absent in agricultural and industrial agri-food firms. Considering the European policy scenario, numerous actors are involved in the development of eco-innovation and the agri-food sector. Their collaboration could stimulate the progress of sustainable activities in agriculture (Blasi et al., 2015; Scott, 2008), thus creating a link between agri-food and eco-innovation systems. This would ultimately improve the competitiveness and sustainability of the sector.

This research has certain limitations, which are associated with possibilities for future research. According to Dul (2016), a methodological limitation of NCA is its greater susceptibility to measurement and sampling err than traditional methods. This limitation is explained by the small percentage of sample observations used to draw the ceiling lines. Another limitation is associated with the geographical scope of the study. The study only covered the Spanish agri-food sector. This analysis could be replicated for other geographical areas of the European Union to seek similarities and dissimilarities in eco-innovation within the sector. Beneficial eco-innovation strategies and policies could thus be identified for each national context to boost eco-innovation within different countries. Moreover, collecting data from countries outside the European Union could offer another future research avenue. Finally, the research only focused on the agri-food sector. Hence, this study could be extended to other low-technology sectors to study eco-innovation and sustainability activities and analyze possible differences between sectors. New eco-innovation and sustainability strategies could thus be designed and implemented to fit each sector and national context.

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CONFLICT OF INTEREST STATEMENT

The authors report there are no competing interests to declare.

ORCID

Nuria Chaparro-Banegas https://orcid.org/0000-0002-5907-5643

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APPENDIX A.

Model I: Agricultural firms - Internal Drivers.

Model	R	R^2	Adjusted R^2	RMSE
1	0.381	0.145	0.099	0.413
2	0.381	0.145	0.109	0.410
3	0.378	0.143	0.116	0.409
4	0.371	0.138	0.120	0.408
5	0.344	0.118	0.109	0.410

Model		Unstandardized	SE	Standardized	t	p
1	(intercept)	−0.122	0.205		−0.594	0.554
	Planning	0.375	0.357	0.182	1.048	0.297
	Goal setting	0.023	0.344	0.012	0.066	0.947
	Human capital	−0.136	0.284	−0.061	−0.478	0.634
	R&D	0.323	0.255	0.185	1.266	0.209
	Monitoring and evaluation	0.158	0.223	0.092	0.708	0.481
2	(intercept)	−0.122	0.204		−0.598	0.551
	Planning	0.387	0.305	0.188	1.268	0.208
	Human capital	−0.130	0.267	−0.058	−0.485	0.629
	R&D	0.327	0.246	0.187	1.326	0.188
	Monitoring and evaluation	0.159	0.221	0.093	0.719	0.474
3	(intercept)	−0.176	0.169		−1.042	0.300
	Planning	0.324	0.276	0.158	1.178	0.242
	R&D	0.307	0.242	0.176	1.269	0.207
	Monitoring and evaluation	0.168	0.219	0.098	0.764	0.447
4	(intercept)	−0.145	0.164		−0.886	0.378
	Planning	0.389	0.262	0.189	1.484	0.141
	R&D	0.379	0.223	0.217	1.699	0.093
5	(intercept)	0.001	0.132		0.001	0.999
	R&D	0.600	0.167	0.344	3.602	< .001

Note: method backward; sample size = 99; SE = Standard Error.

Model II: Agricultural firms - External drivers.

Model III: Industrial agri-food firms - Internal drivers.

Model IV: Industrial agri-food firms - External drivers.

Model	R	R^2	Adjusted R^2	RMSE
1	0.355	0.126	0.033	0.132
2	0.354	0.125	0.052	0.130
3	0.331	0.109	0.055	0.130
4	0.299	0.089	0.053	0.130
5	0.272	0.074	0.056	0.130

