Journal of Environmental Management 389 (2025) 126150

Contents lists available at ScienceDirect

Journal of Environmental Management

journal homepage: www.elsevier.com/locate/jenvman

Research article

Sustainable technological innovations in agriculture: Financial challenges and investment priorities under the European Green Deal

Francisco José Castillo-Díaz [a], Luis J. Belmonte-Ureña [a,*], Francisco Jesús Gálvez-Sánchez [b], Francisco Camacho-Ferre [c]

[a] Department of Economy and Business, University of Almería, Spain
[b] Department of Financial Economics and Accounting, University of Granada, Melilla, Spain
[c] Department of Agronomy, University of Almería, Spain

ARTICLE INFO

Keywords:
Agricultural finance
Sustainable technological innovations (STIs)
Environmental policies
Spanish agriculture
European Green Deal

ABSTRACT

This study explores the important financial challenges faced by Spanish agricultural and livestock companies to meet stringent environmental regulations without compromising their competitiveness. Using a Delphi method integrated with a systematic literature review, the research identifies key sustainable technological innovations (STIs) that require significant financial investment. Priority STIs include renewable energy sources, water use efficiency, by-product management, alternative fertilizers, and digital technologies, among others, each of which plays a key role in mitigating environmental impacts and aligning with overarching European sustainability frameworks, notably the European Green Deal and the 2030 Agenda for Sustainable Development. The findings support the formulation of specific policy recommendations aimed at overcoming the financial constraints that hinder the adoption of STIs. These include designing progressive financing schemes, launching green credit lines with subsidized interest rates, and increasing agri-environmental subsidies linked to STIs adoption. Furthermore, the study advocates the expansion of public-private investment frameworks and the establishment of technical advisory services to support producers in the selection, integration and implementation of appropriate technologies. These measures are essential to reduce economic barriers and accelerate the sector's technological transition to greater environmental and economic resilience.

1. Introduction

The agricultural and livestock sectors of the European Union are currently facing multifaceted crises that have significantly affected their economic sustainability. Over the past four years, these businesses have faced cascading challenges stemming from the COVID-19 pandemic, the Russian invasion of Ukraine and increasingly severe weather patterns associated with climate change. By 2023, 83 % of European farmers reported a sharp increase in production costs, highlighting the growing vulnerability of primary production systems across the continent. Spain, as the fourth largest agri-food economy in Europe, after Italy, Germany and France, has been particularly affected (European Comission & European Investment Bank, 2023; Jagtap et al., 2022). The Spanish agri-food system, encompassing primary production, agro-industrial transformation, and food and beverage marketing, accounts for 8.9 % of the national Gross Value Added, significantly exceeding the European average of 6.4 %. Furthermore, the sector shows a strong export orientation, particularly in fruits, olive oil, vegetables, and pork products, distinguishing it from its main European competitors (Maudos and Salamanca, 2025).

The profitability challenges in the agri-food sector have deeper structural roots. Decades of declining farm gate prices and escalating production costs have limited the economic performance of primary producers (Mohr et al., 2023). One common response has been an increase in enterprise size, as evidenced by EU-wide agricultural census data showing fewer but larger farms across Member States (European Commission, 2023; Neuenfeldt et al., 2019). However, this strategy alone has proven to be insufficient to address the growing complexity of environmental and financial pressures.

In recent years, these structural challenges have been further exacerbated by the ambitious climate and sustainability policies of the European Union, including the European Green Deal and the "Farm to

* Corresponding author.
E-mail addresses: fcastillo@ual.es (F.J. Castillo-Díaz), lbelmont@ual.es (L.J. Belmonte-Ureña), fjgalvez@go.ugr.es (F.J. Gálvez-Sánchez), fcamacho@ual.es (F. Camacho-Ferre).

https://doi.org/10.1016/j.jenvman.2025.126150
Received 27 January 2025; Received in revised form 25 May 2025; Accepted 6 June 2025

Fork" strategy. These initiatives have introduced transformative targets for 2030, including a 50 % reduction in pesticide use and risk, a 20 % reduction in fertilizer and antimicrobial use, and a requirement for at least 25 % of agricultural land to be certified organic. These targets are closely aligned with the United Nations' Sustainable Development Goals (SDGs) under the 2030 Agenda. To this end, the European Union seeks to implement a model of production and consumption grounded in circular economy principles (European Comission, 2020a; UN, 2015a). Previous research identifies resource efficiency and the adoption of innovative technologies as the primary areas for improvement in circular economy policies (Sanz-Torró et al., 2025). Moreover, funding sources play a critical role in shaping the growth trajectory of the circular economy (Ma et al., 2025).

Achieving these goals requires a fundamental restructuring of food production systems. One of the main avenues toward this transformation is the modernization of agricultural models through the adoption of sustainable technological innovations (STIs) (Cagliero et al., 2021; MAPA & Cajamar, 2022; Mohr et al., 2023). However, the transition to these innovations is financially intensive, requiring substantial capital investments at a time when many producers already face liquidity constraints. Thus, short-, medium-, and long-term financing instruments have become critical, serving functions ranging from addressing input cost inflation to funding technological modernization (European Commission & European Investment Bank, 2023).

In this regard, several public institutions have launched financial support mechanisms to facilitate this transition. In particular, the new Common Agricultural Policy (CAP) incorporates a transversal objective aimed at sectoral modernization, offering dedicated subsidies for STIs adoption. Additionally, programs under the Next Generation EU initiative have targeted digitalization across economic activities, including agriculture. Simultaneously, financial institutions have begun to offer interest rate reductions on loans for environmentally friendly technologies, particularly for equipment designed to reduce the ecological footprint of farming operations (ECB, 2022; MAPA & Cajamar, 2022).

In parallel, the EU has developed a taxonomy to guide sustainable investments, with primary production included as a target sector. Regulation (EU) 2020/852 reinforces the necessity of channeling capital into practices that enhance environmental efficiency in primary production (European Parliament, 2020). Despite these developments, the European Investment Bank (EIB) reported a financing shortfall of € 62.3 billion in 2022, a 33 % increase since 2017 (fi-compass, 2023). This reveals a persistent deficit in the capital required to realize the proposed modernization of the agri-food sector, underscoring the need for a phased investment strategy adapted to the characteristics of diverse production models (Lv et al., 2023; Yuan et al., 2024).

Despite notable regulatory and financial progress at the EU level, significant gaps remain in academic literature. First, there is a lack of research providing clear prioritization criteria for the adoption of STIs in agriculture and livestock farming (Castillo-Díaz et al., 2023). This absence hampers producer decision making and weakens the impact of public policy tools, especially in the face of an annual financing gap exceeding 62 billion euros, a gap that continues to grow (fi-compass, 2023). Furthermore, it constitutes a barrier to sustainability progress. Technological, economic, and informational obstacles emerge as the principal impediments to achieving sustainability through circular economy approaches (Yusuf et al., 2025). To date, there is no evidence-based roadmap outlining which STIs should be prioritized to maximize both environmental and economic outcomes, particularly within a key agri-food economy like Spain. Given that producers cannot feasibly implement all innovations simultaneously, it is essential to develop a progressive, financially sustainable investment plan, with Spain serving as a strategically significant context for such analysis (ECB, 2022; Lv et al., 2023; Maudos and Salamanca, 2025; Monasterolo et al., 2024).

Second, although some studies have identified emerging technologies within specific agricultural or livestock subsectors, there is a lack of integrated cross-sectoral analyses that consider both domains collectively and assess their alignment with the SDGs through expert judgment. This shortcoming limits the development of multi-sector roadmaps capable of identifying shared priorities and synergies between value chains.

Third, much of existing research is based solely on reviews of the literature, lacking primary data derived from experts with first-hand sectoral experience. Fourth, the rapid pace of technological change necessitates ongoing updates to existing studies to maintain their policy relevance and applicability for policy (Gamage et al., 2023; Sánchez-Montesinos et al., 2021; Sanz-Cobena et al., 2017; Subeesh and Mehta, 2021).

This study seeks to address these gaps through an applied analysis of the financial barriers to STI adoption under the European Green Deal, focusing on the Spanish agri-food sector. The research uses a Delphi method, conducted in 2024, to obtain expert input and generate a strategic investment prioritization framework. Spain is presented as a compelling case study, given the technological advancement and diversity of its agri-food system, and its pivotal role within the EU.

Accordingly, the research aims to answer the following questions:

- Q_1: What are the key investment priorities in STIs for Spain's agri-food sector, based on expert insights?
- Q_2: How are these prioritized STIs aligned with the SDGs of the 2030 Agenda?
- Q_3: Which specific technologies are considered strategic within the expert-identified financing priorities?

The general objective of this research is to identify investment priorities in sustainable technological innovations within the Spanish agri-food sector and assess their alignment with the SDGs, using the Delphi methodology. Three specific objectives are pursued:

- OE_1: To identify the main investment priorities in STIs according to expert assessments.
- OE_2: To analyze the relationship between the prioritized STIs and their contribution to the SDGs.
- OE_3: To determine which STIs correspond to the most relevant financing lines, as defined by expert consensus.

