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From risk to resource: understanding farmers' perceptions of wastewater reuse

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Abstract
The use of treated wastewater in agriculture represents an innovative and sustainable strategy to addressing the growing issue of water scarcity. This study examines farmers' perceptions of risk associated with the reuse of this resource in a context of limited water availability and climate change. The work was based on a field survey of a sample of farmers in Southern Italy. Collected data on socioeconomic characteristics and information on farmers' experiences and attitudes toward the use of wastewater in irrigation were analysed using multivariate techniques. Through principal component analysis (PCA), three main dimensions of perceived risk have been highlighted, related to environmental, market and health concerns. Based on these dimensions, cluster analysis has identified five distinct farmer profiles, differentiated by the level and nature of risk perception, degree of regulatory knowledge, and farmers' openness to innovation. The findings indicate that risk perception is associated with demographic factors, including age and level of education, as well as with knowledge and training. The study emphasises the importance of targeted and differentiated information and training strategies in overcoming reluctance and promoting broader and more informed adoption of wastewater reuse in agriculture, thereby contributing to more resilient and sustainable agricultural production.

Keywords Wastewater, Risk perception, Innovations adoption, Farmers profiles

Introduction

In recent years, drought has become an increasingly significant issue in Italy, particularly affecting the Southern regions (Zollo et al. 2016; Tramblay et al. 2020). Climate change has led to a global increase in temperatures (IPCC 2022) and a higher frequency of unusual weather events, which are expected to intensify in the coming years (Tramblay et al. 2020; Caporali et al. 2021). Among these, reduced water availability and irregular rainfall are straining on the natural water cycle, with significant repercussions for economic sectors and local communities (Trnka et al. 2022; Raihan 2023). Agriculture is among the sectors most affected, having suffered significant economic losses due to reduced yields across most irrigated crops (Cammalleri et al. 2020; Ripple et al. 2022). Besides the direct effects of drought, a further problem concerns the access to water for irrigation as agricultural water demand often exceeds supply (Li et al. 2022a; Ingrao et al. 2023), prompting farmers to seek alternative strategies (Keyhanpour et al. 2021) such as the construction of basins, the use of wells and the development of water storage systems (Ricart et al. 2018; Ward 2022; Martínez-Dalmau et al. 2023). Although these measures can provide temporary support, they are often insufficient to cope with climate trends, underscoring the need for more structural and integrated water governance policies (Bhaduri et al. 2021; Ward 2022).

In this context, one of the emerging and most discussed solutions at the international level is the reuse of treated urban wastewater for irrigation (Singh 2021; Manganiello et al. 2024). This practice involves recovering urban wastewater through advanced treatment to ensure its quality and environmental and health safety (Christou et al. 2024). For many areas affected by inadequate water resources, it represents a widely implemented initiative in agriculture.

Although the use of treated wastewater has already been tested in various agricultural contexts in Europe and developing countries (Minhas et al. 2022; Colella et al. 2021), its large-scale adoption is still limited by multiple factors (Younas et al. 2021; Tariq et al. 2023). Firstly, its use is conditioned by the regulatory framework, which varies significantly from one country to another depending on water emergency conditions and the availability of conventional water resources (Ortega-Pozo et al. 2022). To harmonise the regulatory framework across EU member states, Regulation (EU) 2020/741 (EU Parliament and Council, 2020) defined specific criteria for the quality of wastewater for irrigation, standardising regulations among member countries and encouraging the adoption of this alternative resource. More recently, Directive (EU) 2024/3019 (European Parliament and Council, 2024) introduced further technical specifications for wastewater treatment, setting stringent safety standards and defining the responsibilities for treatment costs. Although this Directive does not regulate agricultural water reuse directly, it is relevant to the practice because, by improving the quality of treated effluents and encouraging their valorisation, it enhances the feasibility and safety of subsequent reuse.

Secondly, where the use of treated wastewater is guaranteed, farmers' perceptions of risk play a decisive role in its diffusion (Ahmmadi et al. 2021; Garin et al. 2021; Karimi and Ataei 2023; Giannoccaro et al. 2025). The benefits of using this resource have been confirmed by numerous studies (Poustie et al. 2020; Drechsel et al. 2022). They include contributions to productivity, nutrient supply, and consequent savings in fertiliser use, as well as reduced freshwater use. Nevertheless, several critical issues may hinder its adoption by farmers. Concerns persist regarding health and safety, the quality of agricultural products produced with wastewater, and the potential accumulation of contaminants in soil and groundwater (Ofori et al. 2021; Kyriakopoulos et al. 2023; Mishra et al. 2023). Indeed, despite current regulations imposing strict quality requirements for the reuse of water in agriculture, the health risks for agricultural producers and consumers can be significant (Scott et al. 2009; Dickin et al. 2016; Kyriakopoulos et al. 2023; Natasha et al. 2023). The potential presence of pathogens and heavy metals can compromise the quality and safety of agricultural products (Drechsel et al. 2022; Trotta et al. 2024), limiting their marketability and causing potential damage to ecosystems (Daughton and Ternes 1999; Wang et al. 2021; Mishra et al. 2023), alterations to natural habitats and soil contamination (Poustie et al. 2020; De-Los-Ríos-Mérida et al. 2021).

Farmers' risk attitude and risk perception can play a relevant role in the adoption of sustainable farming practices (Trujillo- Barrera et al. 2016; Dessart et al. 2019) or, more specifically, in the wastewater use (Ahmmadi et al. 2021; Garin et al. 2021; Ofori et al. 2021; Sohail et al. 2021; Karimi and Ataei 2023; Manganiello et al. 2024).

Previous research has analysed risk perception from different perspectives. Some authors investigated the relationship between subjective risk perceptions and the socio-demographic and attitudinal characteristics of farmers (van Winsen et al. 2016), while others analysed the influence of individual-level characteristics on risk perceptions of various categories of health and environmental risks (Cummings et al. 2013; Bagheri et al. 2019; Tsakiris et al. 2025). Other studies analysed differences in risk perception across farming systems (Flaten et al. 2005) or classified risk perception in specific domains (Nguyen et al. 2026). Nevertheless, the existing literature reveals a knowledge gap in understanding the multidimensional nature of risk perception and in identifying different farmers' typologies based on human capital characteristics, behavioural orientations, and subjective risk perceptions (Hyland et al. 2016; Eitzinger et al. 2018; Kropf et al. 2024). A more structured analysis of farmers' profiles and perceptions is, therefore, necessary to understand the acceptance of new water management practices and to highlight the interactive mechanisms through which different perceptual dimensions - environmental, health-related, and market-related - combine with individual characteristics in the transition from risk avoidance to resource acceptance.

The present work moves in this direction. It aims to identify farmers' profiles based on how their perceptions of environmental, health, and market risks associate with their propensity to use treated wastewater for irrigation, and how risk perceptions align with specific farmers' and farms' characteristics.

The work is based on a survey of farmers in Basilicata, a Southern Italian region particularly vulnerable to drought. Indeed, in recent years, water scarcity has exacerbated the difficulties faced by the agricultural sector in this region, raising concerns about water availability and the sustainability of irrigation practices. The study aims to address two main questions:

1) How does risk perception relate to farmers' decisions to use treated wastewater?
2) Can we associate the perception of risk to the propensity for innovation and can be both relatedto specific farmers' profiles?

