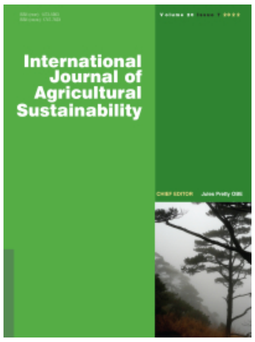

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Towards circular farming: factors affecting EU farmers' decision to adopt emission-reducing innovations

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ABSTRACT
The agriculture and livestock sectors face several challenges related to achieving the current EU environmental objectives. Two of the major policy goals include reducing greenhouse gas emissions and ensuring an increased share of nitrogen, phosphorus, and potassium from renewable sources. Farmers are continuously seeking to adopt technologies and solutions to ensure sustainable food production systems. Adoption of innovation at the farm level based on a circular economy may improve resource efficiency, allow the reuse and recovery of nutrients, and reduce the negative effects of emissions on soil, water, and air. This study aims to identify the factors affecting the adoption of several circular agronomy solutions using a semi-structured questionnaire on a sample of farmers in four EU countries: Spain, Austria, the Czech Republic, and Italy. The results indicated that acceptance of proposed circular innovations is closely related to farmers' environmental objectives, experience, university education, previous experience in innovation adoption, and environmental attitudes. Additionally, institutional support plays a significant role in adoption decisions. Factors affecting adoption decisions may assist policymakers in designing more specific and efficient measures to help farmers meet their current social needs and environmental challenges.

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KEYWORDS
Innovation adoption; farmers' decision; circular economy; farming systems

1. Introduction

Agri-food producers face continuous challenges related to meeting the increasing demand for affordable food while maintaining high environmental and quality standards. The current agricultural system should guarantee an efficient use of resources and increase the reuse and recovery of nutrients while addressing associated environmental issues. However, intensive production systems have led to the inefficient use of nutrients, contributing to water, air, and soil pollution. Traditional and obsolete agricultural practices in livestock and crop production lead to environmental degradation by increasing carbon dioxide (CO2) and other greenhouse gas (GHG) emissions (Rehman et al., 2021). This evidences that conventional agricultural systems are unsustainable and lead to substantial environmental degradation (Singh et al., 2022). Therefore, more effort is needed to ensure the efficient management of nutrients in agricultural systems to reduce GHG and ammonia emissions and the eutrophication of water bodies due to the excessive leakage of nutrients (Svanbäck et al., 2019). On average, agriculture is responsible for 77% of the total nitrogen load in the environment (CEE, 2020). Moreover, approximately 20% of global CO2 emissions are attributed to

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agricultural production (Pata, 2021). Rehman et al. (2021) have reported that a 1% increase in agricultural production increased GHG emissions from 18 to 35%. Of the global GHG emissions (52,300 Mt of CO2 equivalents, CO2e), 3,600 Mt were generated by the 27 European Union countries, of which crop and livestock production represented 13% (478 Mt of CO2e) (Poore & Nemecek, 2018). The 4 countries studied in this research (Austria, the Czech Republic, Italy, and Spain) accounted for 23% of the EU agricultural emissions (Eurostat, 2021), of which Spain represented 10.7%, Italy 8.8%, the Czech Republic 1.9%, and Austria 1.6% (Figure 1).

Within the European agri-food chain, nitrogen use is inefficient, with only one-fifth being transformed into products for human consumption, similar to what occurs with phosphorus and potassium (Circular Agronomics, 2018; Directive 91/676/CEE, 2021). Low nutrient efficiency and poor soil management practices lead to large losses of nutrients and carbon to the environment, which reduces agricultural productivity and increases pollution, hindering the sustainability of the European agri-food chain (Sarteel et al., 2016). That is why one of the main challenges associated with achieving the objectives of the Common Agricultural Policy (CAP) for the European Commission is reducing the loss of nutrients in food production. and achieving environmentally sustainable nutrient levels (CEE, 2020). Additionally, according to the EU commitment (Albarracín-Vacca, 2022), another challenge is reducing GHG emissions by 55% by 2030 compared to the emission levels generated in 1990 to achieve climate neutrality by 2050 (Wolf et al., 2021).

The circular economy (CE) model aims to eliminate the linear model of consumption and subsequent disposal. Its objective is reusing and reinserting inputs into the economy, avoiding the production of waste and high consumption of non-renewable resources (Leiva & Paulovich, 2021). CE models promote the sustainable use of natural resources, thereby, reducing impacts on the ecosystem and human wellbeing (López-Páez & García-Herreros, 2021). Under this model, residues from agricultural biomass and food processing are retained within the food system in the form of renewable resources (inputs), thus, reducing the introduction of new inputs from outside the system (Ortiz Gutiérrez et al., 2022). Adopting CE solutions is crucial to achieve food security and agricultural sustainability (Nordin et al., 2022). Through the introduction of CE principles in agriculture, nitrogen losses can be reduced, while CO2 and other GHGs can be absorbed and retained (Johnson et al., 2007; Preston & Jones, 2006). In recent years, the European agricultural sector has implemented various sustainable technologies focused on circular agriculture, which reduce waste and GHG emissions while producing high-quality food.

The adoption of sustainable innovative technologies in agriculture aims to improve soil, crop, and livestock management (Borges et al., 2019). Adopting innovations involving circular practices, such as the recovery and reuse of nutrients and carbon, improves the efficiency of resources, preserves soil fertility and water quality, and avoids environmental resource degradation for future generations. Nevertheless, innovation adoption faces many constraints that differ across socioeconomic groups, and regions as well as over time (Feder et al., 1985).

The main objective of this study was to analyze the factors affecting farmers' decision to adopt circular innovations and solutions developed within the Circular Agronomics H2020 project (Circular Agronomics, 2018). The analyzed solutions introduced circularity within livestock farming activities, which is based on the principles of resource recyclability and waste minimization. Considering that one of the measures proposed within the European Green Deal is to reduce

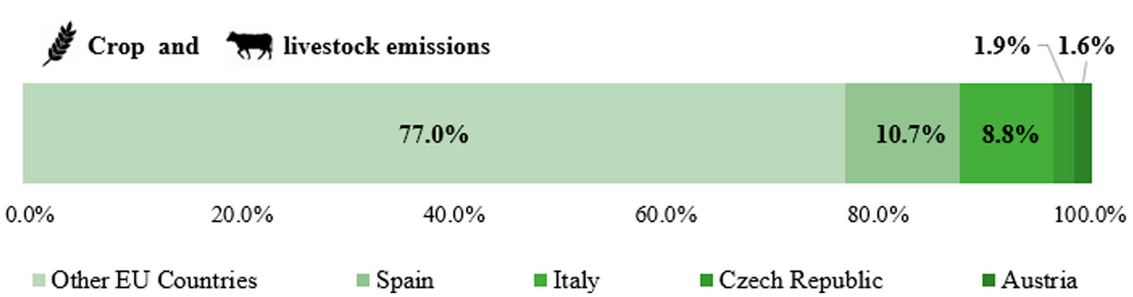

Figure 1. GHG emissions from the EU agricultural sector (Eurostat, 2021).