To achieve these objectives, the paper is organized as follows: Section 2 presents the theoretical framework and research hypotheses; Section 3 describes the methodology; Section 4 discusses the results and their implications; and Section 5 concludes with policy recommendations and future research directions.

2. Theoretical framework

2.1. Financing needs of the primary sector

The financial pressures faced by the primary sector have profoundly reshaped the borrowing patterns of agricultural and livestock enterprises. Approximately 60 % of these businesses rely on financing, either through self-funding or external sources. Among the most sought-after financial instruments are medium-term loans, credit lines, overdrafts, and factoring. Since 2017, financing volumes for short, medium, and long-term loans have increased by 80 % (European Comission & European Investment Bank, 2023).

As a result of these trends, primary producers are increasingly reliant on external financial resources to meet payment obligations, particularly given the compounding profitability crises affecting the sector. Short-term loans are predominantly used to offset rising input costs or address immediate liquidity shortages, often stemming from the limited self-financing capacity of producers themselves (European Comission & European Investment Bank, 2023; Lv et al., 2023; Yuan et al., 2024). This self-financing deficit has been exacerbated by declining operating incomes, driven by falling farm-gate prices and rising input costs, leaving producers with insufficient resources to meet short-term obligations. Additionally, many farmers lack a robust financial buffer, exacerbating their vulnerability to external shocks (Castillo-Díaz et al., 2023; Key, 2022).

According to the EIB, the total investment shortfall in the EU agri-food sector has increased by 33 % compared to 2017 (fi-compass, 2023). This funding gap poses a critical obstacle to the sector's capacity to implement the technological upgrades required for climate adaptation and mitigation. The breakdown of this shortfall across sub-sectors is particularly illuminating: animal production (18.73 billion euros), non-perennial crops (18.14 billion euros), perennial crops (11.26 billion euros), mixed farming (9.78 billion euros), and other activities (4.32 billion euros).

France, Ireland, and Spain are among the EU Member States where external bank financing is most frequently required by primary farmers (European Commission and European Investment Bank, 2019). Conversely, private or individual financing predominates in Baltic and Eastern European countries. This territorial variation highlights how regional disparities in financing availability influence the economic resilience of agricultural enterprises.

Spain's case is particularly relevant given its strategic role in ensuring EU food security, especially in the supply of vegetables and other key exports to Member States (Castillo-Díaz et al., 2023). Consequently, ensuring adequate access to financial resources for Spanish agricultural producers is not only a national imperative but also a matter of European food sovereignty and economic stability.

A wide range of technological solutions are currently available to the sector, including renewable energy systems, precision agriculture and livestock technologies, digital process automation, agri-biotechnologies, water-efficient systems, and intelligent machinery. However, the scale of the existing financial gap necessitates a phased and strategic approach to modernization (Gamage et al., 2023; Sánchez-Montesinos et al., 2021; Sanz-Cobena et al., 2017; Subeesh and Mehta, 2021). In this process, priority should be given to those technologies with the greatest capacity to cope with the climate crisis and, at the same time, improve the economic efficiency of farms (Castillo-Díaz et al., 2023), as well as adapting to the needs of each agricultural sector (Lv et al., 2023; Yuan et al., 2024).

2.2. *Relationship between environmental sustainability policies and increased demand for financial resources*

In 2015, the United Nations introduced the 2030 Agenda for Sustainable Development, a comprehensive framework that addresses global economic, social, and environmental challenges through 17 SDGs and 169 goals. A core priority of this agenda is to promote sustainable agricultural and livestock practices that balance economic, social, and environmental considerations (UN, 2015).

The European Union has been proactive in implementing the 2030 Agenda, exemplified by initiatives such as the European Green Deal, which seeks to achieve carbon neutrality by 2050. Furthermore, the EU has championed a shift toward a circular economy model, emphasizing sustainable production and consumption practices. Policies like the "Farm to Fork" strategy aim to mitigate the negative externalities of food production and combat climate change (European Comission, 2019, 2020a, 2020b; Sanz-Torró et al., 2025).

Although these sustainability policies are essential for ensuring the long-term viability of the agricultural sector (ECB, 2022; Lv et al., 2023; Yuan et al., 2024), they impose substantial structural and financial demands on enterprises (Castillo-Díaz et al., 2023).

To navigate these challenges, it is critical to develop a clear investment roadmap. Such a roadmap can guide the allocation of financial resources toward priority STIs, enabling enterprises to adopt environmentally sustainable practices while maintaining competitiveness (Lv et al., 2023; Yuan et al., 2024). Moreover, increasing the adoption of STIs has been identified as a key area for improvement to accelerate the transition toward a circular economy model of production and consumption across EU Member States (Sanz-Torró et al., 2025). This is particularly crucial for Spanish agricultural and livestock enterprises, which are recognized for their efficient production systems but face considerable barriers to accessing the capital required for technological upgrades (Castillo-Díaz et al., 2023).

Furthermore, aligning financial mechanisms with sustainability objectives can provide a framework for stakeholders, including policymakers, financial institutions, and industry leaders, to allocate funding effectively. Such alignment ensures that investment efforts are not only targeted but also maximize environmental and economic returns (Castillo-Díaz et al., 2023; Lv et al., 2023; Yuan et al., 2024).

Based on the theoretical analysis and context outlined above, the following research hypotheses were formulated.

- H_1: There are significant differences in investment prioritization for STIs in the Spanish agri-food sector, as perceived by experts, in response to the challenges posed by the European Green Deal and increased financing demands.
- H_2: The STIs prioritized by experts are significantly associated with the achievement of the Sustainable Development Goals outlined in the 2030 Agenda.
- H_3: Certain specific technologies can be considered strategically aligned with the most relevant financing lines identified by expert consensus.

3. Methodology

The methodology employed in this study combines two qualitative scientific techniques to identify priority STIs requiring significant capital investment for agricultural and livestock enterprises in Spain.

3.1. *Expert consultation*

To validate or reject the research hypotheses H_1 and H_2, a Delphi methodology was applied. This qualitative research technique is well established for its effectiveness in facilitating expert consensus on complex and emerging issues through a structured, iterative process involving multiple rounds of anonymous questionnaires (Ghazy et al., 2022; Landeta, 2006; Landeta and Lertxundi, 2024; Moutinho et al., 2024).

The Delphi method has been widely applied across disciplines such as social sciences, public health, economics, and strategic planning, due to its ability to systematize expert judgment in uncertain or underexplored contexts. Participants in this study were selected based on their demonstrated expertise in evaluating investment priorities in STIs within the Spanish agricultural and livestock sectors. All participants responded to a series of structured questionnaires specifically designed to address the study's objectives and hypotheses (Ghazy et al., 2022; Landeta, 2006; Landeta and Lertxundi, 2024; Moutinho et al., 2024).

One of the key strengths of the Delphi method lies in its capacity to encourage individual reflection and iterative refinement of expert opinions, while minimizing the influence of dominant voices through anonymized responses. It is particularly well-suited for contexts requiring the structured aggregation of specialized knowledge, especially when traditional in-person formats such as workshops or focus groups are less feasible or risk groupthink. However, the method also presents limitations, such as the challenge of selecting a balanced expert panel, potential time intensiveness due to multiple rounds, and strong dependence on the quality of questionnaire design and response analysis (Ghazy et al., 2022; Landeta, 2006; Landeta and Lertxundi, 2024; Moutinho et al., 2024).

In comparison to other qualitative techniques (*e.g.*, focus group, workshops), the Delphi method offers several advantages. Its anonymity ensures more candid contributions, its remote and asynchronous nature allows for geographically diverse participation, and its structured iteration fosters rigorous consensus-building (Landeta and Lertxundi, 2024), a particularly valuable asset when addressing complex issues with high strategic relevance, such as STIs financing in agriculture.

- **Participants**

The expert panel included 21 individuals in the first round of surveys, with 14 participants continuing to the second round, where consensus was reached. This sample exceeded the minimum threshold of 10 experts recommended in Delphi studies to ensure reliable results (Landeta, 2006; Landeta and Lertxundi, 2024; Okoli and Pawlowski, 2004).

Experts were selected based on their substantial knowledge of STIs relevant to the agricultural and livestock sectors in Spain, with specific emphasis on mitigating climate change and aligning with the 2030 Agenda's SDGs. All participants had a minimum of five years of professional experience in public or private roles related to agriculture, sustainability, or technological innovation. The educational qualifications were notable: 100 % of the participants had a university degree, 75 % had a master's degree and 50 % had a Ph.D. (Table 1).