Answering these questions can provide valuable insights for developing more effective and targeted water resource management policies.

The work is articulated as follows. After a literature review on risk perception (Section "Literature Review"), Section "Methodology and Analysis" describes the data and methods used in the study, and Section "Results" presents the empirical results. Sections "Discussion" and "Conclusions" present the main conclusions of the work and discuss their implications for implementing sustainable water management strategies. Limitations and future research paths are underlined in Section "Limitations and future research".

Literature review

Wastewater reuse for irrigation as eco-innovation

The reuse of treated wastewater for irrigation can be intended as an eco-innovation that incorporates multiple innovative dimensions simultaneously. It activates technological, organisational and institutional changes and generates complex environmental, economic and social effects. Moreover, the reuse of wastewater represents a concrete application of the circular economy logic (Michetti et al. 2019), promoting the transition towards a more sustainable use of water resources and the closure of material cycles. In fact, by recovering water and nutrients from urban effluents and reintegrating them into agricultural production systems, reuse practices help close resource loops, reduce waste, and enhance resource efficiency, thereby fostering more resilient and circular agro-environmental systems (Kyriakopoulos 2023; Kyriakopoulos et al. 2023).

As eco-innovation, the adoption of treated wastewater for irrigation can be analysed within the theoretical framework of innovation adoption models. A substantial body of literature shows that adoption of innovations may depend on structural, social and cognitive factors. A significant barrier to adopting a new practice is the lack of knowledge about its direct and indirect effects (Ahsan et al. 2022; Chen et al. 2002). Kang and Park (2011) highlighted how the combination of awareness and knowledge increases perceptions of an innovation's performance and, consequently, increases its acceptance. Conversely, a deficit in these attributes can generate uncertainty or amplify perceptions of possible risks associated with innovations (Slovic 1987; Huijts et al. 2019; Scovell et al. 2022).

Risk and uncertainty are key determinants in decision-making and directly affect the rate of innovation adoption in agriculture (Feder 1980; Shapiro et al. 1992).

Dessart et al. (2019) have systematised the literature on behavioural factors affecting the adoption of sustainable farming practices and have offered a theoretical framework useful for analysing any farming decision, including the adoption of innovations. They classify behavioural factors according to the "distance" from the specific decision-making. In this framework, they clearly distinguish the role and the effects of risk tolerance (or risk attitude), a "dispositional" factor related to the personality and transversal to multiple behaviours, and that of perceived risk, a "cognitive" factor that is proximal to the decision in question and can depend on subjective probabilities and loss aversion.

These two factors can be highly relevant when considering farmers' decisions about the use of treated wastewater, as this input is perceived simultaneously as a valuable resource and a potential source of uncertainty and threat, generating ambivalent attitudes among farmers.

Risk attitude and risk perception

It has been highlighted that the combined action of individual risk perception and the farmer's attitude towards risk plays a crucial role in defining the propensity to adopt an innovation (Ghadim et al. 2005; Li et al. 2021). As previously underlined, risk attitude reflects more stable preferences and personality traits that influence how individuals generally respond to perceived risk (Figner and Weber 2015; Frey et al. 2023), while risk perception refers to the way individuals subjectively assess the likelihood and severity of negative outcomes associated with an innovation.

The concept of risk attitude integrates several aspects relating to psychology, neuroscience, and behavioural economics. It is related to individual preferences and personality traits, reflecting the extent to which individuals find perceived risk attractive or unattractive and consequently prefer to face or avoid it (Figner and Weber 2015).

According to the psychological approach, risk attitude is the result of individual characteristics, such as age, education, and gender, as well as the domain and the cultural and economic contexts in which decision-making occurs (Antle 1987; Raftery et al. 2001; Frey et al. 2023). Cultural values, such as individualism and collectivism, can shape risk attitudes; however, the patterns can vary by context and measurement approaches, and opposite hypotheses can support the relationship between values and risk preferences (Rieger et al. 2015).

About risk perception, Slovic (1987) emphasised its multiple determinants by developing the so-called psychometric paradigm: cognitive factors, emotional factors, utilitarian assessments and shared values, all play a role in defining individual perceptions of risk, contributing in a significant and differentiated way (Ghadim et al. 2005; Hellerstein et al. 2013). According to Rogers (1975), perceived risk is the subjective cognitive assessment of two dimensions: the severity of the risk and individual susceptibility. Perceived severity expresses the level of seriousness attributed to a given event, while perceived susceptibility represents the degree to which individuals consider themselves exposed or vulnerable to that event. Further studies have analysed risk perception in the context of innovation adoption, confirming that this concept is highly subjective and complex, shaped predominantly by intuitive and emotional cognitive processes rather than rational and conscious ones (Greiner et al. 2009; Dessart et al. 2019).

Risk perception varies across socioeconomic and cultural contexts, as well as the type of innovation being considered (Eitzinger et al. 2018; Fahad and Wang 2018; Dessart et al. 2019). Therefore, the decision-making process in conditions of actual or potential risk is dynamic. Before actual use, farmers form preconceptions about the economic and productive effects of innovation (Greiner and Gregg 2011), but practical experience allows for a gradual reworking of initial beliefs through the integration of specific, contextualised knowledge (Ghadim et al. 2005; Alam et al. 2024). In this context, learning and the possibility of gradual experimentation would play a central role in reducing uncertainty and redefining perceived risk (De Buck et al. 2001; Greiner et al. 2009; Pfeiffer et al. 2021). Caswell and Zilberman (1986) found that the availability of reliable information and targeted training programmes are key factors in reducing risk perception, as they improve skills related to the use of innovation, clarify expected performance and help reduce perceived complexity (Kumar et al. 2018; Pfeiffer et al. 2021).

The role of risk perception in the acceptance of sustainable practices

Several empirical studies have shed light on the role of risk in the adoption of innovative agricultural practices, such as irrigation with treated wastewater. These studies have investigated two main aspects. A first approach analysed risk within the frame of behavioural models aimed at predicting the intention to adopt agricultural innovative practices.

Among them, a few works included risk attitude in their analysis. Lombardi et al. (2025) recognise risk aversion as a characteristic of firms' managers that can affect the decision to introduce new sustainable practices. They operationalised risk aversion using multiple price lists, following Tanaka et al. (2010), and found that risk aversion negatively affects the intention to adopt treated wastewater for irrigation. Trujillo-Barrera et al. (2016) analysed the effects of risk tolerance and perceived risk in the context of the adoption of sustainable agricultural practices. They found that the relationship between expected economic rewards and the adoption of sustainable practices is strengthened by risk tolerance: the more risk-averse the farmer, the higher the economic rewards must be to push towards sustainable practices. Moreover, risk tolerance negatively moderates the relationship between risk perception and the adoption of new agricultural practices.

Indeed, most empirical studies have focused on perceived risks rather than on risk attitude. They concur that perceived health risks (e.g., pathogen contamination), environmental risks (e.g., soil quality and salinity), and social risks (consumer acceptance) critically influence willingness to use this resource (Karimi et al. 2023; Tawfik et al. 2025). Dey et al. (2025), using an extended TPB model, found that risk perception negatively influences farmers' intention to adopt sustainable practices by amplifying concerns over yield losses, costs, or uncertainties. It operates through direct and indirect paths: directly reducing intention and indirectly via attitudes, norms, or control beliefs.