GHGs to achieve climate neutrality by 2050 (Wolf et al., 2021), understanding the drivers and limitations affecting the acceptance of CE initiatives from the farmers' perspective is highly relevant. Furthermore, it is crucial to delve deeper to understand the main factors motivating farmers to introduce circular innovations into their production systems. Knowing farmers' expectations and needs may help policymakers establish more specific action schemes and regulations focused on increasing the adoption of innovations aimed at reducing GHG emissions and support the transition towards more sustainable practices. This study contributes to the scarce literature on the factors influencing the adoption of circular farming innovations in a comparative manner in different EU countries. It also introduces farmers' environmental attitudes using the new ecological paradigm (NEP) scale and farmers' preferences for agribusiness objectives using the Analytic Hierarchy Process (AHP) as two additional dimensions of the extended theory of planned behaviour (TPB). Furthermore, this study seeks to update the knowledge regarding the factors affecting farmers' expectations and decisions towards introducing circularity through innovation at the farm level.

2. Literature review

The growing interest in circular agricultural innovation solutions and technologies and their adoption relies on their positive impact on the environment (Dorr et al., 2021; Fan et al., 2018). Understanding the factors affecting farmers' adoption of technological innovation is key to improving agricultural sustainability and efficiency. Different studies have used both social and economic approaches to identify the main reasons farmers decide to adopt innovative and more sustainable solutions. However, the adoption process is too complex and multidimensional to be fully understood; additional and continuous efforts are needed to deeply analyze this process, which is closely related to the regions, countries, and sectors involved as well as the global economic context. Meijer et al. (2015) have suggested that innovation can be a concept and that technical information can be perceived as new. Therefore, the circular agricultural concept is based on introducing changes to conventional models of production, moving towards agriculture systems in which the re-use of waste and revaluation of by-products resulting from agricultural and livestock production are necessary. These innovations are expected to optimize the efficient use of resources and reduce environmental impacts (Juárez et al., 2021).

Adoption may also be defined as the process by which producers decide to incorporate new techniques or technologies into their existing production systems (Martínez & Gómez, 2012; Taghouti et al., 2021). Rogers (1963) defined the adoption process as the mental process an individual goes through from first hearing about an innovation until its final adoption. Innovation adoption at the farm level implies changes aimed at improving productivity and increasing efficiency in the use of resources (Cuevas et al., 2013). However, different factors influence farmers' adoption decisions with regard to sustainable agricultural technologies, as can be observed in different systemic literature reviews (Serebrennikov et al., 2020).

Focusing on sustainable agricultural practices or technologies, several studies have implemented different qualitative and quantitative methodologies to identify the determinant factors affecting the adoption of agricultural innovations (Abegunde et al., 2019; Knowler & Bradshaw, 2007). Some studies are based on the theoretical framework of the TPB proposed by Ajzen (1991), which considers the impact of additional constructs on behaviour as an extended model of the reasoned action theory (Ajzen & Fishbein, 1980). The conceptual model of the TPB explaining the intention to perform a behaviour considers environmental attitudes, preferences, subjective norms (social and personal), and perceived behaviour control as constructs that influence decision making (Despotović et al., 2019; Le, 2010). López and Requena (2005) have indicated that there are many variables related to the characteristics of farmers and their exploitations included in the analyses of causality of adoption in the agricultural field (such as farmer age, education, dedication to agriculture, access to information channels, opinions and environmental attitudes, farm size, and other characteristics) that are relevant to the adoption decision of more sustainable practices in agriculture. Jha et al. (2021) and Bonke and Musshoff (2020) have shown that farmers' environmental attitudes and behaviours strongly influence their decisions to adopt sustainable agricultural technologies. Furthermore, it has been demonstrated that the attitude of farmers towards the environment can be an extended dimension of the TPB, which, combined with other determinant factors, should be a significant construct explaining farmers' intentions and behaviours (Ahmed et al., 2021). Burli et al. (2021) argue that farmers' decisions to adopt or not adopt sustainable solutions depend not only on their environmental attitudes and opinions but also on different attributes, mainly related to the innovation, farm, and farmers themselves. The initial investment, expected benefits, maintenance costs, and farm structure as well as the farmers' socioeconomic characteristics and preferences towards alternative sustainable actions are also significant (Burli et al., 2021). Alomia-Hinojosa et al. (2018) and Iiyama et al. (2018) have indicated that the decisions to adopt innovative agricultural technologies could be influenced by farmers' preferences and the perceived advantages of the innovations. Barbarán (2014) suggests that structural (age, education level, and farm size) and attitudinal variables are determining factors affecting the adoption of sustainable solutions at the farm level. Further, Läpple and Van Rensburg (2011) argue that environmental attitudes and social learning are important determinants of adoption decisions. Borges et al. (2019) have indicated that the underlying motivations for innovation adoption may also involve psychological constructs in addition to economic aspects.

The activities of the agricultural sector in Europe are highly regulated, with some of these regulations potentially playing important roles in farmers' adoption decisions. Many new technologies and innovations have already been developed in the European agricultural sector. However, not all the proposed innovative solutions are focused on circularity as a means of improving resource efficiency and the re-use and recovery of nutrients (such as manure treatment and application).

Recently, circularity has gained relevance within the European agriculture system. However, studies focusing on innovation adoption decisions that introduce circularity at the farm level are still in an initial stage. Given this background, there is a clear need to delve deeper to provide updated answers to this identified gap. At this point, it is important to determine the factors affecting European farmers' decision-making regarding circular agricultural innovations, including their profile, psychological aspects including their environmental attitudes and preferences, and other economic aspects related to the innovations.