Although participants met the required inclusion criteria, their expertise was concentrated on specific agricultural sub-sectors, particularly greenhouse and open-field vegetables, herbaceous crops (e.g., cereals, legumes, oilseeds, and forages), and woody crops (e.g., citrus, olives, almonds). In livestock, their knowledge focused on white pig farming, beef and dairy cattle, and sheep-goat production. While this thematic concentration is a limitation, these subsectors represent the most economically significant domains within Spanish agriculture and livestock production (Maudos and Salamanca, 2025).

- **Questionnaire design**

Two structured questionnaires were developed to guide the Delphi process (MTASE, & INSHT, 2019; Roopa and Rani, 2012). In the first round, open-ended questions solicited expert opinions on STI groups that should be prioritized for short- and medium-term investment, and experts were also asked to align these innovations with specific SDGs.

In the second round, a closed-response questionnaire with a Likert scale (0–10) was implemented. Here, 0 represents "completely disagree" and 10 indicates "completely agree." The Likert scale provided a nuanced capture of expert opinions, aligning with international best practices for Delphi studies (González-Yebra et al., 2023). First-round responses informed the second-round questionnaire.

- **Sampling strategy**

After the first round questionnaire, experts were invited to participate by email, with online surveys conducted using Google Forms to maximize accessibility and efficiency. The iterative design of the Delphi process allowed participants to refine their opinions based on summarized group feedback, enhancing consensus building and data reliability.

The Delphi study was conducted between May and July 2024, providing sufficient time for iterative analysis and refinement of responses. To ensure validity, mechanisms were in place for participants to express objections or additional thoughts at each stage (Landeta, 2006; Landeta and Lertxundi, 2024).

Table 1
Participants' origin in the study.

Origin	Percentage (number)
First round	
Universities and research centers	61.9 % (13)
Private companies	23.8 % (5)
Administration	14.3 % (3)
Second round	
Universities and research centers	50.0 % (7)
Private companies	28.6 % (4)
Administration	21.4 % (3)

Source: Own elaboration.

- **Consensus criteria**

Consensus was achieved when at least 70 % of participants scored an item as 7 or higher on the Likert scale, following internationally recognized criteria (Bernabeu et al., 2021; Collado et al., 2022).

3.2. *Systematic review of scientific literature*

To address Hypothesis H_3, a systematic literature review was conducted following the completion of the Delphi consultation. First, to identify specific STIs within the groups previously established by the expert panel. Second, to correlate the capital investment suggested by the panel with the future capital demand of agricultural and livestock enterprises.

The systematic review followed the snowballing approach (citation chaining), a widely recognized method for tracing key citations and uncovering interconnected knowledge networks (Batlles-delaFuente et al., 2022; Kitchenham, 2004). This process began by analyzing scientific publications written in English, using Scopus as the primary database. Scopus was selected for its comprehensive coverage and status as the largest global scientific repository (Elsevier, 2023).

The search equation included terms such as *STIs, sustainable innovations, green technologies*, and *technological innovations in agriculture and livestock*, with a geographic focus on Spain. The initial search was limited to the 2014–2023 period, reflecting the most relevant and recent literature. Book chapters were excluded in favor of journal articles and conference proceedings, which offered greater methodological consistency (Batlles-delaFuente et al., 2022).

A total of 18 publications were identified in this phase. Eight of these were excluded after analysis of the abstract. The remaining 10 publications formed the basis for initiating the reference chain review procedure and identifying the publications used for the review process. Furthermore, related publications recommended by the publisher on the article download site were included, as well as documents that cited the publications themselves due to the low number of publications identified and the partial adequacy of the publications.

In a second phase, the review incorporated official publications from public and international bodies, including reports from the Directorate-General for Agriculture and Rural Development of the European Commission and the European Investment Bank, as well as the Observatory for the Digitalization of the Spanish Agri-Food Sector, managed by the Government of Spain (MAPA & Cajamar, 2022, 2023). These complementary data sources were critical for contextualizing STIs within the Spanish agricultural sector and ensuring that findings were tailored to local conditions while maintaining relevance to broader European trends.

Overall, 44 publications were reviewed using the snowball method, comprising both academic and institutional sources. This hybrid review approach provided a solid empirical basis for identifying specific STIs aligned with the Delphi panel's priorities and contextualizing them in Spain's political and economic environment.

4. Results

This section presents the findings of the study, highlighting the priority STIs and their implications for agricultural and livestock enterprises in Spain.

4.1. STIs for agricultural and livestock farms

4.1.1. Identification of innovations: first round of consultations

The first round of the Delphi process identified key STIs categories that agricultural and livestock producers in Spain should prioritize to advance environmental sustainability and comply with the SDGs of the 2030 Agenda.

Table 2 shows the main lines of financing identified in the first round of consultations. Their importance will be identified shortly with the results of the second phase (Section 4.1.2). The following were highlighted:

- In the agricultural sector, the following STIs were highlighted: digitization, promotion of biodiversity, proximity markets, renewable energies, robotization, use of alternative fertilizers and phytosanitary products, waste management and reuse of by-products and water efficiency.
- In the livestock sector, the following STIs were highlighted: alternative food, alternative veterinary products, livestock by-product management, livestock digitization, manure management, proximity markets, promotion of biodiversity, renewable energies and water efficiency.

The STIs in Table 2 support several SDGs of the 2030 Agenda, with contributions outlined in Table 3. These innovations improve SDG 2 by promoting sustainable agriculture in economic, social and environmental dimensions, ensuring equitable food production. They also contribute to SDG 12 by encouraging responsible consumption and reducing food waste in the agri-food sector. Additionally, STIs help to achieve SDGs like SDG 3, SDG 6, SDG 9, and SDG 15 through improved veterinary products, climate change solutions, resource efficiency, and ecosystem protection.

4.1.2. Prioritization of innovations: second round of consultations

Figs. 1 and 2 show the consensus reached among respondents during the second phase of the Delphi methodology on which STIs groups should receive the most financial investment from farmers and livestock enterprises (see Fig. 3).

4.1.2.1. Agricultural enterprises. Fig. 1 illustrates that the highest investment priority for agricultural enterprises is the implementation of renewable energy systems. In second place are technologies aimed at improving water-use efficiency, followed by waste and by-product management solutions. Ranked fourth and fifth, respectively, are the adoption of alternative fertilizers (*e.g.*, biofertilizers) and alternative plant protection products (*e.g.*, biopesticides). Technologies associated with digitalization occupy the sixth position. Biodiversity enhancement

Table 2
Agricultural and livestock practices that will capitalize the resources of Spanish agricultural and livestock farms.

Agriculture	Livestock
Digitization: sensor technology, IoT, AI	Alternative feed sources and feed additives
Promotion of biodiversity	Alternative veterinary products
Proximity markets	Livestock by-product management
Renewable energy sources	Livestock digitization: sensor technology, IoT, AI
Robotization	Manure management, especially slurry
Use of alternative fertilizers	Proximity markets
Use of alternative plant protection products	Promotion of biodiversity
Waste management and by-product utilization	Renewable energy sources
Water efficiency	Robotization
	Water efficiency

Source: Own elaboration. Note: STI categories are listed alphabetically.

Table 3
Relationship between STIs and SDGs met by agricultural and livestock farms.

Sustainable Technological Innovation (STIs)*	Related SDGs	Explanation
Agriculture		
Digitalization: sensor technology, IoT, artificial intelligence, etc.	SDG 2, SDG 9, SDG 12	- Adoption of advanced technologies - Improved production efficiency - Improved agricultural productivity
Promotion of biodiversity	SDG 2, SDG 12, SDG 15	- Biodiversity and ecosystem protection - Sustainable management of natural resources
Proximity market	SDG 2, SDG 8, SDG 11, SDG 12	- Local consumption and reduction of transportation - Support for small local farms - Strengthening local economies
Renewable energy sources	SDG 2, SDG 7, SDG 12, SDG 13	- Use of renewable energy - Reduced dependence on fossil fuels
Robotization	SDG 2, SDG 9, SDG 12	- Adoption of advanced technologies, - Improved Resource Use Efficiency - Improved agricultural productivity
Use of alternative fertilisers	SDG 2, SDG 12	- Improved agricultural productivity and sustainability - Responsible use of fertilizers
Use of alternative plant protection products	SDG 2, SDG 12, SDG 15	- Improved agricultural productivity - Reduced environmental impact of agrochemicals - Biodiversity protection
Waste management and use of by-products	SDG 2, SDG 9, SDG 12	- Integral use of resources - Development of industries that reuse by-products
Water efficiency	SDG 2, SDG 6, SDG 12	- Water efficiency and conservation - Efficient use of resources
Livestock		
Alternative feed sources and feed additives	SDG 2, SDG 12, SDG 13	- Improved food productivity and sustainability - Sustainable food sources, - Reduction of methane emissions
Alternative veterinary products	SDG 2, SDG 3, SDG 12	- Improved animal health and reduction of antimicrobial resistance - Sustainable use of veterinary products
Livestock by-product management	SDG 2, SDG 9, SDG 12	- Integral use of resources - Development of industries that reuse by-products
Livestock digitization: sensor technology, IoT, AI	SDG 2, SDG 9, SDG 12	- Adoption of advanced technologies, - Resource use efficiency - Improved agricultural productivity
Manure management (mainly manure)	SDG 2, SDG 6, SDG 7, SDG 12, SDG 13	- Prevention of water pollution - Improved waste management - Reduction of greenhouse gas emissions - Generation of biogas from manure
Proximity markets	SDG 2, SDG 8, SDG 11, SDG 12	- Local consumption and reduction of transportation - Support for small local farms - Strengthening local economies
Promotion of biodiversity	SDG 2, SDG 12, SDG 15	- Protection of biodiversity and ecosystems

(*continued on next page*)

Table 3 (*continued*)

Sustainable Technological Innovation (STIs)*	Related SDGs	Explanation
Renewable energy sources	SDG 2, SDG 7, SDG 12, SDG 13	- Sustainable management of natural resources - Use of renewable energy - Reduced dependence on fossil fuels
Robotization	SDG 2, SDG 9, SDG 12	- Adoption of advanced technologies, - Improved production efficiency
Water efficiency	SDG 2, SDG 6, SDG 12	- Water efficiency and conservation, - Efficient use of resources

Source: Own elaboration. Note: STI categories are listed in alphabetical and sectoral order.