A second research domain examines how various socio-demographic and contextual factors influence farmers' risk attitudes and perceptions. Most studies agree that higher levels of education and greater knowledge are associated with lower risk perception and greater acceptance (Michetti et al. 2019; Tawfik et al. 2025). Education and knowledge operate through cognitive pathways, enhancing individuals' capacity to process technical information about treatment processes, evaluate information regarding water quality and safety, and make informed risk-benefit assessments (Michetti et al. 2019). Farmers' perceptions of risks associated with wastewater irrigation can also be influenced by socio-demographic factors such as gender, age, experience, and income (Woldetsadik et al. 2018; Dang and Pham 2022), even if age, education, and experience are tightly intertwined with each other, and are related to social values and beliefs affecting the attitude towards new practices. As an example, younger farmers with higher levels of education were found to be more open to innovation and to use new water management techniques (Serote et al. 2021; Sánchez-Cañizares et al. 2022).

The distinction between risk attitude and risk perception is conceptually relevant and is particularly important for identifying public policies. Risk attitude and perception together influence decision-making and adoption choices, but while acting on personality traits can be more difficult and calls for a long-term strategy, intervening on perceptions of specific risks can be more concrete and effective (Dessart et al. 2019).

The present study focuses exclusively on risk perceptions, as they represent a more actionable and policy-relevant dimension of risk-related behaviour, allowing for targeted interventions that can more readily inform and shape effective public strategies. Moreover, if we can connect observable variables, such as socio-demographic factors, to farmers' risk perceptions, and these profiles can be related to different behaviours in terms of wastewater reuse for irrigation, farmers could be segmented to address specific policies to remove the barriers to the adoption of new practices (Dessart et al. 2019). Therefore, understanding how socio-demographic factors relate to risk perceptions is essential for identifying actionable farmer profiles, designing communication strategies, developing tailored extension services, and developing policies that promote sustainable wastewater reuse.

Methodology and analysis

The study adopts an exploratory research design based on the collection of primary data through a survey (Hyland et al. 2016; Kropf et al. 2024). The aim is to analyse farmers' risk perceptions regarding the reuse of treated wastewater and their relationships with socio-economic characteristics, knowledge and information, and attitudes towards innovation. Survey-based approaches are widely used in the literature to investigate decision-making processes and adaptive behaviours in agricultural and environmental contexts (Eitzinger et al. 2018; Deh-Haghi et al. 2020). This study uses a convenience-based, non-probabilistic sample. As a result, the findings do not statistically represent the whole population of farmers. However, the exploratory aim of the study helps identify distinct farmer profiles in terms of risk perception, openness to innovation, and willingness to use treated wastewater for irrigation.

The study area

Data were collected through a field survey on a sample of irrigated farms located in the Basilicata region, specifically in the Metapontino area (Fig. 1), the centre of the region's intensive irrigated agriculture. Since 2022, in line with the climatic trends observed in Southern Italy, in Basilicata, the frequency and intensity of extreme drought events have increased significantly (Bentivenga and Piccarreta 2023; Istat 2025), with substantial repercussions on agricultural production (Istat 2024). According to ISTAT data (2024), in 2022, the agricultural sector suffered a 0.7% decrease in production volume, associated with reductions in cultivated land and labour inputs. The combination of water scarcity and infrastructure inefficiencies (e.g. leaks in distribution networks) is a critical factor in crop yield stability, exacerbating the vulnerability of farms in structurally disadvantaged areas (Ingrao et al. 2023). A substantial weight of irrigated agriculture characterises the Metapontino area, which is therefore particularly exposed to these critical issues. Although local farmers have adopted mitigation strategies – such as the construction of wells and tanks for rainwater collection, the implementation of micro-irrigation systems and the adoption of advanced water management technologies (Massari et al. 2021) – these interventions, while effective in the short term, do not guarantee systemic resilience in the medium to long term. Therefore, exploring alternative solutions such as the reuse of treated wastewater is a viable option for the sustainability of the regional agricultural sector.

Fig. 1 Study area - Basilicata region and Metapontino area

The data collection

A semi-structured questionnaire was administered to a sample of farmers in Basilicata who own irrigated farms. The questionnaire was divided into four thematic sections, designed to cover the aspects relevant to the analysis comprehensively:

- Human capital: socio-demographic variables (age, level of education, agricultural training) and information on the farm's income.
- Farm characteristics and water management: structural data (area, crop patterns, infrastructure) and information on irrigation practices, with a focus on the motivations behind adopting innovative technologies.
- Knowledge: farmers' level of knowledge and awareness of wastewater reuse regulations (e.g. Regulation (EU) 2020/741) and water quality requirements for the irrigation of food crops.
- Perceptions of risks associated with wastewater reuse: farmers' concerns include accumulation of contaminants in soils, equipment clogging, potential compromise of product quality, and impacts on human and environmental health. This last section of the questionnaire was also intended to collect information on farmers' attitudes toward innovation.

Table 1A in the Appendix describes the main variables included in the questionnaire.

The questionnaire underwent a preliminary pre-test on a sub-sample of farmers to assess clarity and internal consistency. The survey was conducted between July and December 2024 in collaboration with Producer Organisations (POs) that are active in the area. Only irrigated farms with fruits and horticultural crops were included in the sample, and interviews were conducted face-to-face or via digital administration using the Google Forms platform. In this last case, farmers were previously contacted by phone to explain the aims and the structure of the questionnaire, so to minimise differences between interview vs. online respondents (mode effects). All participants were informed about the objectives of the study and provided informed consent.

The selection of the sample was based on farmers' availability and the support of local Producer Organisations (POs). Therefore, the sample is a convenience and non-probabilistic sample. Nevertheless, it is appropriate for exploratory and descriptive analyses primarily aimed at better understanding phenomena (Memon et al. 2025).

The sample

The final sample included 200 farms. Tables 1 and 2 report their main socioeconomic characteristics. The sample accounts for 7,308 hectares of total Utilised Agricultural Area, 80% of which is irrigated. The sample irrigated area (5,857 hectares) represents almost 20% of the regional irrigated area. The average farm size is 36.5 hectares, but there is significant variability, with farms ranging from 2 to 350 hectares. Approximately 50% of farms are under 25 hectares. The average annual irrigation water consumption is

Table 1 Descriptive statistics of the sample

Variables	Average	Standard deviation
Utilised Agricultural Area (hectares)	36.5	40.6
Agricultural irrigated area (hectares)	29.2	32.5
Age (years)	51.4	17.0
Irrigation water quantity (m^3/ha)	3,758.5	1,251.6
Farm management experience (years)	21.8	15.7

Table 2 Frequency distributions of main socio-economic characteristics of the sample

Variable	Frequency
Educational level	
	Primary = 17% Lower secondary school = 25% Higher secondary school = 33.5% Graduation = 24.5%
Professional training during last 3 years	No = 56%
	Yes = 44%
Income level	Up to 15,000 euro = 6.5% From 15,000 to 28,000 euro = 18.5% From 28,000 to 50,000 euro = 33% More than 50,000 euro = 42%
The farm is the main source of income	No = 16.5%
	Yes = 83.5%
Farmer is full time employed on farm	No = 33%
	Yes = 67%

Table 3 Frequency distribution of risk perception items

Perceived risks	Frequency	
	No	Yes
Damages to irrigation system	65%	35%
Unwanted substances accumulation	61%	39%
Worsening of product quality	71%	29%
Alteration of natural habitats	79.5%	20.5%
Groundwater pollution	82%	18%
Increase in soil salinity	79%	21%
Consumers' health risks	72%	28%
Workers' health risks	77.5%	22.5%

3,760 m^3 per hectare, with variability depending on the crops and their respective water requirements. Almost all farms (98%) are specialised in fruit and vegetable production, and only a small proportion of the sample is mainly oriented towards the cultivation of other species, such as maise, sunflowers and sorghum.