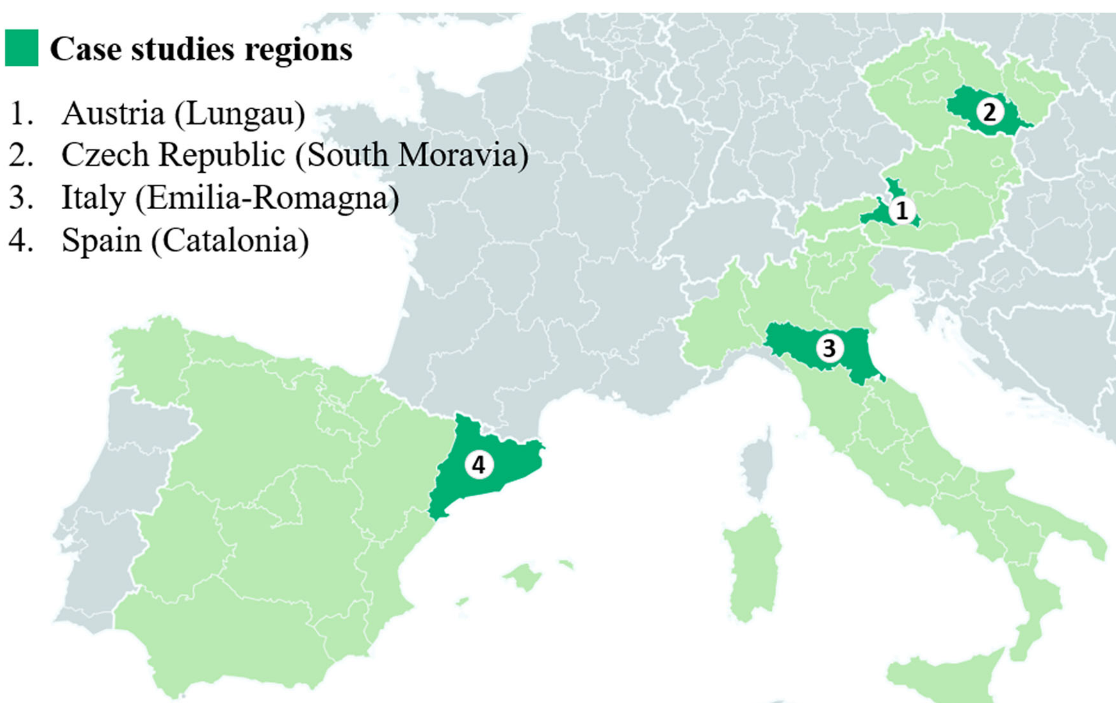

Figure 2. Case study regions where farmers´ survey were applied.

3. Materials and methods

Data was collected from March to August 2021 using a specifically designed face-to-face survey presented to farmers in four EU countries (Figure 2), where four innovative solutions focused on circular agriculture were developed as part of the H2020 European project (Circular Agronomics, 2018). The target population of the study consisted of livestock farmers dedicated to porcine or bovine production located in specific case study regions; they represented the different biogeographic conditions and environmental challenges typically present in the agricultural sector. A simple random sampling procedure was carried out based on the proximity of producers to the research centres in regions where a pilot design (demo) of the innovation was available for demonstration (Institute of agrifood research and Technology, Catalonia, Spain; Lungau, Austria; University of Milano, Emilia Rogmana, Italy; and South Moravia, Czech Republic). The reliability of the sample was mainly based on the inclusion criteria of farm size and socioeconomic variables, including age and gender, to ensure heterogeneity. The innovations presented to the surveyed farmers were: 'fertigation with microfiltered slurry/digestate', 'thermal/solar dryer', 'precision feeding', and 'low-input farming'. All solutions focused on reducing nutrient loss at the farm level and improving environmental sustainability.

A semi-structured questionnaire was designed with an interdisciplinary perspective. It included a wide-ranging set of questions grouped into two main sections. The first section focused on socioeconomic variables – farmer characteristics, farm structural characteristics, and farm management – and psychographic and attitudinal constructs, such as agribusiness objectives, environmental attitudes, and opinions. The second section contained a brief innovation description including technical and economic information (cost and benefit outcomes) and a short video illustrating the technology associated with the four circular solutions mentioned (Table 1). In addition, this section included questions related to the potential adoption of the proposed circular agriculture innovations. The survey was translated into the local language of each study region and applied to farmers between March and August 2021.

The agribusiness objectives of farmers were analyzed using the AHP, a multicriteria technique used to identify social, economic, and environmental preferences. The NEP scale was used to assess farmers' environmental attitudes, and the logit model was used to analyze farmers' reactions to the potential adoption of the proposed innovations as well as the factors affecting their decision. Figure 3 summarizes the developed methodological approach.

3.1. Analytic hierarchy process (AHP)

The AHP method was used to identify farmers' objectives. The AHP is a multicriteria analysis tool (Saaty, 2001) widely used in agricultural research (Cabello, 2017; Kallas & Gil, 2012). The AHP allows for the comparison of tangible and intangible factors by setting priorities (Arriaza & Nekhay, 2010). Compared to other preference methods, the advantage of the AHP as a simple multicriteria decision method is that it is based on simple pairwise comparisons, making the preferences of the compared elements easier for the interviewee to discern (Kallas et al., 2011). Furthermore, its calculation does not require large samples, and preference scores can be determined at the individual level. The scores obtained, unlike those in more complex elicitation methods, represent the relative importance or load of each analyzed item regarding environmental, economic, and social objectives at the farm level. The AHP method involves three stages: (1) modelling, (2) evaluation, and (3) prioritization and synthesis (Torres et al., 2020). In the modelling stage, three factors corresponding to each objective were defined based on a literature review. The reviewed studies focused on agricultural and livestock production as well as management alternatives used in agricultural production systems (De Roest et al., 2018; Payraudeau & van der Werf, 2005; Rafaj et al., 2018; Sánchez-Toledano et al., 2017), as shown in Figure 4.

In the evaluation stage, pair-wise comparisons of all the farmer objectives within each level (a, b, and c) were performed using the verbal AHP scale of 9 point proposed by Saaty (2001), (e.g. ask farmer choice between the economic objective number 1 'Diversify production and marketing channels' and the economic objective number 2 'Increase the sales of farm products'. If both have the same importance assig the value 1, if not, the interviewed farmer has to assign the level of preference (from 1 to 9) to the selected objective).

The meanings of different values in the scale can be summarized as follows: one indicates that both

Table 1. Circular innovations designed and analyzed in the Circular Agronomic project.

Innovation	Objectives	Description	Benefits
Precision feeding	Introducing close loops within livestock to increase nutrient use efficiency and reduce emissions.	Feed is provided to each cow as accurately as possible, taking into account the quality and quantity of the milk produced as well as the stage of lactation. Milk quality is analyzed individually with online sensors.	- Increase in nutrient use efficiency - Reduction of input costs by saving on feed - Reduction of emissions - Improvement of the yield
Fertigation with microfiltered slurry/digestate	Reversing the decrease in soil organic matter and improving the value of digestate as a fertilizer	Slurry/digestate is distributed to current crops through irrigation systems such as rain wings, pivots, rangers, and dripping wings. Microfiltered slurry/digestate is separated into particles with a diameter > 50 µm, so digestate is fluidized and does not present problems such as clinging nozzles and drips.	- Reduction of ammonia and GHG emissions - Increase in the use of mineral fertilizers - Reduction of water waste - Increase in nutrients use efficiency - Increases in crop yield
Thermal/solar dryer	Introducing closed loops within cropland farming (from livestock to cropland farming) and increasing the reuse of manure in a sustainable manner to improve soil fertility.	Separation equipment is introduced in livestock farms for liquid and solid manure fraction. The latter is then deposited in a 'greenhouse' type dryer for solar drying.	- Valorization of pig manure - Reduction of emissions - Reduction of transport costs - Improvement in final product conservation - Simplification of incorporation into the soil
Low-input farming	Introducing closed nutrient cycles at dairy farms and reducing GHG emissions, both features which are usually attributed to extensive farming systems.	In dairy farming, a low amount of purchased inputs, such as concentrated feed, is used to achieve the highest possible proportion of grazing fodder. The focus is not to maximize individual animal performance but instead to achieve a location-adapted, sustainable performance level. In a given geographic region, a specific combination of dairy cow genotypes and diet compositions leads to the most efficient milk production.	- Reduction in working time - Reduction of costs (low-input). - Reduction of pollution

criteria are equally important, while two means that the selected criterion has a slightly higher importance than the other. This importance increases up to nine, which indicates that the selected criterion has absolute importance with respect to the other.