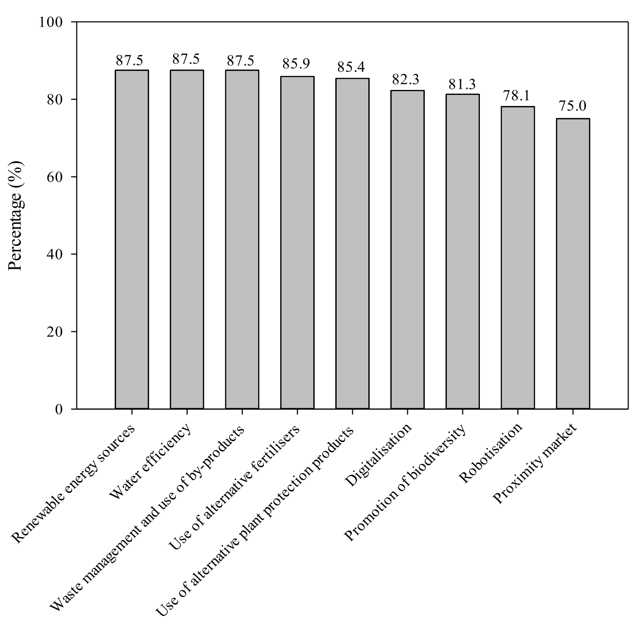

Fig. 1. STIs Requiring the greatest capital investment for Spanish agricultural enterprises. Scale.
Source: Own elaboration.

measures, such as crop diversification and agroecological practices, rank seventh. Robotization and the development of proximity markets are positioned at the lower end of the priority list, likely due to the relatively early stage of their technological development and limited adoption at scale within the sector.

4.1.2.2. Livestock enterprises. Fig. 2 highlights the importance of differences in STIs concerning the future capital demand for Spanish livestock enterprises. The expert panel indicated that four groups of innovations should concentrate capital investment: livestock by-product management, manure management (slurry), digitalization, and alternative veterinary products. These were followed in priority by alternative feed sources, biodiversity promotion, robotization, and water-use efficiency technologies. In particular, there was no consensus on investments in renewable energy systems or proximity markets within the livestock sector. This divergence can be explained by the fact that the primary environmental pressures in livestock production stem from manure management and feed-related emissions, including those associated with feed transportation. As a result, experts prioritized technologies capable of directly addressing these critical environmental challenges.

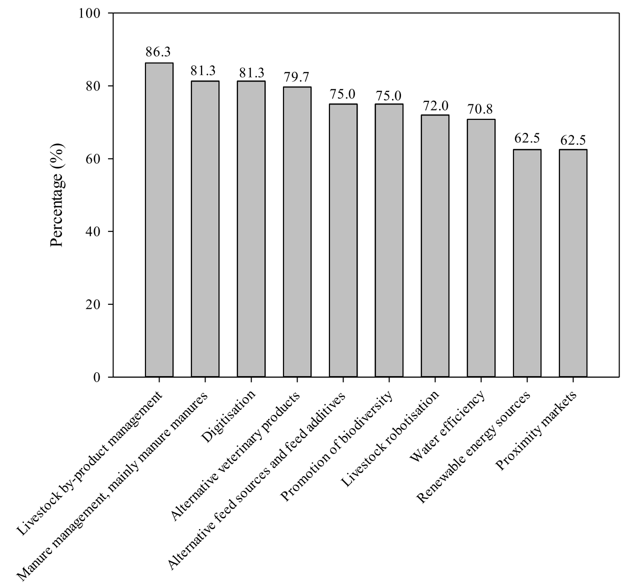

Fig. 2. STIs that require the largest capital investment for Spanish livestock enterprises. Scale.
Source: Own elaboration.

4.1.3. STIs applicable to each group of innovations recommended by specialists

Table 4 presents the specific STIs corresponding to the groups recommended by the specialists, based on the literature review conducted in this study. These innovations contribute to mitigating climate change and aligning with the sustainability criteria established by the SDGs of the 2030 Agenda. The table offers a detailed classification of technologies applied in the agricultural and livestock sectors, organized into several specific categories. Relevant practices have also been included for the categories that did not reach consensus in the Delphi methodology (Figs. 1 and 2).

The alternative fertilizers group includes technologies such as optimized fertilizer use through precision agriculture, the use of nitrification inhibitors, organic fertilizers, controlled release fertilizers, and microalgae-based fertilizers. These practices aim to improve the efficiency of nutrient use, reduce greenhouse gas emissions, and minimize pollution.

The alternative plant protection products group highlights the use of biocontrol (e.g., bioinsecticides, biofungicides), integrated pest management, pheromone traps, and crop biostimulation to increase resistance to pests and diseases. These practices aim to reduce dependence on chemical products and promote biological control, with the goal of mitigating negative environmental impacts.

The digitalization group, which includes sensors, the Internet of Things, and artificial intelligence, is reflected in optimizing fertilizers, remotely monitoring animal welfare, and using data management platforms, all with the objective of improving decision making and increasing efficiency.

In the field of robotics, the mentioned innovations include robots for automated planting and harvesting, automated milking systems in livestock farming, and drones for various agricultural tasks. These technologies enable the automation of repetitive processes, thus improving productivity and reducing labor costs.

Promotion of biodiversity includes techniques such as agroforestry, crop rotation, diversification with native species, and the establishment of agroecological systems that combine crops and livestock. These practices improve the resilience of the ecosystem and promote long-term sustainability.

Finally, in the waste management and by-product utilization group,

Fig. 3. Recommendations made to public and private stakeholders.
Source: Own elaboration.

composting, anaerobic digestion, and biogas production are highlighted. These technologies capitalize on livestock and agricultural by-products to generate renewable energy and fertilizers, contributing to the circular economy and reducing waste.

5. Discussion

This study aimed to identify the most relevant investment priorities in STIs for Spain's primary production sector. To achieve this, a Delphi-based expert consultation was conducted, involving professionals with extensive knowledge of agriculture, sustainability, and technological innovation.

5.1. Discussion of results

The findings obtained from the expert panel confirmed all three research hypotheses (H_1, H_2, and H_3) proposed in Section 2.

First, with regard to H_1 and H_2, the experts highlighted different investment priorities in both agriculture and livestock. In the agricultural sector, the top STIs priorities included renewable energy systems, water-use efficiency technologies, waste and by-product management, and alternative fertilizers. In the livestock sector, an emphasis was placed on by-product and manure management, digitalization technologies, and alternative veterinary products. These findings are clearly reflected in Figs. 1 and 2.

The identified priorities are partially aligned with the investment trends reported by the European Commission and the European Commission& European Investment Bank (2023). According to their data, European agricultural and livestock enterprises anticipate increasing capital needs due to increasing environmental compliance requirements and climate adaptation pressures. Nearly 90 % of enterprises estimate needing between 10,000 and 100,000 euros to reduce energy consumption, improve irrigation efficiency, implement organic practices, digitize operations, or invest in renewable energy systems (Table 5).

A notable divergence emerged between the expert panel and livestock producers regarding renewable energy investments. Although livestock enterprises report high energy consumption, the panelists did not prioritize energy-related STIs for this sector. This apparent discrepancy can be explained by two key factors:

- The main sources of greenhouse gas emissions in the livestock sector come from manure handling, emissions from the animal itself, which can be controlled by feed additives, and feed transport, second, since the main sources of greenhouse gas emissions in the livestock sector come from manure handling, emissions from the animal itself, which can be controlled by feed additives, and feed transport (Ahlberg-Eliasson et al., 2021; Martínez-Fernández et al., 2014; Pepeta et al., 2024).
- Spain has experienced a rapid expansion of renewable energy on farms, particularly solar photovoltaic systems, accelerated by the post-Ukraine war energy crisis and incentivized by EU funding schemes for energy transition. These developments have been especially prominent in monogastric livestock systems, such as pig and poultry farms, which coincides with the professional backgrounds of several panelists, as noted in the methodology section (Castillo-Díaz et al., 2024).