A widespread concern among farmers is the future availability of water resources: 83% of the sample state they are alarmed by the effects of climate change and the increasing frequency of droughts, predicting a progressive reduction in available water resources. In response to these critical issues, 87% of respondents have adopted drip irrigation systems to optimise water use efficiency and reduce consumption. However, structural issues persist regarding the efficiency of local water sources. The primary source of water is irrigation consortia, and 83% of the water consortium users reported problems related to limited water availability and distribution inefficiencies. That makes 122 farmers, 61% of the sample, in favour of using wastewater for irrigation, mainly because it provides access to greater volumes of water than conventional sources, and offers potential agronomic benefits linked to reduced fertiliser use.

The last section of the questionnaire was dedicated to identifying the risks that farmers associate with the use of treated wastewater and their attitudes towards innovation. A higher percentage of farmers perceive the accumulation of undesirable substances and market difficulties for products irrigated with wastewater as relevant risks (Table 3). Just over a third of farmers fear damage to irrigation systems. The least perceived risks are groundwater pollution (18% of farmers surveyed) and increased soil salinity (21%

of the sample). Regarding innovativeness, the attitude of farmers towards innovation was investigated by adapting Rogers' definition of innovators, early adopters, the early majority, the late majority, and laggards. Therefore, farmers were asked how they feel about innovation, whether they are attracted to new technologies and are prompt to invest to be at the forefront, or whether they only adopt new technologies when they are already established and widespread. The distribution of the sample by innovation attitude is reported in Table 4. Only 10% of the sample can be classified as "innovators", but about one-third of the surveyed farmers feel themselves as "early adopters".

Methods

The analysis of the collected data was divided into three steps.

In the first phase, items related to the perceived risks associated with using wastewater for irrigation were analysed using a Principal Component Analysis (PCA) based on tetrachoric correlation matrix (Hair et al. 2019). This approach enables the information from the initial variables to be summarised into a small number of components, allowing the latent structure of the data to be identified. The suitability of the data for this type of analysis was verified using the Kaiser-Meyer-Olkin (KMO) index, Bartlett's Sphericity Test and the variable-specific measure of sampling adequacy (MSA). Specifically, the Kaiser-Meyer-Olkin (KMO) index was calculated to assess the adequacy of the sample size for factor analysis. A KMO value above 0.7 indicates adequate sampling and supports the validity of factor analysis results, ensuring that the identified factors are reliable and meaningful. Bartlett's Sphericity Test determines whether the correlation matrix deviated significantly from the identity matrix, indicating that the variables were sufficiently correlated. Furthermore, a variable-specific measure of sampling adequacy (MSA) is used to assess the appropriateness of individual variables in the overall analysis. Together, these indices ensure that the data meet the criteria for a robust and reliable analysis. To improve the interpretability of the components, a Varimax orthogonal rotation was applied. As a robustness check, an oblimin rotation was also examined to assess whether allowing correlations among components changes the solution interpretation. The varimax rotation did not change the interpretation of the three components while providing a simpler and more interpretable factor structure, facilitating the identification of variables that load strongly on a single component. The interpretation of the components was based on the factor loading matrix. Component membership was assigned to the component with the highest loading, provided that loading was larger than 0.50 and differed by at least 0.20 from any secondary loading (Hair et al. 2019). A variable related to more than one component (cross- loading variable) can be retained when it is meaningful and contributes to better defining a multidimensional concept.

Table 4 Frequency distribution of surveyed farmers by self-classified innovation attitude

Attitude toward innovation	Frequency
I am attracted to new technologies, I am willing to invest more to be at the forefront, and I am also willing to accept when an innovation proves to be a failure (innovators)	10%
I am interested in new technologies if I think they can bring real advantages or benefits (early adopters)	32%
I am interested in new technologies, but I prefer to make sure that the innovation has real benefits or advantages before investing in it (early majority)	23.5%
I am wary of adopting a new technology. I only adopt a new technology when other people have already adopted it (late majority)	23.5%
I only decide to adopt a new technology when it is already established and widespread (laggards)	11%

The second phase of the work involved conducting an exploratory analysis to investigate any relationships among components related to perceived risks, socioeconomic characteristics, attitudes towards innovation, and levels of knowledge of wastewater for irrigation. To this end, parametric and non-parametric statistical tests (t-tests, ANOVA, chi-square tests, and the Kruskal-Wallis tests) were employed, depending on the nature of the variables.

The third phase of the analysis aimed to identify distinct profiles of farmers based on their perceptions of risk. Therefore, the factor scores derived from PCA were used in a hierarchical cluster analysis applying the Ward's method. The choice of the number of clusters is based on the joint assessment of the dendrogram, the ratio of between-clusters and within-clusters variance, the silhouette index, and the interpretability of the resulting profiles (Hair et al. 2019). The characterisation of the clusters was based on centroid values and further specified by examining relationships between the clusters and variables such as the level of knowledge of regulations, attitude towards innovation, and propensity to use wastewater for irrigation.

PCA was conducted using the Psych package in R. All other analyses were carried out using IBM SPSS Statistics Version 30.0.

Results

The PCA results

By applying PCA to the risk perception items, based on the criterion of eigenvalue higher than 1, three components were extracted that explain 76.7% of the total variance. The meaning of the components can be derived from the factor loadings matrix (Table 5), which reports the correlation between each original variable and each component, with higher values indicating a greater contribution to the component's explanation. The three components can be interpreted as different dimensions of the perceived risk associated with the use of wastewater in agriculture: perceived risk related to the accumulation of undesirable substances and the quality of the final products (Component 1); perceived environmental risk, related to the contamination of soil and natural ecosystems (Component 2); risk for the health of agricultural workers and consumers (Component 3). To better understand the components' meanings, two aspects can be underlined. Firstly, component 1 focuses on the effects of particle accumulation. Undesirable substances and their accumulation can affect both irrigation systems (a physical effect, i.e. a technical risk) and environmental resources (a biological and chemical effect). Secondly, the relevance of "worsening of product quality" for both the first and

Table 5 Factor loadings matrix

Perceived risk items	Component 1	Component 2	Component 3
Unwanted substances accumulation	0.826		0.413
Damages to irrigation system	0.829	0.242	0.154
Groundwater pollution	0.470	0.695	
Increase in soil salinity		0.728	0.290
Alteration of natural habitats	0.107	0.780	0.244
Worsening of product quality	0.546	0.544	0.251
Consumers' health risks	0.224	0.327	0.889
Workers' health risks	0.298	0.200	0.883
Explained variance	25.5%	26.5%	24.6%