In the prioritization and synthesis stages, all comparisons and priorities were estimated using judgments ($\hat{a}_{ijk}$). These are the comparison values of objective *i* against objective *j* for farmer k from the Saaty matrices (Âk). The obtained values were normalized, and their relative importance was calculated for all farmers (Kallas & Gil, 2012).

3.2. Farmers' environmental attitude

The NEP scale was used to analyze the farmers' environmental attitudes. This has allowed researchers to identify pro-environmental and anthropocentric attitudes in previous studies (Moyano Díaz & Palomo

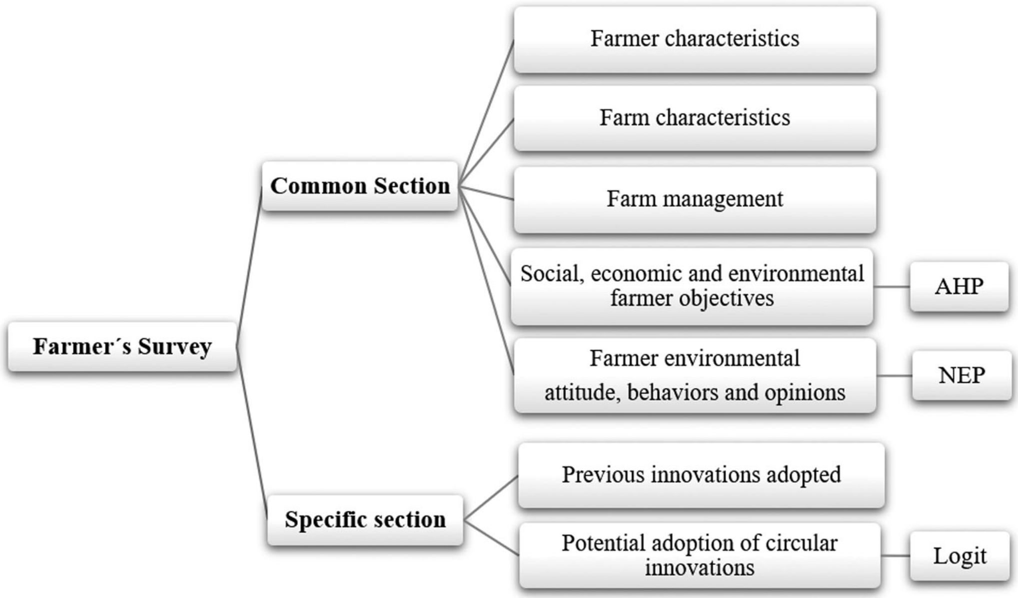

Figure 3. Methodological approach used in this study.

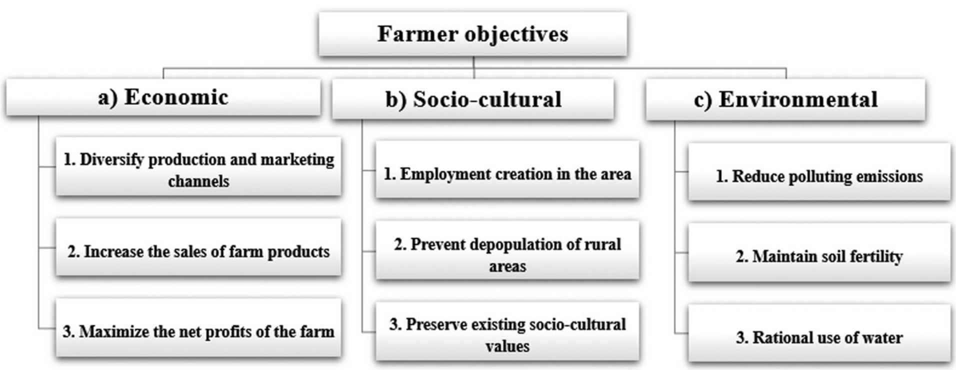

Figure 4. Analytic Hierarchy Process model and selected farmer objectives.

Vélez, 2014), resulting in the incorporation of several constructs as part of general environmental awareness measurement systems (Vozmediano Sanz & San Juan Guillén, 2005). The NEP scale integrates different items that involve two latent dimensions: 'ecocentric' and 'anthropocentric' attitudes (Table 2) (Gomera et al., 2013).

The NEP scale statements were evaluated on a Likert scale consisting of nine points, from 'strongly disagree' (number one) to 'strongly agree' (number nine). Principal Component Analysis (PCA) was applied using the Statistical Package for the Social Sciences (SPSS version 26.0). PCA was performed to extract two factors (eigenvalues higher than one unit) with varimax rotation to regroup the items in the two major dimensions. The suitability of the data for the application of the reduction technique was tested using the Kaiser-Meyer-Olkin (KMO) test; values greater than 0.6 indicated that the technique could be applied (Samian et al., 2015). Latent dimensions associated with 'ecocentric' and 'anthropocentric' attitudes were identified. Ecocentric attitudes were those related to an individual's commitment to environmental preservation. Individuals with ecocentric attitudes display concerns regarding ecosystems; their values, behaviours, and beliefs are

Table 2. Environmental attitudes based on the New Ecological Paradigm scale (Torres el al., 2020).

Latent dimension	Items
Anthropocentric	• The balance of nature is resistant enough to tolerate the impacts caused by industrialized countries.
	• Over time, humans can learn how nature works and be able to control it.
	• Human ingenuity will ensure that we do not turn the Earth into an uninhabitable place.
	• Humans exist to dominate nature.
	• Humans have the right to modify the environment to adapt it to their needs.
Ecocentric	• Plants and animals are as entitled to existence as human beings are.
	• The balance of nature is very delicate and easily alterable.
	• Under a 'business as usual' scenario, a major ecological catastrophe is imminent.
	• Despite our special abilities, humans are still conditioned by the laws of nature.
	• To achieve sustainable development, a balanced economic background that controls industrial growth is required.

aligned with environmental protection. Conversely, anthropocentric attitudes relate to the belief that natural resource exploitation involves valuing the environment for its benefits to people and reflect anthropocentrism as the most important component of life (Simsar et al., 2021). Both dimensions describe farmers' predominant environmental attitudes, with different signs indicating attitude clarity. A clear ecocentric attitude (+, −), indicates that a given farmer agrees with ecocentric items and disagrees with anthropocentric items, whereas a clear anthropocentric attitude (-, +) corresponds to a farmer that disagrees with ecocentric items and agrees with anthropocentric items. When the farmer shows an undefined attitude, both values are given the same sign (+, + or –, −) (Torres et al., 2020).