Therefore, the productive specialization of the respondents likely influenced their prioritization of investment areas in sustainable technological innovations.

Second, the study also confirmed hypothesis H_2, as prioritized STIs were consistently related to specific SDGs, particularly SDGs 2, 3, 6, 9, 12, and 15. These results suggest a clear connection between expert-identified STI categories and multidimensional sustainability targets. Other research conducted within the EU framework contrasts with our results. These have identified the relationship between the SDGs and the environmental variable on a multisectoral scale, represented by greenhouse gas emissions. These investigations indicated that SDG 4 and SDG 17 contribute directly to the driving force of environmental policy. They also indicated that other SDGs, such as SDGs 1, 3, 8 and 15, drive the achievement of the goals indirectly (Kluza et al., 2021). Other research indicates that, in the agricultural sector, the most relevant SDGs in the economic domain are 1 and 2; in the social domain, 3, 5, 10 and 12; and in the environmental domain, 6, 13, 15 and 17 (Atapattu et al., 2024). Therefore, the SDGs identified in this study partially overlap with those found in the broader literature, reinforcing the idea that STIs are effective instruments for advancing sustainability in its economic, social, and environmental dimensions.

5.2. Policy recommendations

Based on the findings of expert consultations and systematic review of the literature (Figs. 1 and 2; Tables 2–4), this study proposes a series of policy and financial recommendations to improve the adoption of sustainable technological innovations in the Spanish agri-food sector.

First, it is recommended to establish progressive and phased

Table 4
Examples of STIs to be applied in each group of practices recommended by respondents.

STIs group	Practice	Reference
Use of alternative fertilizers	- Optimized fertilizer use (Precision agriculture)	Thamarai et al. (2024)
	- Use of nitrification inhibitors	Sanz-Cobena et al. (2017)
	- Organic fertilizers (compost, biofertilizers)	(Castillo-Díaz et al., 2022; Gamage et al., 2023; Romero-Gámez and Suárez-Rey, 2020)
	- Controlled-release fertilizers	Govil et al. (2024)
Use of alternative plant protection products	- Use of biological control products (bioinsecticides, biofungicides, biobactericides, etc.)	Sánchez-Montesinos et al. (2021)
	- Integrated pest management with beneficial organisms (e.g., natural predators) or techniques like biofumigation	(Acebedo et al., 2022; Castillo-Díaz et al., 2022)
	- Use of pheromone or attractant traps	Ahmad and Kamarudin (2011)
Digitalization: sensor technology, IoT, AI, etc.	- Crop digitalization for optimizing fertilizer and water use through sensors and AI tools	(MAPA & Cajamar, 2022; Subeesh and Mehta, 2021)
	- Soil moisture sensors for precision irrigation	(MAPA & Cajamar, 2022; Subeesh and Mehta, 2021)
	- Data management platforms for integrated farm management	(MAPA & Cajamar, 2022; Subeesh and Mehta, 2021)
	- AI tools for resource optimization and improving agricultural and livestock productivity	MAPA & Cajamar (2022)
	- Drones for crop monitoring, soil health, and input application	(MAPA & Cajamar, 2022; Subeesh and Mehta, 2021)
	- Sensors and IoT for remote monitoring of environmental and animal conditions (e.g., gases, animal health)	(MAPA & Cajamar, 2022; Terence et al., 2024)
	- Remote monitoring of animal welfare using IoT	(Bhaskaran et al., 2024; MAPA & Cajamar, 2022)
	- Precision feeding	Zuidhof (2020)
Robotization	- Robots for automated planting and harvesting	(Fountas et al., 2020; MAPA & Cajamar, 2022; Subeesh and Mehta, 2021)
	- Robots for automatic milking and livestock management	(MAPA & Cajamar, 2022; Rodenburg, 2017)
	- Robots for pruning, weeding, phenotyping, and other repetitive tasks in agriculture	(Fountas et al., 2020; MAPA & Cajamar, 2022; Subeesh and Mehta, 2021)
	- Robots for sorting and packaging in the agroindustry	(Fountas et al., 2020; MAPA & Cajamar, 2022; Subeesh and Mehta, 2021)
	- Robots for pest and disease control	(Fountas et al., 2020; MAPA & Cajamar, 2022)
Promotion of biodiversity	- Agroforestry	Abdul-Salam et al. (2022)
	- Crop rotation to improve soil health	(Chan and Heenan, 1996; Strobl, 2022)
	- Crop diversification with native species	Strobl (2022)
	- Agroecological systems combining crops, trees, and livestock	Puech and Stark (2023)
	- Promotion of ecological corridors and living hedges in crops	Wehling and Diekmann (2009)
	- Restoration of degraded soils through integrated systems	Marín-Guirao et al. (2019)
Renewable energy sources	- Installation of solar panels on farms for energy self-sufficiency	Schallenberg-Rodriguez et al. (2023)
	- Use of biogas produced from manure and agricultural by-products	Li et al. (2016)
	- Use of agricultural biomass to generate energy	Saleem (2022)
Water efficiency	- Smart irrigation systems (drip irrigation with soil moisture sensors)	(Jain, 2023; MAPA & Cajamar, 2022)
	- Water recirculation and reuse in livestock farming	Cornejo-Ponce et al. (2020)
	- Desalination and wastewater treatment for agricultural use	(Burn et al., 2015; J. Hristov et al., 2021)
Proximity markets	- Promotion of direct sales and consumption of local products	Enthoven & Van den Broeck (2021)
	- Digital platforms for sales and distribution in local markets	(MAPA & Cajamar, 2022; Yang et al., 2024)
Alternative veterinary products	- Alternative veterinary products (phytobiotics, prebiotics, probiotics)	(Rafiq et al., 2022; Shehata et al., 2022)
	- Promotion of animal health through natural nutritional supplements	Guil-Guerrero et al. (2016)
Waste management and by-product utilization	- Anaerobic digestion of manure	Ahlberg-Eliasson et al. (2021)
	- Composting of manure and agricultural by-products to produce organic fertilizers	Gilardi et al. (2016)
	- Use of manure in biogas systems	Li et al. (2016)
	- Separation and treatment of manure solids and liquids for more efficient use	Rico et al. (2012)
	- Transformation of waste into value-added products (bioplastics, fertilizers)	(Castillo-Díaz et al., 2022; Schrader et al., 2015)
	- Use of livestock by-products for the food industry	Achmon et al. (2016)
Alternative feed sources and feed additives	- Additives in the diet (e.g., fats, tannins)	(A. N. Hristov, 2024; Martínez-Fernández et al., 2014; Pepeta et al., 2024)
	- Use of insects as an alternative protein source for livestock	(Belhadj Slimen et al., 2023; Gałęcki et al., 2021)

Source: Own elaboration.

financing programs to support the adoption of STIs, as their implementation is not economically feasible for many farms, particularly small and medium-sized operations. These programs should prioritize technologies that offer the greatest environmental benefits and the highest economic returns, based on the findings of this study. Furthermore, financing schemes should be tailored to the specific characteristics of each farm, requiring prior technical and financial feasibility assessments.

Second, financial institutions should develop targeted financial instruments, such as subsidized credit lines or hybrid loan products,

Table 5
Investment volume required by European primary sector companies to improve environmental sustainability and address climate change. In percent.

Investment Type	1-10,000 €	10,001–100,000 €	100,001–500,000 €	500,001–1,000,000 €	>1,000,000 €
Reduce energy and fuel consumption	41	60	53	49	34
Irrigation, crop protection, etc.	49	34	41	41	53
Organic farming	8	4	6	8	10
Digitalization of operations	1	1	0	1	1
Renewable energy sources	1	1	0	1	2

Source: Own elaboration based on European Comission and European Investment Bank (2023).

directly linked to the implementation of prioritized STIs. These instruments should include grace periods, reduced interest rates, and eligibility criteria based on verifiable environmental impact, in order to enhance their effectiveness and alignment with the SDGs.

Third, public administrations should reinforce existing support mechanisms, including ecoschemes and agri-environmental subsidies, by incorporating more rigorous technological criteria. Although the implementation of STIs is currently considered in the allocation of subsidies, it would be advisable to strengthen this link, providing explicit incentives for the adoption of sustainable technologies.

Fourth, given the strategic importance of the primary sector for the Spanish economy, it is essential to promote public–private financing mechanisms, such as revolving funds or shared guarantee schemes. This approach would help mitigate perceived financial risks and expand access to capital for the adoption of STIs.

Fifth, recognizing that most Spanish farms are small and medium enterprises (SMEs), flexible and accessible financial tools should be designed specifically for SMEs, young farmers and cooperatives, addressing their unique financial and operational constraints.