KMO = 0.75; Bartlett's K-squared = 335.380, df = 28, p-value < 0.001

Table 6 Descriptive statistics of components values by innovativeness category

Perceived risk	Innovativeness category	Mean	Std. Deviation
Accumulation Risk (Component 1)	Innovators	-0.6098	0.3424
	Early adopters	-0.3184	0.8126
	Early majority	-0.1539	0.9129
	Late majority	0.5441	1.0652
	Laggards	0.6470	1.1228
Environmental Risk (Component 2)	Innovators	-0.4739	0.3351
	Early adopters	-0.3902	0.6290
	Early majority	0.2074	1.1374
	Late majority	0.2823	1.2110
	Laggards	0.5199	0.9514
Health Risks (Component 3)	Innovators	-0.3706	0.3837
	Early adopters	-0.3822	0.4453
	Early majority	-0.1127	0.9224
	Late majority	0.6758	1.3089
	Laggards	0.2460	1.2007

Table 7 Kruskall-Wallis test on differences of perceived risks' components by farmers' innovation attitude

	Kruskall-Wallis statistic	Sig.	Eta squared effect size η^2
Component 1: Accumulation Risk	36.572	< 0.001	0.14
Component 2: Environmental Risk	20.523	< 0.001	0.09
Component 3: Health Risk	20.133	< 0.001	0.08

Note: Sig. = asymptotic p-value (not adjusted; one omnibus test per component)

second components suggests that this risk is considered connected to both product market characteristics, and the effects of the exchange roots-soil that systemically impact on the product quality.

Farmers' characteristics and risk perception components

Risk perception increases with age, and there are statistically significant differences between age classes. More specifically, farmers aged 55 or older report higher levels of perceived risks across all three risk dimensions. Furthermore, information and knowledge play an important role. In all three risk areas, farmers who are not informed about wastewater regulations report significantly higher risk perceptions than those with some or full knowledge. Similar results emerged regarding levels of education and participation in professional agricultural training courses, suggesting that access to information and formal education are associated with lower risk perceptions.

Risk perception is closely linked to openness to innovation. More specifically, farmers who state themselves to have more innovative attitudes (innovators and early adopters) tend to perceive risks less than those with less innovative attitudes (Table 6). A comparison of the distributions of component values across different categories of innovators reveals statistically significant differences across all three dimensions of perceived risk (Table 7). Pairwise comparisons better specify these relationships. Perceived accumulation risk varies significantly across categories of innovativeness. The differences are less pronounced when environmental and health risks are taken into account. They are significant only when comparing extreme groups of innovativeness, while differences are mostly not statistically significant in the intermediate categories (Table 8).

Table 8 Pairwise comparison of perceived risks' components by farmers' innovation attitude categories

Sample 1-Sample 2 comparison	Component 1: Accumulation risk		Component 2: Environmental risk		Component 3: Health risk	
	Statistic test	**Mod. Sig.[a]**	**Statistic test**	**Mod. Sig.[a]**	**Statistic test**	**Mod. Sig.[a]**
Innovators-Early adopters	-0.996	1.000	-0.073	1.000	0.424	1.000
Innovators-Early majority	-1.657	0.974	-1.797	0.724	-1.244	1.000
Innovators-Late majority	-4.229	**0.000**	-2.209	0.272	-2.222	0.263
Innovators-Laggards	-3.834	**0.001**	-3.032	**0.024**	-4.210	**0.000**
Early adopters -Early majority	-0.975	1.000	-2.400	0.164	-0.488	1.000
Early adopters -Late majority	-4.549	**0.000**	-2.972	**0.030**	-1.426	1.000
Early adopters -Laggards	-3.760	**0.002**	-3.715	**0.002**	-2.622	0.087
Early majority-Late majority	-3.328	**0.009**	-0.533	1.000	-1.200	1.000
Early majority-Laggards	-2.872	**0.041**	-1.770	0.768	-2.762	**0.058**
Late adopters - Laggards	-0.215	1.000	-1.344	1.000	1.005	1.000

Note: The "Statistic test" columns report the standardized test statistic (z) from Dunn's pairwise comparisons, and "Mod. Sig." the corresponding (adjusted) significance values. [a] Significance values have been adjusted by the Bonferroni correction for multiple tests

Table 9 Descriptive statistics of components values by willingness to use wastewater for irrigation and Mann-Whitney test on differences results

Would you use treated wastewater for irrigation?	Accumulation risk	Environmental risk	Health risk
No	0.513	0.422	0.494
Yes	-0.735	-0.269	-0.315
Mann-Whitney test - U statistic	2590.5	3052.5	3016.5
Sig. (*asymptotic p-value)*	< 0.001	< 0.001	< 0.001

Table 10 Mean of perceived risk components by clusters

	Accumulation risk	Environmental risk	Health risk	Number of cases
Cluster 1: Experimenters	-0.719	-0.370	-0.475	89
Cluster 2: Product Concerned	1.206	-0.325	-0.692	38
Cluster 3: Health Concerned	0.834	-0.742	1.564	25
Cluster 4: Environment Concerned	-0.138	2.258	-0.616	17
Cluster 5: Cautious	-0.012	0.822	1.289	31

Finally, the same three risk components were related to farmers' propensity to use wastewater for irrigation. Farmers who are in favour of using wastewater report a significantly lower perception of risk than those who do not declare themselves willing to use it (Table 9). These findings are consistent with those reported in the literature (Dessart et al. 2019).

The cluster analysis results

Cluster analysis was applied to factor scores for the three dimensions of perceived risk. Five distinct clusters were identified that reflect different farmers' profiles according to risk perception in using wastewater for irrigation. The silhouette analysis yielded an average score of 0.54, indicating reasonable cluster quality with good overall cohesion and separation (Rousseeuw 1987). Table 10 shows the average values of the three components for each cluster. As factor scores derived from principal component analysis are standardised variables with a mean of zero and a standard deviation of one, values below zero indicate the cluster is characterised by values lower than the sample mean.

In contrast, values above zero imply that the variable is higher than the sample mean. The magnitude of deviation from zero thus quantifies the extent of differentiation from the central tendency, facilitating the characterisation of the cluster. The box plots (Fig. 2) illustrate the internal distribution of each cluster and help to characterise it better.