3.3. Farmers' decision to adopt the circular farming solutions

The logit model was implemented to estimate the likelihood of farmers adopting the proposed circular innovations (Luna-Mena et al., 2016). The Logit Model is a nonlinear, binary choice model that assumes that individuals choose between two alternatives with a logistic distribution (McFadden, 1973). This model has allowed researchers to estimate the probability of an event occurring based on one of two values (0 = would not adopt; 1 = would adopt), using the maximum likelihood method (Cramer, 1999; Maddala, 1983).

$$P[Y=1 \mid X_1 \ldots X_n] \rightarrow P[Y=0 \mid X_1 \ldots X_n] = 1 - P[Y=1 \mid X_1 \ldots X_n].$$

The probability model depends on the parameters´ vector $\beta = (\beta_0, \beta_1, \ldots \beta_n)$, which represents the explanatory factors described above: NEP, AHP outcome, farmers and farm characteristics, attitudinal opinions, and innovation description.

$$P[Y=1 \mid X_1 \ldots X_n] = p(X_1 \ \ldots X_n;\beta),$$

where Y represents an adoption decision, ($Y = 1$) corresponds to an adoption decision regarding the proposed technology, and ($Y = 0$) corresponds to the non-adoption of the proposed technology. $X_1 \ldots X_n$ are explanatory variables.

The empirical specification of the logit model is:

$$p(X_1 \ \ldots X_n;\beta) = G[\,\beta_1 X_1 + \ldots + \beta_n X_n],$$

and the logistics distribution function model is:

$$G(x) = \frac{e^x}{1 + e^x}.$$

The probability that adoption occurs is given by:

$$P[Y=1 \mid x_1 \ldots x_n] = \frac{1}{1 + e^{(-\beta_0 - \beta_1 x_1 - \beta_2 x_2 \ldots - \beta_n x_n)}},$$

where β_0 is an intercept, and $\beta_1 \ldots \beta_n$ are the coefficients of the independent variables representing their impact on the likelihood of the adoption of circular agronomic innovations.

Considering the natural logarithms in the previous expression, a linear expression model was obtained:

$$Logit[P(Y=1)] = Ln\left[\frac{P[Y=1 \mid X_1 \ldots X_n]}{1 - P[Y=1 \mid X_1 \ldots X_n]}\right] = \beta_0 + \beta_1 X_1 + \beta_2 X_2 + \ldots + \beta_n X_n.$$

Explanatory variables were identified from a literature review and selected using Pearson's correlation analysis on SPSS (version 24.0). Highly correlated independent variables and those identified as significant in previous studies were included in the first regression model. The Wald backward and forward methods were used for the final set of selected variables, retaining only the significant variables in the model. The Hosmer–Lemeshow goodness-of-fit test was used to evaluate the global fit of the model. This statistic is used in logistic regression for models with continuous covariates and small sample sizes (Botero Soto, 2021).

In addition, the deviation ('−2LL' = 2 log-likelihood) that measures how well the model fits the data was estimated. Cox and Snell's R-squared test was used to estimate the proportion of variance explained by the independent variables, and Nagelkerke's R-squared metric was used to correct the scale of the statistic to cover the full range from 0 to 1.

4. Results

A first analysis was carried out to understand the farmers' intention to adopt ('adopters') or not ('non-adopters') in terms of their demographic and personal characteristics, farm income, and physical and geographic characteristics of their farms. The results (Table 3) showed that the adopters were almost exclusively male farmers, whereas the gender composition of non-adopters was more balanced, with a statistically significant difference between the two groups. Older farmers were also better represented among adopters, highlighting the correlation between the time a farmer has been involved in farming activities and their likelihood of adoption. Furthermore, the results showed that agricultural training and professional agricultural education were highly heterogeneous across the two farmer groups. Adopters had a slightly higher proportion of farmers with university degrees, while the percentage of farmers with only practical experience was higher among non-adopters. Additionally, a higher proportion of farmers with previous adoption experience demonstrated a tendency to attend various courses, conferences, and workshops related to farming activities. However, the differences between proportions of adopters and non-adopters were not statistically significant.

The proportion of farmers belonging to an agricultural association was almost twice as high among adopters than among non-adopters, with a statistically significant difference. Adopters were more active members of professional associations potentially seeking cooperation with other farmers to share the risks and economic burden associated with implementing certain innovations. A higher proportion of adopters were farmers whose unique economic activity was agriculture compared to non-adopters, who exhibited other off-farm income sources.

Regarding the economic variables, the results of the survey showed a higher proportion of adopters belonging to vertically integrated companies and a stronger reliance on loans than that of non-adopters. The loans of adopters were mainly related to investments in construction, machinery, and equipment, whereas those of non-adopters were associated with ensuring cash flows and financing daily operations. Adopters tended to diversify their marketing channels by selling to more clients than non-adopters. Furthermore, the proportion of large farms (> 75 ha) was higher in the adoption group than that in the non-adoption group. Finally, soil quality and fertility, measured by farmers' subjective estimates on a 10-point Likert scale, did not play a significant role in farmers' innovation decisions.

Table 3. General characteristics of adopters versus non-adopters (past 10 years).

Factors	Adopters (*N* = 119)	Non-adopters (*N* = 29)	*t*-stat/χ^2
Gender (% of males)	91.96	72	6.996***
Age (%): *< 35 years*	19.09	36	2.462
35–44 years	20.91	20	0.00
45–54 years	23.64	16	0.316
55–64 years	23.64	16	0.316
> = 65 years	12.73	12	0.00
Training: *agricultural university (%)*	33.04	28	0.063
practical experience (%)	54.46	72	1.906
vocational training (%)	38.39	40	0.00
courses/conferences/ workshops (%)	43.75	24	2.547
multiple training activities (%)	2.68	4	0.00
Association membership (%):	67.8	37.93	7.584***
producer association membership (%)	33.9	13.79	3.579*
agrarian union membership (%)	48.31	24.14	4.591**
environmental NGO membership (%)	4.24	0	0.309
Exclusively employed in agriculture (%)	67.8	48.28	3.047*
Part of a vertically integrated company (%)	25.42	13.79	11.452***
% of farms in debt:	61.02	41.38	14.784***
- loan to invest in construction (%)	70.83	50	4.074**
- loan to invest in machinery/equipment (%)	59.72	41.67	3.078*
- loan to cover operational expenses (%)	16.67	25	0.00
Agricultural insurance (%)	86.44	72.41	0.00
Number of main clients	3.12	1.46	2.582**
Farm size: < = 25 ha	24.58	21.43	0.011
26–50 ha	22.03	28.57	0.237
51–75 ha	9.32	21.43	2.155
76–100 ha	11.86	7.14	0.146
>100 ha	32.2	21.43	0.789
Land fertility (10 is max)	6.36	6.17	0.483
Degree of erosion (10 is max)	2.63	2.45	0.401