Sixth, private investment in R&D, innovation and sustainability should be encouraged through fiscal incentives, including corporate and personal income tax deductions. These incentives would stimulate both companies and individual producers to invest in sustainable technologies.

Finally, it is crucial to establish complementary technical advisory services to support producers in the evaluation, selection, and implementation of appropriate STIs. This requires promoting public–private partnerships to strengthen agricultural extension systems and improve technology transfer in rural areas.

6. Conclusions

This study identifies nine priority STIs groups for agriculture, renewable energy, water efficiency, waste management, alternative fertilizers and plant protection products, digital transformation, biodiversity promotion, agricultural robotization, and proximity markets. Parallelly, eight priority areas for the livestock sector were identified, including byproduct management (particularly manure), livestock digitalization, alternative veterinary products, alternative feed sources, biodiversity promotion, robotization, and water use efficiency.

The results emphasize the critical role of customized short- and long-term financing mechanisms to enable the adoption of these innovations. Public and private capital must be strategically aligned to support structural transformations in agricultural and livestock production systems, ensuring alignment with the SDGs of the 2030 Agenda. To this end, the study advocates for the creation of a public-private subsidized loan program, which could mitigate financial barriers for producers while driving investment in STIs. Such a program could serve as a scalable model for addressing the financial challenges facing agricultural systems around the world.

The theoretical implications of this research extend to the fields of sustainability transitions and sociotechnical systems. By explicitly linking financial mechanisms to structural transformations in production methods, this study bridges a key gap in the existing literature, which often neglects the financial dimension of technological adoption.

On a practical level, the study provides concrete policy recommendations for the design of adaptive financial instruments, sensitive to the regional heterogeneity of agricultural practices, technological readiness, and environmental constraints. The results also point to the urgent need for:

- Progressive and tailored financing and subsidy programs.
- Expansion and reinforcement of existing agri-environmental support schemes.
- Creation of targeted credit lines related to the implementation of STIs.
- Dedicated grant mechanisms for SMEs, cooperatives and young farmers.
- Tax incentives to promote private investment in sustainable technologies by both corporations and individual producers.
- Crucially, the establishment of technical advisory services to support producers in selecting, planning, and implementing appropriate innovations.

However, the study is not without limitations. First, it focuses exclusively on primary production in Spain, which may constrain the generalizability of its findings. However, the Spanish agri-food system offers a representative and advanced model in the European context. Second, the panel of experts consulted was largely concentrated in specific subsectors, greenhouse and open field vegetables, herbaceous and woody crops (such as citrus, olives, and almonds), and livestock farming focused on white pigs, beef and dairy cattle, and sheep–goat systems, which may have influenced the results.

Future research should include other countries and assess the economic impact of STIs in various contexts. Long-term studies are also needed to evaluate the effectiveness of financial mechanisms and the influence of policy, technology, and market dynamics on their adoption. This would enhance understanding of how to achieve sustainable agriculture without compromising competitiveness.

CRediT authorship contribution statement

Francisco José Castillo-Díaz: Writing – review & editing, Writing – original draft, Visualization, Validation, Supervision, Software, Resources, Project administration, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Luis J. Belmonte-Ureña:** Writing – review & editing, Writing – original draft, Visualization, Validation, Supervision, Software, Resources, Project administration, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Francisco Jesús Gálvez-Sánchez:** Writing – review & editing, Writing – original draft, Visualization, Validation, Supervision, Software, Resources, Project administration, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Francisco Camacho-Ferre:** Writing – review & editing, Writing – original draft, Visualization, Validation, Supervision, Software, Resources, Project administration, Methodology, Investigation, Formal analysis, Data curation, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgements

The authors would like to thank the University of Almeria and the 'Plan Propio de Investigación y Transferencia- PPIT 2024' and Proyectos de Fortalecimiento de Grupos de Investigación, en el marco del en el marco del Programa Operativo FEDER Andalucía 2021-2027. Número: P_FORT_GRUPOS_2023/13.

Data availability

No data was used for the research described in the article.

References

Abdul-Salam, Y., Ovando, P., Roberts, D., 2022. Understanding the economic barriers to the adoption of agroforestry: a Real Options analysis. J. Environ. Manag. 302 (PA), 113955. https://doi.org/10.1016/j.jenvman.2021.113955.

Acebedo, M.M., Diánez, F., Santos, M., 2022. Almeria's green pest management revolution: an opportunity that arose from a food safety alert. Agronomy 12 (3), 1–13. https://doi.org/10.3390/agronomy12030619.

Achmon, Y., Harrold, D.R., Claypool, J.T., Stapleton, J.J., Vandergheynst, J.S., Simmons, C.W., 2016. Assessment of tomato and wine processing solid wastes as soil amendments for biosolarization. Waste Manag. 48, 156–164. https://doi.org/10.1016/j.wasman.2015.10.022.

Ahlberg-Eliasson, K., Westerholm, M., Isaksson, S., Schnürer, A., 2021. Anaerobic digestion of animal manure and influence of organic loading rate and temperature on process performance, microbiology, and methane emission from digestates. Front. Energy Res. 9 (December), 1–16. https://doi.org/10.3389/fenrg.2021.740314.

Ahmad, S.N., Kamarudin, N., 2011. Pheromone trapping in controlling key insect pests: progress and prospects. Oil Palm Bulletin 62 (May 2011), 12–24.

Atapattu, A.J., Ranasinghe, C.S., Nuwarapaksha, T.D., Udumann, S.S., Dissanayaka, N.S., 2024. Sustainable agriculture and sustainable development goals (SDGs). In: Emerging Technologies and Marketing Strategies for Sustainable Agriculture, pp. 1–27. https://doi.org/10.4018/979-8-3693-4864-2.ch001 (Issue April.

Batlles-delaFuente, A., Abad-segura, E., González, M., Cortés-García, F.J., 2022. An evolutionary approach on the framework of circular economy applied to agriculture. Agronomy 12, 620. https://doi.org/10.3390/agronomy12030620.

Belhadj Slimen, I., Yerou, H., Ben Larbi, M., M'Hamdi, N., Najar, T., 2023. Insects as an alternative protein source for poultry nutrition: a review. Front. Vet. Sci. 10 (August). https://doi.org/10.3389/fvets.2023.1200031.

Bernabeu, A., Carratala-Munuera, C., Quesada, J.A., Llacer, J., Lopez-pineda, A., Sellers, F., Gil-Guillen, V., Bernabeu, R., Cheikh-Moussa, K., Orozzco-Beltran, D., 2021. Expert consensus for primary management of reproductive health: a Delphi study. Ir. J. Med. Sci. 190, 677–684. https://doi.org/10.1007/s11845-020-02380-7.

Bhaskaran, H.S., Gordon, M., Neethirajan, S., 2024. Development of a cloud-based IoT system for livestock health monitoring using AWS and python. Smart Agric. Technol. 9 (June), 100524. https://doi.org/10.1016/j.atech.2024.100524.

Burn, S., Hoang, M., Zarzo, D., Olewniak, F., Campos, E., Bolto, B., Barron, O., 2015. Desalination techniques - a review of the opportunities for desalination in agriculture. Desalination 364, 2–16. https://doi.org/10.1016/j.desal.2015.01.041.

Cagliero, R., Licciardo, F., Legnini, M., 2021. The evaluation framework in the new CAP 2023–2027: a reflection in the light of lessons learned from rural development. Sustainability 13 (10). https://doi.org/10.3390/su13105528.

Castillo-Díaz, F.J., Batlles-delafuente, A., Belmonte-Ureña, L.J., Camacho-Ferre, F., 2023. Impact of environmental policies on the profitability of greenhouse agriculture in southeastern Spain. Sustain. Dev. 31 (5), 3639–3656. https://doi.org/10.1002/sd.2616.

Castillo-Díaz, F.J., Belmonte-Ureña, L.J., Abad-Segura, E., Camacho-Ferre, F., 2024. Perception of photovoltaic energy consumption in the Spanish primary sector. An environmentally profitable alternative. J. Environ. Manag. 357 (March), 120840. https://doi.org/10.1016/j.jenvman.2024.120840.

Castillo-Díaz, F.J., Belmonte-Ureña, L.J., Camacho-Ferre, F., Tello-Marquina, J.C., 2022. Biodisinfection as a profitable fertilization method for horticultural crops in the framework of the circular economy. Agronomy 12, 521. https://doi.org/10.3390/agronomy12020521.

Chan, K.Y., Heenan, O.P., 1996. The influence of crop rotation on soil structure and soil physical properties under conventional tillage. Soil Tillage Res. 37 (2–3), 113–125. https://doi.org/10.1016/0167-1987(96)01008-2.

Collado, R.C., Ramos, C.F., Casado, I.G., Macián, F.M., 2022. Delphi consensus on the diagnosis and treatment of patients with short stature in Spain: GROW - SENS study. J. Endocrinol. Investig. 45 (4), 887–897. https://doi.org/10.1007/s40618-021-01696-0.