Cluster 1 (Experimenters), which represents the largest group (44.5% of respondents), is characterised by a substantial internal homogeneity and a level of risk perception

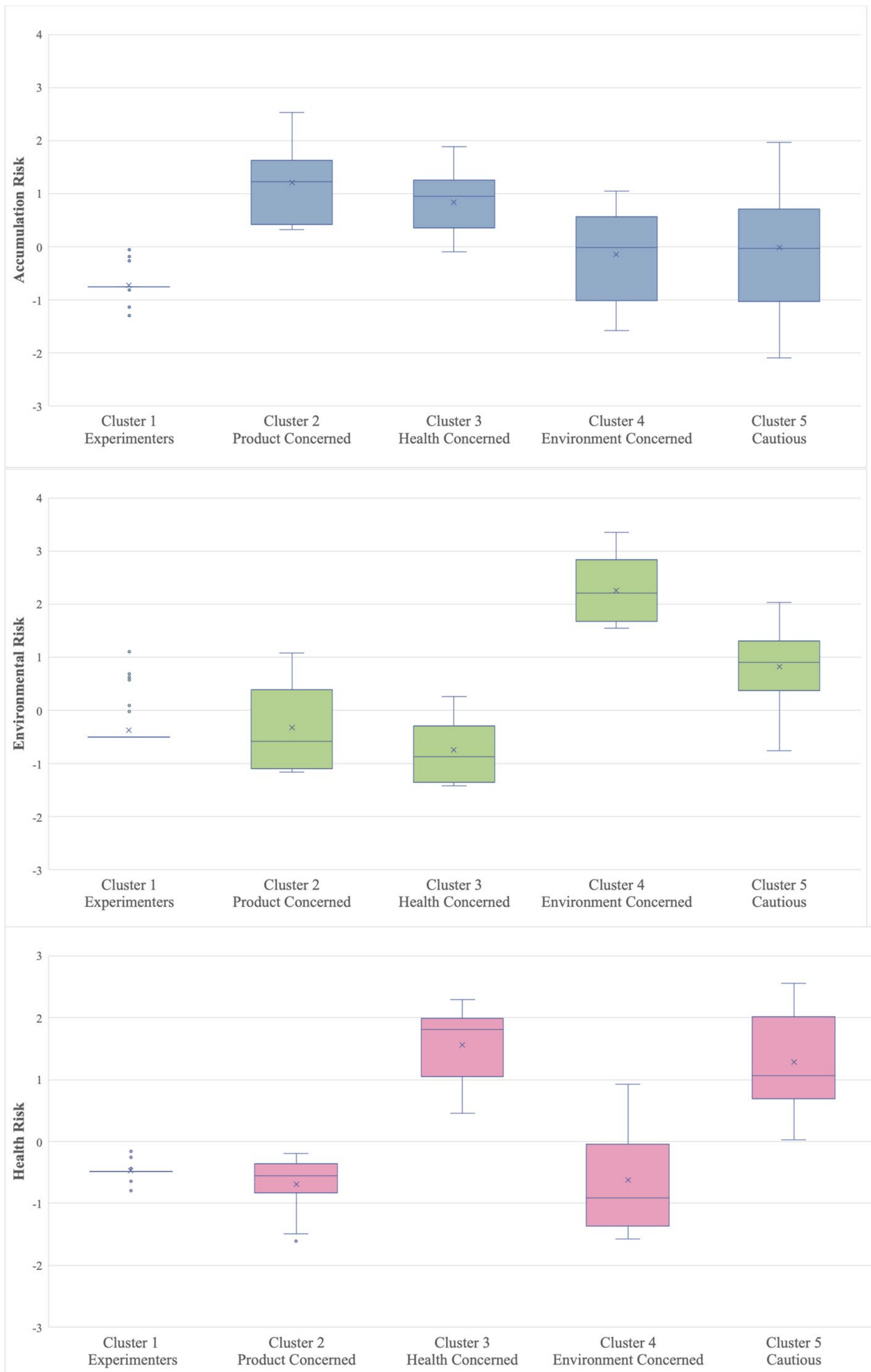

Fig. 2 Distributions of risk perception components by clusters

below the sample average for all dimensions analysed. This cluster represents a low-risk reference group, exhibiting consistently negative scores across all dimensions, indicative of minimal accumulation, environmental, and health concerns. Cluster 2 (Product Concerned, 19.0% of the sample) exhibits similar characteristics to those of Cluster 1 (Experimenters) in terms of environmental and health risk perception. However, it differs from Cluster 1 in that it has the highest perception of accumulation risk, the highest value observed across all clusters. This profile suggests a specific sensitivity to pollutant accumulation, compared to a less marked assessment of the other two risks. Cluster 3 (Health Concerned, 12.5% of cases) is characterised by the highest perception of health risk among all clusters. Concern about the accumulation of unwanted substances is also high, while the value for environmental risk is negative. That could reflect greater attention to the direct consequences of the accumulation of unwanted substances on health, rather than to environmental aspects.

Environmental risk is particularly felt in Cluster 4 (Environment Concerned), which represents the smallest group in terms of numbers (8.5% of respondents). It is generally associated with a low perception of health risk. This last aspect distinguishes it from Cluster 5 (Cautious, 15.5% of the sample), in which both environmental and health risks are particularly relevant. In contrast, the perception of accumulation risk is highly differentiated within the group.

Risk perception and farmers' profiles

Regarding the attitude toward innovation and willingness to use treated wastewater for irrigation, Figs. 3 and 4 show the distribution of the farmers across clusters and clearly illustrate the differences between them. More specifically, Cluster 1 comprises farmers who are more open to innovation and are also more willing to utilise wastewater. In Cluster 1, more than 70% of farmers can be identified as innovators or early adopters (Fig. 3), and 93% are propense to use treated wastewater for irrigation (Fig. 4). In contrast, Clusters 3 and 5 exhibit a lower propensity to innovate and are also more cautious