Coefficients

Model		Unstandardized	SE	Standardized	t	p
1	(intercept)	0.734	0.101		7.291	< .001
	Political and regulatory framework	0.112	0.066	0.267	1.713	0.093
	Subsidies and other financial incentives	0.049	0.054	0.137	0.911	0.367
	Competitor pressure	−0.070	0.064	−0.180	−1.092	0.280
	Customer pressure	0.064	0.060	0.166	1.073	0.289
	Voluntary agreements	−0.017	0.098	−0.024	−0.178	0.859
2	(intercept)	0.719	0.055		13.072	< .001
	Political and regulatory framework	0.112	0.065	0.266	1.725	0.091
	Subsidies and other financial incentives	0.050	0.053	0.138	0.930	0.357
	Competitor pressure	−0.071	0.064	−0.181	−1.109	0.273
	Customer pressure	0.064	0.059	0.167	1.087	0.282
3	(intercept)	0.724	0.055		13.225	< .001
	Political and regulatory framework	0.130	0.062	0.309	2.102	0.041
	Competitor pressure	−0.067	0.063	−0.172	−1.057	0.296
	Customer pressure	0.074	0.058	0.192	1.274	0.209
4	(intercept)	0.735	0.054		13.668	< .001
	Political and regulatory framework	0.106	0.057	0.252	1.840	0.072
	Customer pressure	0.048	0.053	0.125	0.912	0.366
5	(intercept)	0.762	0.045		16.875	< .001
	Political and regulatory framework	0.114	0.057	0.272	2.019	0.049

Note: method backward; sample size = 99; SE = Standard Error.

Model	R	R^2	Adjusted R^2	RMSE
1	0.420	0.177	0.131	0.380
2	0.420	0.176	0.140	0.378
3	0.418	0.175	0.148	0.376
4	0.416	0.173	0.156	0.375

Coefficients

Model		Unstandardized	SE	Standardized	t	p
1	(intercept)	−0.086	0.151		−0.572	0.569
	Planning	0.116	0.267	0.079	0.435	0.665
	Goal setting	−0.048	0.266	−0.030	−0.179	0.858
	Human capital	−0.073	0.192	−0.045	−0.378	0.706
	R&D	0.460	0.239	0.287	1.929	0.057
	Monitoring and evaluation	0.251	0.167	0.172	1.497	0.138
2	(intercept)	−0.088	0.150		−0.589	0.557
	Planning	0.094	0.236	0.064	0.399	0.691
	Human capital	−0.087	0.175	−0.054	−0.497	0.620
	R&D	0.454	0.235	0.283	1.934	0.056
	Monitoring and evaluation	0.247	0.165	0.170	1.494	0.139
3	(intercept)	−0.093	0.148		−0.624	0.534
	Human capital	−0.071	0.169	−0.044	−0.417	0.677
	R&D	0.514	0.180	0.321	2.860	0.005
	Monitoring and evaluation	0.270	0.155	0.186	1.747	0.084
4	(intercept)	−0.125	0.126		−0.991	0.324
	R&D	0.488	0.168	0.304	2.907	0.005
	Monitoring and evaluation	0.261	0.152	0.179	1.712	0.090

Note: method backward; sample size = 97; SE = Standard Error.

Model	R	R^2	Adjusted R^2	RMSE
1	0.377	0.142	0.044	0.154
2	0.377	0.142	0.066	0.153
3	0.373	0.139	0.083	0.151
4	0.364	0.132	0.095	0.150
5	0.309	0.096	0.077	0.152

Coefficients

Model		Unstandardized	SE	Standardized	t	p
1	(intercept)	0.529	0.113		4.693	< .001
	Political and regulatory framework	0.033	0.101	0.049	0.324	0.747
	Subsidies and other financial incentives	0.005	0.068	0.013	0.079	0.937
	Competitor pressure	0.035	0.074	0.078	0.478	0.635
	Customer pressure	0.095	0.099	0.151	0.955	0.345
	Voluntary agreements	0.177	0.099	0.268	1.791	0.080
2	(intercept)	0.528	0.111		4.764	< .001
	Political and regulatory framework	0.035	0.097	0.051	0.358	0.722
	Competitor pressure	0.036	0.071	0.081	0.512	0.611
	Customer pressure	0.095	0.098	0.151	0.969	0.338
	Voluntary agreements	0.179	0.093	0.272	1.925	0.061
3	(intercept)	0.551	0.090		6.118	< .001
	Competitor pressure	0.042	0.069	0.094	0.618	0.540
	Customer pressure	0.097	0.097	0.154	0.995	0.325
	fs_buenasp 0.178		0.092	0.269	1.930	0.060
4	(intercept)	0.549	0.089		6.140	< .001
	Customer pressure	0.122	0.087	0.195	1.405	0.166
	Voluntary agreements	0.178	0.092	0.270	1.950	0.057
5	(intercept)	0.622	0.073		8.508	< .001
	Voluntary agreements	0.204	0.091	0.309	2.255	0.029

Note: method backward; sample size = 50; SE = Standard Error.
Software: JASP Team (2023). JASP (Version 0.18.1) [Computer software].