Cornejo-Ponce, L., Vilca-Salinas, P., Lienqueo-Aburto, H., Arenas, M.J., Pepe-Victoriano, R., Carpio, E., Rodríguez, J., 2020. Integrated aquaculture recirculation system (Iars) supported by solar energy as a circular economy alternative for resilient communities in arid/semi-arid zones in southern south America: a case study in the camarones town. Water (Switzerland) 12 (12), 1–17. https://doi.org/10.3390/w12123469.

ECB, 2022. Good Practices for Climate-Related and Environmental Risk Management. Eurpean Cental Bank. November, 2–3.

Elsevier, 2023. Scopus. https://www.elsevier.com/es-es/solutions/scopus.

Enthoven, L., Van den Broeck, G., 2021. Local food systems: reviewing two decades of research. Agric. Syst. 193, 103226. https://doi.org/10.1016/j.agsy.2021.103226.

European Comission, 2019. The European Green Deal. Office of the European Union, Brussels, Belgium, pp. 1–28.

European Comission, 2020a. A Farm to Fork Strategy for a Fair, Healthy and Environmentally-Friendly Food System. Office of the European Union, Brussels, Belgium, pp. 1–23.

European Comission, 2020b. A new circular economy action plan. In: For a Cleaner and More Competitive Europe. Office of the European Union. Brussels, Belgium, 23. https://eur-lex.europa.eu/resource.html?uri=cellar:9903b325-6388-11ea-b735-01aa75ed71a1.0018.02/DOC_1&format=PDF.

European Comission, & European Investment Bank, 2023. Survey on financial needs and access to finance of EU agricultural enterprises 1–72. https://www.fi-compass.eu/sites/default/files/publications/Survey_on_financial_needs_and_access_to_finance_of_EU_agricultural_enterprises_0.pdf.

European Commission, 2023. EXPLORE FARM INCOMES Farm Economics Overview Based on 2021 FADN Data. DG Agriculture and Rural Development. Analysis and Outlook Unit, November.

European Parliament, 2020. Regulation (EU) 2020/852 of the European Parliament and of the Council of 18 June 2020 on the establishment of a framework to facilitate sustainable investment. Off. J. Eur. Union 210–230, 2018(2. https://eur-lex.europa.eu/legal-content/ES/TXT/PDF/?uri=CELEX:32020R0852.

fi-compass, 2023. Financing Gap in the Agriculture and Agri-Food Sectors in the EU, Report, vol. 32. EARFD. https://www.fi-compass.eu/library/market-analysis/financing-gap-eu-agricultural-and-agri-food-sectors.

Fountas, S., Mylonas, N., Malounas, I., Rodias, E., Santos, C.H., Pekkeriet, E., 2020. Agricultural robotics for field operations. Sensors 1–27.

Gałęcki, R., Zielonka, Ł., Zasępa, M., Gołębiowska, J., Bakuła, T., 2021. Potential utilization of edible insects as an alternative source of protein in animal diets in Poland. Front. Sustain. Food Syst. 5 (June), 1–8. https://doi.org/10.3389/fsufs.2021.675796.

Gamage, A., Gangahagedara, R., Gamage, J., Jayasinghe, N., Kodikara, N., Suraweera, P., Merah, O., 2023. Role of organic farming for achieving sustainability in agriculture. Farming Syst. 1 (1), 100005. https://doi.org/10.1016/j.farsys.2023.100005.

Ghazy, S., Tang, Y.H., Mugumya, K.L., Wong, J.Y., Chan, A., 2022. Future-proofing Klang Valley's veins with REBET: a framework for directing transportation technologies towards infrastructure resilience. Technol. Forecast. Soc. Change 180 (February), 121666. https://doi.org/10.1016/j.techfore.2022.121666.

Gilardi, G., Pugliese, M., Gullino, M.L., Garibaldi, A., 2016. Effect of different organic amendments on lettuce fusarium wilt and on selected soilborne microorganisms. Plant Pathol. 65 (5), 704–712. https://doi.org/10.1111/ppa.12460.

González-Yebra, O., Aznar-Sánchez, J.A., Velasco-Muñoz, F., López-Felices, B., 2023. A methodological proposal for the sociocultural valuation of ecosystem services. Agric. Econ. 69 (2), 68–77. https://doi.org/10.17221/298/2022-AGRICECON.

Govil, S., Van Duc Long, N., Escribà-Gelonch, M., Hessel, V., 2024. Controlled-release fertiliser: recent developments and perspectives. Ind. Crop. Prod. 219 (June). https://doi.org/10.1016/j.indcrop.2024.119160.

Guil-Guerrero, J.L., Ramos, L., Moreno, C., Zúñiga-Paredes, J.C., Carlosama-Yépez, M., Ruales, P., 2016. Plant-food by-products to improve farm-animal health. Anim. Feed Sci. Technol. 220, 121–135. https://doi.org/10.1016/j.anifeedsci.2016.07.016.

Hristov, A.N., 2024. Invited review: advances in nutrition and feed additives to mitigate enteric methane emissions. J. Dairy Sci. 107 (7), 4129–4146. https://doi.org/10.3168/jds.2023-24440.

Hristov, J., Barreiro-Hurle, J., Salputra, G., Blanco, M., Witzke, P., 2021. Reuse of treated water in European agriculture: potential to address water scarcity under climate change. Agric. Water Manag. 251 (March), 106872. https://doi.org/10.1016/j.agwat.2021.106872.

Jagtap, S., Trollman, H., Trollman, F., Garcia-garcia, G., Parra-l, C., Duong, L., Martindale, W., Munekata, P.E.S., Lorenzo, J.M., Hdaifeh, A., 2022. The Russia-Ukraine conflict: its implications for the global food supply chains. Foods 1–23. February.

Jain, R.K., 2023. Experimental performance of smart IoT-enabled drip irrigation system using and controlled through web-based applications. Smart Agri. Technol. 4 (March), 100215. https://doi.org/10.1016/j.atech.2023.100215.

Key, N., 2022. The determinants of beginning farm success. J. Agric. Appl. Econ. 54 (2), 199–223. https://doi.org/10.1017/aae.2022.6.

Kitchenham, B., 2004. Procedures for performing systematic reviews. In: Keele University Technical Report TR/SE-0401.

Kluza, K., Zioło, M., Bąk, I., Spoz, A., 2021. Achieving environmental policy objectives through the implementation of sustainable development goals. The case for European Union countries. Energies 14 (8). https://doi.org/10.3390/en14082129.

Landeta, J., 2006. Current validity of the Delphi method in social sciences. Technol. Forecast. Soc. Change 73, 467–482. https://doi.org/10.1016/j.techfore.2005.09.002.

Landeta, J., Lertxundi, A., 2024. Quality indicators for Delphi studies. Futures and Foresight Science 6 (1). https://doi.org/10.1002/ffo2.172.

Li, F., Cheng, S., Yu, H., Yang, D., 2016. Waste from livestock and poultry breeding and its potential assessment of biogas energy in rural China. J. Clean. Prod. 126, 451–460. https://doi.org/10.1016/j.jclepro.2016.02.104.

Lv, W., Zhang, Z., Zhang, X., 2023. The role of green finance in reducing agricultural non-point source pollution—an empirical analysis from China. Front. Sustain. Food Syst. 7 (July). https://doi.org/10.3389/fsufs.2023.1199417.

Ma, Q., Xu, B., Bititci, U., 2025. Unpacking financial aspects of circular economy: a systematic literature review. J. Environ. Manag. 384 (April), 125507. https://doi.org/10.1016/j.jenvman.2025.125507.

MAPA, Cajamar, 2022. Diagnóstico inicial del estado de la transformación digital del sector agroalimentario español. Ministerio de Agricultura Pesca y Alimentacion y Cajamar.

MAPA, Cajamar, 2023. Análisis del estado actual de la digitalización del sector agroalimentario español. Ministerio de Agricultura Pesca y Alimentacion y Cajamar.

Marín-Guirao, J.I., de Cara-García, M., Crisol-Martínez, E., Gómez-Tenorio, M.A., García-Raya, P., Tello-Marquina, J.C., 2019. Association of plant development to organic matter and fungal presence in Association of plant development to organic matter and fungal presence in soils of horticultural crops. Ann. Appl. Biol. 1, 1–10. https://doi.org/10.1111/aab.12501.

Martínez-Fernández, G., Abecia, L., Arco, A., Cantalapiedra-Hijar, G., Martín-García, A.I., Molina-Alcaide, E., Kindermann, M., Duval, S., Yáñez-Ruiz, D.R., 2014. Effects of ethyl-3-nitrooxy propionate and 3-nitrooxypropanol on ruminal fermentation, microbial abundance, and methane emissions in sheep. J. Dairy Sci. 97 (6), 3790–3799. https://doi.org/10.3168/jds.2013-7398.