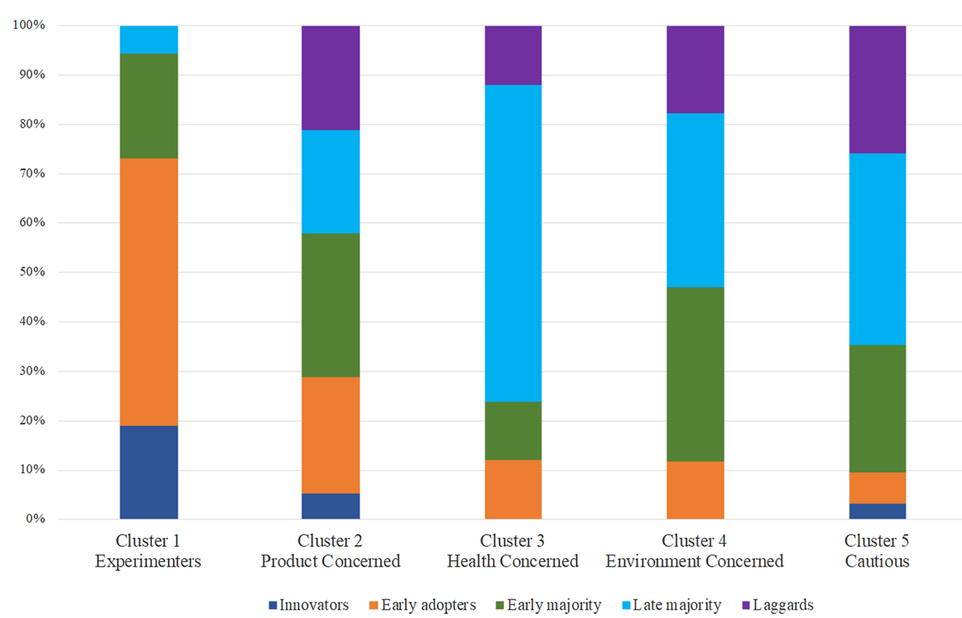

Fig. 3 Distribution of clusters by attitude of farmers toward innovation

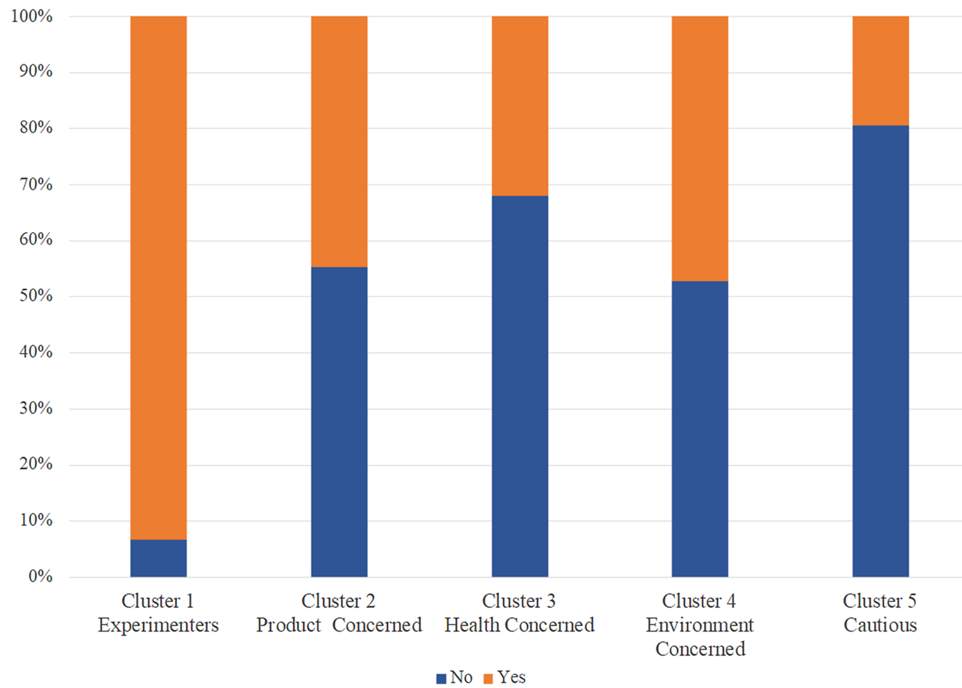

Fig. 4 Distribution of clusters by willingness to use treated wastewater for irrigation

in the possibility to use wastewater. Indeed, laggards and late majority of adopters represent 76% of farmers in Cluster 3 and 64,5% in Cluster 5, and the share of farmers who are propense to use wastewater are 32% and 19.4%, respectively. In general, there is a statistically significant relationship between cluster membership and these two elements (Attitude toward innovation by cluster: χ^2 = 96.689, $P < .001$; Cramer's V = 0.348, $P < .001$. Willingness to use wastewater by cluster: χ^2= 75.980, $P < .001$; Cramer's V = 0.616, $P < .001$).

By analysing the socio-demographic and attitudinal characteristics of the different clusters, it is possible to define more accurate farmer profiles that can help identify strategies and tools to support the use of unconventional water resources. Detailed information on each profile is reported in Tables 2A and 3A in the Appendix.

Cluster 1: Experimenters

The Experimenters show a significantly low perception of the risks associated with using treated wastewater for irrigation purposes. Contrary to what one might assume, the reduced perception of risk is not associated to a lack of awareness of opportunities and threats related to this resource, but rather to a high degree of knowledge of current regulations on wastewater use. That suggests that knowledge of regulations and safety guidelines contributes to rationalising risk assessment, orienting it towards a perspective of management and mitigation rather than alarmism (Ghadim et al. 2005; Kang and Park 2011; Kumar et al. 2018; Pfeiffer et al. 2021). From a socio-demographic perspective, members of this cluster are distinguished by a higher level of education and a lower average age, indicating a clear correlation between the quality of human capital, the degree of regulatory knowledge and learning, and the perception of risk. Similarly, as highlighted in the literature, these factors correlate with the adoption of innovative practices (Eitzinger et al. 2018; Fahad and Wang 2018; Dessart et al. 2019). The positive attitude of these farmers towards innovation is related to a strong acceptance of wastewater use: 93% of farms are in favour of this practice. In line with this orientation, about 73% of the Experimenters self-identify as "innovators" and "early adopters" in agricultural innovation contexts, highlighting a proactive orientation towards the adoption of new technologies. In essence, this first cluster represents a segment of relatively highly informed, educated and young farmers, whose high level of knowledge and constant professional development can be translated into a moderate perception of risk and a marked openness to alternative sustainable practices.

Cluster 2: Product concerned

The members of this cluster show a very low perception of the risks to human health (for agricultural workers and consumers) and environmental risk associated with the use of treated wastewater. That suggests that farmers in this cluster consider these aspects negligible or effectively mitigated. On the contrary, their primary concern is focused on the risk of accumulation of undesirable substances and the quality of agricultural products. This concern can be intrinsically linked to potential damage to irrigation systems and, more significantly, to the negative economic implications of reduced product quality. The possible reduction in market price and increase in production costs suggest that this cluster is highly sensitive to factors that directly affect profitability and commercial competitiveness (Greiner et al. 2009; Joffre et al. 2019; Regan 2019). Unlike Experimenters, Product Concerned farmers do not show specific characteristics with respect to age, education or knowledge of the regulation. That suggests that these factors do not primarily shape their perceptions of risk and priorities. A distinctive feature of this cluster is their marked tendency to allocate a large portion of their production to direct sales on the market and to associations (on average, 37% of production, higher than for other clusters). This commercial strategy supports the hypothesis that product quality and its perception by the market and end consumer are priorities (Alsa'di et al. 2024), justifying their selective concern about risks that could compromise this quality and, consequently, their ability to sell and retain customers. Therefore, farmers in this cluster can be described as pragmatic and strongly market-oriented, with a risk assessment that is mainly centred on protecting the quality and economic value of agricultural products over other environmental or health considerations, which seems to play a less immediate or relevant role in their operations and sales strategy.

Cluster 3: Health concerned

This profile of farmers shows a high level of awareness and prioritisation of risks to human health, both for consumers and agricultural producers, associated with wastewater use. This concern is predominant and associated with considerable apprehension about the accumulation of undesirable substances in agricultural products. That suggests a strong emphasis on direct health and food safety implications (Ekane et al. 2021; Tinh et al. 2021). Approximately 60% of these farmers are unaware of the regulations governing wastewater use, and 72% have a low level of education. These data suggest a potential association between information/education deficits and a greater perception of risk, particularly in complex and unexplored areas, such as the use of unconventional water resources. Consistent with these observations, 68% of this cluster is not inclined to use wastewater, stating clear reluctance to adopt this practice. Knowledge seems to be a key factor in overcoming concerns about using wastewater, and 76% of the cluster deem it necessary to receive adequate training for its safe and correct use.

Age is also a distinctive and significant factor for this cluster, as 64% of its members are over 65. Belonging to an older age group is associated with a lower propensity to keep up to date with new regulations and technologies, and with greater caution or risk aversion (Serote et al. 2021; Msaki et al. 2022). Their self-identification further supports the picture of them as "late majority" or "laggards" in innovation contexts. That suggests a general tendency to preserve traditional practices and greater hesitation to adopt new agricultural methods.