***, **, * == > Significance at 1%, 5%, 10% level.

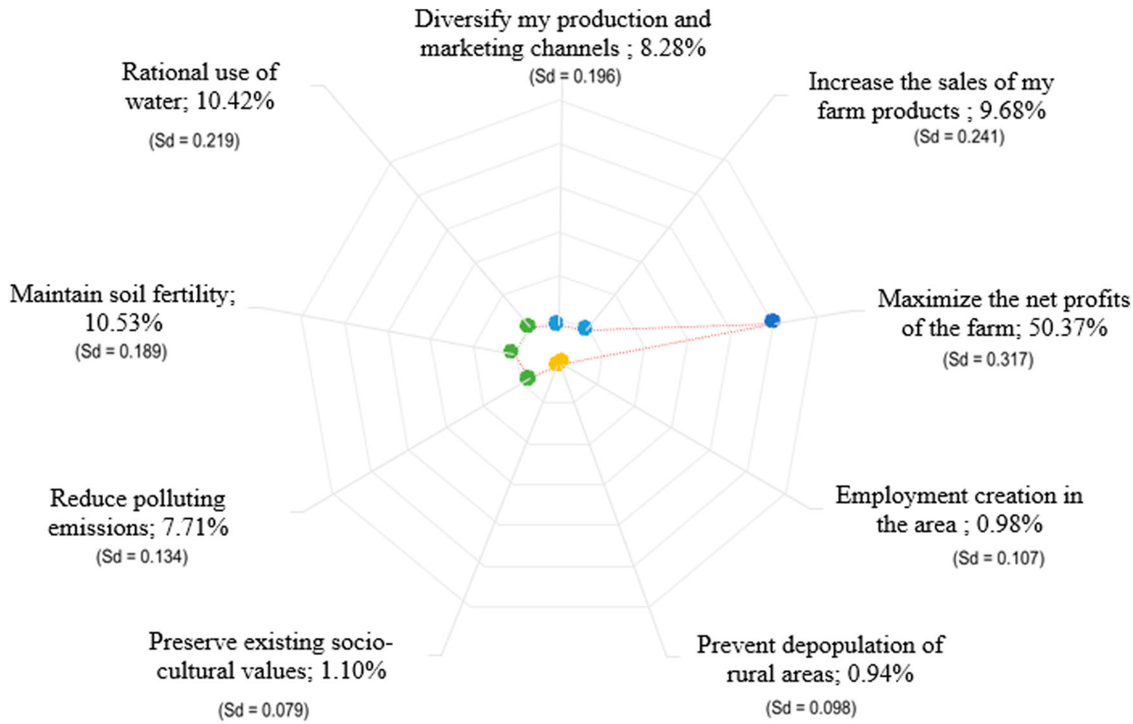

Figure 5. Farmers' preferences for different objectives according the relative weight obtained by the AHP methodology (SD = Standard deviation).

4.1. Farmers' preferences and objectives at the farm level

The AHP results (Figure 5) showed that, at the farm level, farmers prioritized economic aspects over environmental and sociocultural objectives, reaching a cumulated relative importance of 68.33%, 28.66%, and 3.01%, respectively. The 'maximization of farm net profit' objective was assigned the highest relative importance, while the 'preserving sociocultural values' and 'preventing rural areas depopulation' objectives were assigned the lowest. The 'relative importance' of all preferences were obtained through corresponding Saaty matrices structured based on farmers' comparisons between the elements of each conglomerate and using the row geometric mean method.

4.2. Farmers environmental attitudes

The KMO test was applied to the NEP scale items. The results showed a KMO value of 0.75, indicating the goodness of fit of the PCA methodology. The internal consistency of the NEP scale (Cronbach's alpha) was 0.74, indicating adequate consistency. Two components were extracted from the PCA: 'ecocentric' and 'anthropocentric' factors, with a total explained variability of 51.4%. The environmental attitudes of farmers were determined based on both dimensions.

The results (see Figure 6) showed that only 28% of the farmers surveyed exhibited a predominantly ecocentric attitude, with the majority of these considering that nature should be protected regardless of any potential direct benefits. An anthropocentric attitude was displayed by 20% of the farmers, agreeing with the statement that protecting nature should only be done to improve the quality of human life. Furthermore, they agreed that human beings are able to control nature and their resources. The remaining farmers (52%) were identified as having undefined or contradictory environmental attitudes, exhibiting both ecocentric and anthropocentric attitudes. In all cases, the ecocentric dimension was more important than the anthropocentric dimension for all farmers.

A graphical representation of the distribution of farmers' environmental attitudes can be seen in Figure 7. The points below the blue dotted line

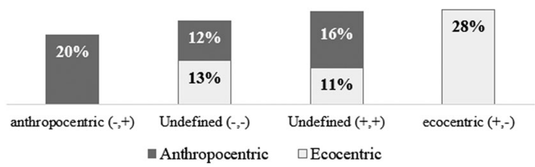

Figure 6. Environmental attitudes of farmers (NEP scale).

represent farmers with a predominantly ecocentric environmental attitude, whereas those above it corresponds to farmers with a more anthropocentric attitude.

This figure also shows whether the environmental attitude that characterizes each farmer was clearly defined, depending on the quadrant in which farmers are located. As shown in the figure, the farmers who exhibited an ecocentric attitude (dots below the diagonal line) are mostly willing to adopt the innovations presented (ratio of green dots to red dots = 6.75). While those who exhibited an anthropocentric attitude (points above the blue line), are less willing to adopt these innovations (ratio of green dots = 1.45 compared to red dots).

4.3. Factors affecting the adoption decision

The factors affecting the decision to adopt were analyzed using a binary logistic regression method. The dependent variable describing the potential adoption was dichotomous (would adopt = 1; would not adopt = 0). The independent variables used in the model corresponded to socioeconomic characteristics, and environmental attitudes and preferences about objectives. Variables included in the model were considered based on their significance in the theory of innovation adoption and empirical studies from the literature review. The model goodness of fit was R^2 Nagelkerke = 0.607, explaining 60.7% of the variance. The Hosmer–Lemeshow test results (Chi square = 7.986; *df* = 8; *p*-value = 0.435), indicated the prediction capacity of the model is highly reliable.

The results in Table 4, showed that the presence of 'off-farm income' reduced farmers' probability to adopt the proposed circular agriculture innovations This could be because farmers with additional sources of income are less dependent on farm activities. Similar results were identified by Genius et al. (2006).