Maudos, J., Salamanca, J., 2025. Observatorio sobre el sector agroalimentario de las regiosnes españolas. Informe 2023. Cajamar e IVIE.

Mohr, F., Diogo, V., Helfenstein, J., Debonne, N., Dimopoulos, T., Dramstad, W., García-Martín, M., Hernik, J., Herzog, F., Kizos, T., Lausch, A., Lehmann, L., Levers, C., Pazur, R., Ruiz-Aragón, V., Swart, R., Thenail, C., Ulfeng, H., Verburg, P.H., et al., 2023. Why has farming in Europe changed? A farmers' perspective on the development since the 1960s. Reg. Environ. Change 23 (4), 1–17. https://doi.org/10.1007/s10113-023-02150-y.

Monasterolo, I., Mandel, A., Battiston, S., Mazzocchetti, A., Oppermann, K., Coony, J., Stretton, S., Stewart, F., Dunz, N., 2024. The role of green financial sector initiatives in the low-carbon transition: a theory of change. Glob. Environ. Change 89 (July), 102915. https://doi.org/10.1016/j.gloenvcha.2024.102915.

Moutinho, J. da A., Fernandes, G., Rabechini, R., 2024. Evaluation in design science: a framework to support project studies in the context of University Research Centres. Eval. Progr. Plann. 102 (July 2023), 102366. https://doi.org/10.1016/j.evalprogplan.2023.102366.

MTASE, & INSHT, 2019. NTP 283: Encuestas: metodología para su utilización. Ministerio de Trabajo y Asuntos Sociales y Instituto Nacional De Seguridad e Higiene en el trabajo.

Neuenfeldt, S., Gocht, A., Heckelei, T., Ciaian, P., 2019. Explaining farm structural change in the European agriculture: a novel analytical framework. Eur. Rev. Agric. Econ. 46 (5), 713–768. https://doi.org/10.1093/erae/jby037.

Okoli, C., Pawlowski, S.D., 2004. The Delphi method as a research tool : an example, design considerations and applications. Inf. Manag. 42, 15–29. https://doi.org/10.1016/j.im.2003.11.002.

Pepeta, B.N., Hassen, A., Tesfamariam, E.H., 2024. Quantifying the impact of different dietary rumen modulating strategies on enteric methane emission and productivity in ruminant livestock: a meta-analysis. Animals 14 (5). https://doi.org/10.3390/ani14050763.

Puech, T., Stark, F., 2023. Diversification of an integrated crop-livestock system: agroecological and food production assessment at farm scale. Agric. Ecosyst. Environ. 344 (December 2022), 108300. https://doi.org/10.1016/j.agee.2022.108300.

Rafiq, K., Tofazzal Hossain, M., Ahmed, R., Hasan, M.M., Islam, R., Hossen, M.I., Shaha, S.N., Islam, M.R., 2022. Role of different growth enhancers as alternative to in-feed antibiotics in poultry industry. Front. Vet. Sci. 8 (February), 1–9. https://doi.org/10.3389/fvets.2021.794588.

Rico, C., Rico, J.L., García, H., García, P.A., 2012. Solid - liquid separation of dairy manure: distribution of components and methane production. Biomass Bioenergy 39, 370–377. https://doi.org/10.1016/j.biombioe.2012.01.031.

Rodenburg, J., 2017. Robotic milking: technology, farm design, and effects on work flow. J. Dairy Sci. 100 (9), 7729–7738. https://doi.org/10.3168/jds.2016-11715.

Romero-Gámez, M., Suárez-Rey, E.M., 2020. Environmental footprint of cultivating strawberry in Spain. Int. J. Life Cycle Assess. 25 (4), 719–732. https://doi.org/10.1007/s11367-020-01740-w.

Roopa, S., Rani, M., 2012. Questionnaire designing for a survey. Continuining Education 46 (December), 273–277. https://doi.org/10.5005/jp-journals-10021-1104.

Saleem, M., 2022. Possibility of utilizing agriculture biomass as a renewable and sustainable future energy source. Heliyon 8 (2), e08905. https://doi.org/10.1016/j.heliyon.2022.e08905.

Sánchez-Montesinos, B., Santos, M., Moreno-Gavíra, A., Marín-Rodulfo, T., Gea, F.J., Diánez, F., 2021. Biological control of fungal diseases by trichoderma aggressivum f. Europaeum and its compatibility with fungicides. Journal of Fungi 7 (8). https://doi.org/10.3390/jof7080598.

Sanz-Cobena, A., Lassaletta, L., Aguilera, E., Prado, A. del, Garnier, J., Billen, G., Iglesias, A., Sánchez, B., Guardia, G., Abalos, D., Plaza-Bonilla, D., Puigdueta-Bartolomé, I., Moral, R., Galán, E., Arriaga, H., Merino, P., Infante-Amate, J., Meijide, A., Pardo, G., et al., 2017. Strategies for greenhouse gas emissions mitigation in Mediterranean agriculture: a review. Agric. Ecosyst. Environ. 238, 5–24. https://doi.org/10.1016/j.agee.2016.09.038.

Sanz-Torró, V., Calafat-Marzal, C., Guaita-Martinez, J.M., Vega, V., 2025. Assessment of European countries' national circular economy policies. J. Environ. Manag. 373. https://doi.org/10.1016/j.jenvman.2024.123835. May 2024.

Schallenberg-Rodriguez, J., Rodrigo-Bello, J., Río-gamero, B. Del, 2023. Agrivoltaic: how much electricity could photovoltaic greenhouses supply. Energy Rep. 9, 5420–5431. https://doi.org/10.1016/j.egyr.2023.04.374.

Schrader, J.A., Grewell, D., Graves, W., 2015. Bioplastics and biocomposites for sustainable horticultural containers : performance and biodegradation in home compost bioplastics and biocomposites for sustainable horticulture containers : performance and biodegradation in home compost. Acta Hortic. 1–8. https://doi.org/10.17660/ActaHortic.2017.1170.142, 2015.

Shehata, A.A., Yalçın, S., Latorre, J.D., Basiouni, S., Attia, Y.A., El-Wahab, A.A., Visscher, C., El-Seedi, H.R., Huber, C., Hafez, H.M., Eisenreich, W., Tellez-Isaias, G., 2022. Probiotics, prebiotics, and phytogenic substances for optimizing gut health in poultry. Microorganisms 10 (2), 1–34. https://doi.org/10.3390/microorganisms10020395.

Strobl, E., 2022. Preserving local biodiversity through crop diversification. Am. J. Agric. Econ. 104 (3), 1140–1174. https://doi.org/10.1111/ajae.12265.

Subeesh, A., Mehta, C.R., 2021. Automation and digitization of agriculture using artificial intelligence and internet of things. Artificial Intelligence in Agriculture 5, 278–291. https://doi.org/10.1016/j.aiia.2021.11.004.

Terence, S., Immaculate, J., Raj, A., Nadarajan, J., 2024. Systematic review on internet of things in smart livestock management systems. Sustainability 16 (10), 1–37. https://doi.org/10.3390/su16104073.

Thamarai, P., Deivayanai, V.C., Saravanan, A., Vickram, A.S., Yaashikaa, P.R., 2024. Carbon mitigation in agriculture: pioneering technologies for a sustainable food system. Trends Food Sci. Technol. 147 (March), 104477. https://doi.org/10.1016/j.tifs.2024.104477.

UN, 2015. Draft Outcome Document of the United Nations Summit for the Adoption of the Post-2015 Development Agenda, vol. 13689. The World Bank Group A to Z 2016. https://doi.org/10.1596/978-1-4648-0484-7_post_2015_development_agenda.

Wehling, S., Diekmann, M., 2009. Importance of hedgerows as habitat corridors for forest plants in agricultural landscapes. Biol. Conserv. 142 (11), 2522–2530. https://doi.org/10.1016/j.biocon.2009.05.023.

Yang, R., Liu, J., Cao, S., Sun, W., Kong, F., 2024. Impacts of agri-food e-commerce on traditional wholesale industry: evidence from China. J. Integr. Agric. 23 (4), 1409–1428. https://doi.org/10.1016/j.jia.2023.10.020.

Yuan, X., Zhang, J., Shi, J., Wang, J., 2024. What can green finance do for high-quality agricultural development? Fresh insights from China. Soc. Econ. Plann. Sci. 94 (November 2023), 101920. https://doi.org/10.1016/j.seps.2024.101920.

Yusuf, H., Fors, H., Galal, N.M., Elhabashy, A.E., Melkonyan, A., Harraz, N., 2025. Barriers to implementing circular citrus supply chains: a systematic literature review. J. Environ. Manag. 373 (September 2024), 123963. https://doi.org/10.1016/j.jenvman.2024.123963.

Zuidhof, M.J., 2020. Precision livestock feeding: match of the supply with nutrient requirements of individual animals. J. Appl. Poultry Res. 29 (1), 11–14. https://doi.org/10.1016/j.japr.2019.12.009.