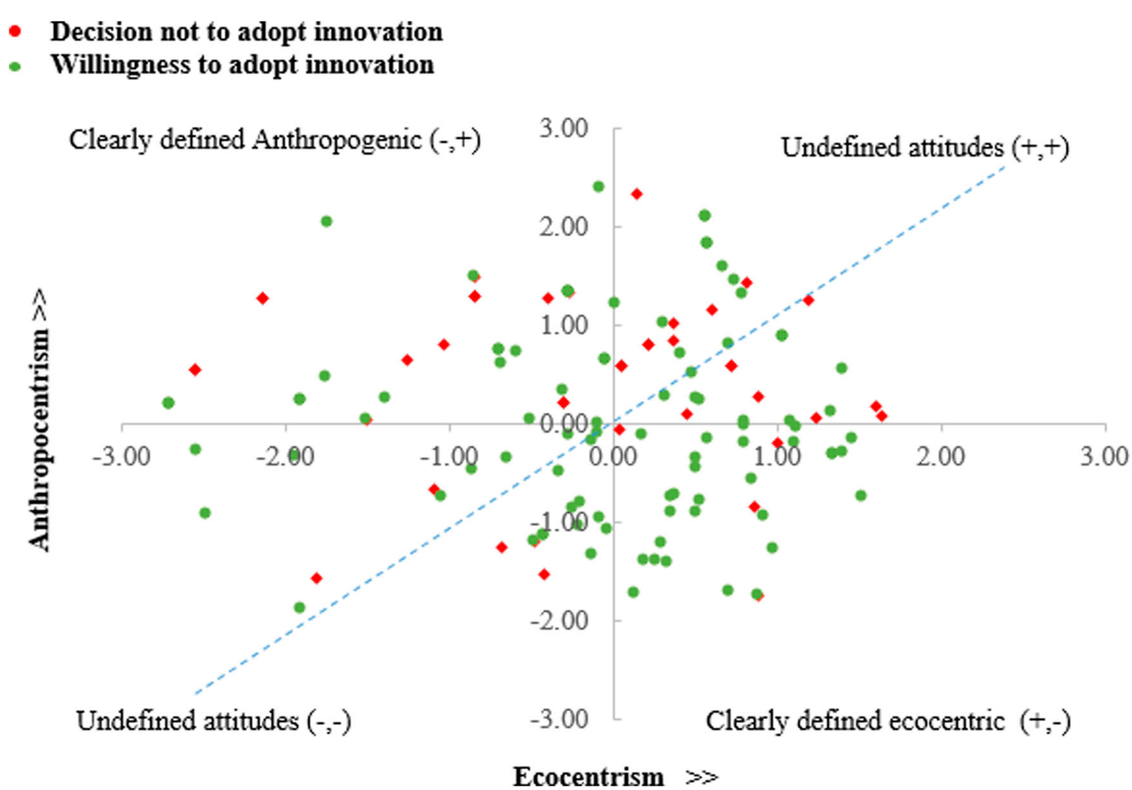

Figure 7. Farmers' environmental attitudes and adoption decisions.

Table 4. Logistic regression analyses.

Variables	Coefficient (β)	Odds Exp (β)
Intercept	−6.447*	0.002
Country	−0.801	0.449
Off-farm income source	−0.047***	0.954
Farm size	0.686**	1.985
Farm located in vulnerable area	1.487*	4.425
Trust in family and friends	−2.005***	0.135
Innovation adopted in the last 10 years	1.944**	6.988
Diversified slurry management	0.834**	2.302
Tank volume	−0.022***	0.978
Opinion that the government should encourage innovations	0.643***	1.903
Opinion Non-farm income is necessary to financial security	−0.597***	0.551
Number of family members aged 19–59	0.683**	1.979
Practical experience	2.094**	8.117
Vocational training	1.728**	5.629
University training	2.825**	16.858
Ecocentric attitude	1.323***	3.757
Diversification of production and marketing channels	−5.425**	0.004
Maximization of net profits (cost reduction)	−3.690**	0.025
Prioritization of environmental objectives	3.290**	26.843

***, **, * == > Significance at 1%, 5%, 10% level.

They found that income from nonfarm business activities and employment in other nonfarm sectors negatively influenced the probability of innovation adoption. 'Farm size' positively influenced farmers' adoption decisions. As large farms have more economic resources, they can better meet adoption costs and have a greater need to use their resources efficiently. Läpple and Van Rensburg (2011) and Taghouti et al. (2021) obtained similar results, indicating that farm size is a robust and positive predictor of adoption over time. The location of a farm in a 'vulnerable area' owing to nitrate contamination increased the likelihood of implementing new solutions and practices. This is because low fertility and unfavourable soil conditions may encourage farmers to look for technologies that help them tackle such problems and allow them to better adapt to the restrictions of vulnerable areas. This outcome aligns with the results obtained by Tadesse and Belay (2004), who found that farmers' decisions to adopt soil conservation measures were positively influenced by their perception of soil erosion. According to Tey et al. (2014), farmers' vulnerability generates a greater probability of adopting solutions that reduce a problem. The 'trust in family and friends' variable was found to significantly undermine the probability of adoption.

Farmers' experience regarding the adoption of innovations in the last 10 years had a positive effect on the adoption of the proposed circular farming solutions. This may be related to the fact that producers take advantage of positive experiences from previous adoptions and are, therefore, more prone to adopt new technologies. Zhou et al. (2008) also found that the experience of previous adoption of similar technologies had a positive effect, as farm administrators had become well-acquainted with the technology and benefited from its adoption. The use of diversified devices and infrastructure as solutions for 'slurry management' at the farm level had a positive effect on the probability of adoption when compared with farmers who relied on a single infrastructure solution (such as a tank deposit of slurry). Farmers' tendency to investigate and implement improved solutions for slurry use increased the likelihood of adoption, similar to how the adoption experience of farmers increased the probability of new adoption. Tank volume had a negative effect on adoption decisions. This could be because larger tanks may last longer and require fewer modifications, thereby, reducing the need to adopt other innovations.

The analysis of the farmers' opinions showed that adoption probability increases when farmers agree with the statement 'the government should encourage innovations' in agriculture (84% of farmers believe that the government and public institutions should encourage the implementation of new technologies in agriculture through subsidies, tax benefits, and other measures). Contrastingly, farmers with the opinion that 'non-farm income is necessary to the financial security of the farm' were less likely to adopt innovation. Additionally, a higher number of working-age members (19–59 years old) increased the probability of adopting the proposed innovations.

Variables related to farmers' training and education – practical experience, vocational training, and university training – were highly significant in explaining their adoption decisions, with university training showing the strongest positive effect. Similarly, Dhraief et al. (2019), Akudugu et al. (2012), and Mzoughi (2011) found that education had a significant effect on farmers' adoption of modern agricultural production technologies. Regarding farmers' environmental attitudes, a clearly defined ecocentric attitude increased the probability of adopting the proposed circular agricultural innovations. Similarly, a study on the adoption of nutrient management practices among farmers in the Irish Republic showed that ecocentric attitudes increased the adoption of a greater number of nutrient management practices. In contrast, farmers identified as having anthropocentric attitudes were found to be more likely to place greater emphasis on the economics of environmental issues and were less likely to adopt nutrient management practices (Buckley et al., 2015).

Furthermore, the analysis of farmers' preferences with regard to the sustainability objectives, estimated through the AHP method, showed that farmers gave the highest relative importance to the maximization of benefits and the lowest to sociocultural objectives. This is consistent with the results reported by Sánchez-Toledano et al. (2017). These sustainable objective preferences were demonstrated to be relevant when it comes to understanding farmers' adoption decisions. Prioritization of the economic objectives 'improve production diversification and distribution channels' and 'maximize net profits by reducing cost' significantly reduced the odds of adopting the proposed innovations. In the former case, the results may be explained by the fact that implementing sustainable technologies, such as solar dryers or nano-filters, are two competing objectives that require considerable capital investment and are not focused on increasing farm productivity. According to Lozano Cabedo (2013), farmers consider organic farming systems to be less profitable than traditional ones owing to the lower yield obtained without considering other issues such as receiving complementary subsidies or obtaining higher revenue from the product. He also argued that farmers consider organic farming to require an increased workload, time, and dedication, all of which raise costs. In the latter case, the goal of maximizing net profits by reducing costs also affects investment costs, leading to the adoption of fewer innovations. The lack of valuation of environmental goods and predominance of economic objectives decrease the chances of adopting sustainable technologies. Thus, the economic dimension prevails when it comes to adopting unsustainable systems (Blandi et al., 2018).

Finally, the model estimation showed that the prioritization of environmental goals increased the probability of adoption. These results agree with those of Sánchez-Toledano et al. (2017), who found that farmers with greater interest in ecological objectives are more likely to adopt sustainable technological innovations. This finding may be justified by farmers implementing sustainable technologies to achieve their environmental goals and improve their compliance with environmental regulations.

5. Discussion

The need to implement actions that promote the reduction of emissions and allow a more efficient use of resources in agricultural farming systems has led to the generation of innovative technological solutions. However, the effectiveness of these innovations mainly depends on their acceptance by farmers, initial investment, and ease of use. Understanding the adoption process and factors affecting farmers' preferences and decisions may facilitate the implementation of potential improvements related to both agricultural sustainability and efficiency. The adoption of agricultural innovations depends on farmers' socioeconomic factors as well as their environmental attitudes and preferences. It further depends on the characteristics of the innovation as well as the availability of subsidies and support from public institutions for accompanying farmers during the process, among other factors highlighted in the literature. According to Serebrennikov et al. (2020), the adoption of innovations may differ between regions, depending on customs, environmental conditions, and regulations. For small farmers, the adoption of innovations represents a great effort given the lack of information on new technologies and high costs of operating and implementing them, which are the main barriers to adoption. In our study, the factor that contributed the most to the adoption behaviour of circular innovations to reduce emissions and improve resource efficiency was farmers' prioritization of environmental objectives over social or economic objectives. Furthermore, the adoption behaviour was clearly related to 'ecocentric' attitudes. Education and experience were also of high importance as proxies for farmers' subjective knowledge of the level of farming activities. Akudugu et al. (2012) argued that the number of years of formal schooling creates a favorable attitude towards the acceptance of new practices, which is why the complexity of technologies has a negative effect on the decision to adopt in farmers with lower education. Pathak et al. (2019) indicated that the ability of a farmer to use new technologies acquired through education, training, and experience increases the likelihood of adopting agricultural technology. These empirical findings indicate that attitudes and preferences play an important role in predicting the intention to adopt, reflecting that farmers' concerns about the environment promote the adoption of circular innovations. Our results are similar to those of previous studies that focused on the adoption of more environmentally friendly production systems, such as organic farming (Genius et al., 2006; Koesling et al., 2008; Läpple & Van Rensburg, 2011; López-Felices et al., 2023; Meijer et al., 2015; Mzoughi, 2011).

The findings of this study provide an initial roadmap for policymakers when establishing action schemes aimed at reducing GHG emissions at the farm level. It showed the importance of raising awareness among farmers about the benefits of implementing circular agriculture at both economic (improving efficiency) and environmental levels by promoting strong resource reuse policies, such as using biofertilizers. Such promotion can also be achieved through training, accompanying farmers during and after the adoption process, and disseminating good practices. Supporting farmers' transition to more sustainable production systems using circular innovations is crucial because of the novelty and lack of experience in applying such innovations.

6. Conclusions

Studies focusing on the factors affecting circular innovation adoption on farms in the EU are lacking. This study addressed this gap in knowledge by analyzing farmers' opinions, environmental attitudes, expectations, agribusiness objectives, and acceptance of several circular solutions and technologies aimed at closing the loop of nutrients and reducing emissions at the farm level.

The factors identified as having the greatest impact on farmers' decisions to adopt circular agricultural innovations were environmental objectives, education level (university education), previous innovation adoption experience, and clearly defined ecocentric attitudes. Other factors, such as locations in vulnerable areas, also significantly increased the probability of adoption.

The results showed that the majority of farmers (84%) believe that government and public institutions should encourage the implementation of new technologies in agriculture through direct payments that support investments in emission reduction solutions and through tax reduction schemes. This is in accordance with the EU policy, where investments are made in emission reduction and mitigation practices through the CAP, as these are considered essential for the promotion of agricultural sustainability.

This finding allows us to suggest that a climate change mitigation and adaptation intervention scheme should be designed to endorse farmers in their decision to adopt the requisite innovations (e.g. structural one-off subsidies for investment in sustainable innovations/technologies). Additionally, with the CAP support, intervention tools for emission reduction in the livestock sector should be introduced through various measures, including yearly subsidies to cover the operating costs of emission-reducing innovations and lower-tax schemes for low GHG emissions and nutrient recovery. (e.g. through fertilizer type modifications, farm circularity implementation, and nutrient recycling).

Farmers' characteristics, environmental attitudes, and preferences for agribusiness objectives are relevant factors that should be considered when implementing agricultural policies that better fit their needs and increase the adoption of sustainable innovations and technologies. One of the main implications of public policies aimed at improving and promoting the adoption of circular agricultural innovations is the strengthening of innovation dissemination processes. This is because access to information and knowledge promotes a greater capacity or willingness to adopt technological solutions in terms of circular agriculture, as evidenced by the present research findings. Previous experience and a high level of training increase the likelihood of adopting innovation. Factors that motivate farmers to increase the adoption of circular farming innovations, such as farmers' objective preferences, may assist policymakers in designing more specific and efficient policy measures that can help farmers face changing social needs and current environmental challenges, including the reduction of GHG emissions and improved nutrient recovery within EU farms.

Although the sample procedure and data collection in this study were considered to be reliable, the results obtained from this study should be interpreted with caution, considering the relatively limited sample size within each case study and the hypothetical nature of the adoption decision. Exhibiting a potential acceptance of the innovations analyzed does not necessarily translate to real-life adoption. Furthermore, the moment in which data collection took place, in the recent Post-Covid period, could have contributed to creating a specific occasion and context that may have affected farmers' perceptions and interests. Additionally, the results should be interpreted only in light of the specific circular innovations analyzed in this research, which were developed within the case studies and presented to farmers in demo sites. In this context, it is worth mentioning the need for future research to extend this study to other circular innovations, technologies, or practices and classify factors affecting adoption based on the complexity level of each circular innovation. Furthermore, there is a need to widen the sample size, not only in the regions analyzed but also in other countries in Europe, since policy interventions and regulations are adopted at the EU level, affecting all European member countries. Agri-food sectors other than livestock farming should also be assessed to carry out a heterogeneity analysis regarding the adoption of circular farming. From a methodological perspective, other adoption models and theories could also be tested, such as the Technology Acceptance Model (Mohr & Kühl, 2021), the unified theory of acceptance and use of technology (Ronaghi & Forouharfar, 2020) and the adoption model based on the extended TPB.

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Authors' contributions

Conceptualization and formal analysis, writing – review and editing S.O.H, methodology, review and supervision Z.K, review and editing D.S. and F.T. review and supervision S.N.M. All authors have read and agreed to the publication of this manuscript.

Availability of data and material

The dataset generated and analyzed in the current study is available at Zenodo, a public repository [https://doi.org/10.5281/zenodo.7620395].

Code availability

Not applicable

Consent to participate

The survey in which this study is based was anonymous. Survey participation was voluntary.

Consent for publication

Participants were informed about the use, privacy, and confidentiality of the obtained data, and informed consent was obtained through an online survey. All authors accept full responsibility for all the aspects of the work described.

Disclosure statement

No potential conflict of interest was reported by the author(s).

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Ethics approval

The Ethics Committee of the Polytechnical University of Catalunya had no objections to the publication of the results of this study.

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