Cluster 4: Environment concerned

Comprising a small number of farmers, this cluster's primary concern is the environmental risks associated with wastewater use. This strong focus on ecological impacts is associated with a significantly low perception of risk to human health (of workers and consumers), suggesting a differentiated assessment of potential hazards. A key characteristic of this cluster is the information gap: 56% of farmers are unaware of the regulations governing wastewater use and its practical implications before its use. This lack of information on regulations and quality requirements for this resource co-occurs with their greater concern for the environment, as limited access to clear guidelines or to information on safety measures may be associated with heightened apprehension about potential ecological damage (Huijts et al. 2019; Scovell et al. 2022). Indeed, 53% of farmers in this cluster state to be willing to use wastewater for irrigation and, in terms of innovation adoption, this cluster ranks predominantly between the "early majority" and the "late majority". This implies that farmers in this cluster may be willing to adopt new practices, such as wastewater use, but only after observing the adoption and success of others. Their propensity for innovation seems to be evidence-based, requiring validation by other actors before implementation proceeds (Scovell et al. 2022).

Cluster 5: Cautious

The last cluster shows a high perception of risk regarding the environmental and health impacts of wastewater use, while there is significant variability in accumulation risk. Demographically, the Cluster 5 is similar to Cluster 3: on average, farmers are 64 years old and, crucially, have a low level of education (77% of the cluster has a primary education). Additionally, 78% of these farmers are unaware of legislation and regulations governing wastewater use. These factors, age, low levels of education, and, in particular, limited specific information and knowledge, are strongly associated with this profile. The combination of these factors suggests that these farmers' uncertainty and resistance to innovation might not stem from a conscious assessment of risks and benefits, but rather from a lack of information that prevents a complete understanding of practices and safety guarantees (Slovic 1987; Shapiro et al. 1992; Greiner et al. 2009; Scovell et al. 2022; Alam et al. 2024). Consistent with these aspects, an overwhelming majority of farmers belonging to this cluster (81%) are not inclined to use wastewater for irrigation. This high percentage of reluctance could be associated with a stronger perception of risk, also related to a limited familiarity with existing safety measures and regulations, and a general aversion to risk that has also been reported in other studies for older and less educated groups (Li et al. 2021). All that translates into marked resistance to the adoption of innovative practices such as wastewater irrigation, highlighting the need for interventions to bridge the information gap and promote training and regulatory learning.

Discussion

The use of treated wastewater for irrigation is emerging as a viable strategy to address the pressing challenges of climate change and the increased demand for water resources (Singh 2021; Karimi and Ataei 2023; Manganiello et al. 2024). In line with recent studies linking wastewater reuse to the principles of the circular economy, this practice represents a key component of sustainable resource management in agriculture (Kyriakopoulos 2023). Nonetheless, the widespread implementation of this practice may be impeded by farmers' perceptions of risk, which are profoundly shaped by individual variables and the context in which they operate (Ahmmadi et al. 2021; Garin et al. 2021; Younas et al. 2021; Karimi and Ataei 2023; Mishra et al. 2023; Tariq et al. 2023).

The present work firstly aimed to provide insights into how risk perception associates with farmers' willingness to use treated wastewater. Our results indicate that farmers' propensity to use treated wastewater for irrigation is strongly associated with their risk perception. The findings also reveal a strong association between risk perception and the inclination toward innovation, suggesting that as risk perception intensifies, a notable decline in the intention to adopt innovative solutions may occur (Greiner et al. 2009; Pfeiffer et al. 2021; Karimi and Ataei 2023). These results confirm the findings of previous studies, which posit that perceptions of various risk types can catalyse innovative behaviours, thereby influencing individual decision-making processes (Ismail et al. 2012; Sohail et al. 2021). In this respect, risk perception can represent a relevant barrier to the diffusion of reclaimed water within sustainable and circular agricultural systems.

A second aim of the work was to determine whether perceptions of risk and the propensity for innovation are associated with specific farmer profiles. We identified five distinct farmers' profiles, each characterised by specific concerns related to environmental, accumulation and health risks. These profiles can be associated with higher or lower levels of innovativeness, as well as with factors such as educational level, age and knowledge of regulations. For instance, the cluster identified as Experimenters exhibited a markedly low perception of risk, which was associated with their comprehensive understanding of regulations and safety protocols. In contrast, clusters such as the Health Concerned and the Cautious, who have limited familiarity with this resource and the relevant regulations, report higher levels of perceived risks, particularly those related to health and product quality. These findings align with previous research in the domain. Indeed, the significance of information in alleviating risk perception is extensively documented in the literature (Caswell and Zilberman 1986; Kumar et al. 2018; Pfeiffer et al. 2021; Sabbagh and Gutierrez 2022; Kyriakopoulos et al. 2023; Ahmed et al. 2024). The results suggest that transparent and accessible communication regarding legal requirements and wastewater treatment procedures could substantially mitigate resistance and promote the utilisation of this unconventional resource (Slovic 1987; De Buck et al. 2001; Greiner et al. 2009; Kang and Park 2011; Joffre et al. 2019).

At the same time, factors such as age, education, and professional training serve a pivotal role in shaping an individual's openness to novel practices. Younger farmers with higher levels of education, such as the Experimenters, are more likely to perceive the wastewater reuse as an opportunity rather than a potential hazard. In contrast, older farmers with lower educational backgrounds tend to adopt a more cautious stance, which can be associated with a scarcity of information or a general aversion to risk (Serote et al. 2021; Msaki et al. 2022; Sánchez-Cañizares et al. 2022). Indeed, age and education are associated with differences in risk perception and attitude and can be related with farmers' openness to innovation.

An innovation-oriented attitude is associated with an increased likelihood of utilising wastewater for irrigation. These findings are supported by existing literature: farmers characterised by a more innovative profile, as delineated by Rogers (1983), display a greater inclination to adopt alternative solutions, particularly if they have previously engaged with complex technical innovations (Lubell et al. 2011; Thompson et al. 2019; Li et al. 2021, 2022a; Kaine and Wright 2022; Ahmed et al. 2024). Consequently, addressing factors that can influence farmers' innovative attitudes is essential for enhancing the adoption of new practices. Peer influence and social networks can be related with farmers' willingness to adopt innovations (Rogers 1983). That highlights the significance of fostering strong social connections and facilitating information dissemination to encourage more innovative behavioural patterns (Ren et al. 2022).

Farmers do not assess risks in the same way. In our sample, Product Concerned farmers are primarily concerned with product outcomes and focus on the potential economic repercussions of wastewater use, given that a worsening in product quality could adversely affect their market competitiveness (Daughton and Ternes 1999; Drechsel et al. 2022). Environment Concerned farmers, on the other hand, focus on environmental implications, but are willing to adopt new practices if their benefits are demonstrated. These differences indicate that, to promote wastewater adoption, tailored messages are necessary. For some farmers, emphasising the economic advantages (Poustie et al. 2020; Drechsel et al. 2022) and microbiological safety (Khan et al. 2022) may prove more effective. For others, highlighting the environmental sustainability of wastewater use could yield more persuasive outcomes (Poustie et al. 2020; Trotta et al. 2024; Tella et al. 2025).

Conclusions

This empirical study had an exploratory aim and used a non-probabilistic sample; therefore, its results cannot be generalised, but they can provide some insights into the issue of wastewater use in agriculture. Indeed, the identification of farmers' profiles, even within a specific sample, highlights relationships between socio-demographic characteristics, openness to innovation, and risk perception that could inform the debate on the potential for the wider adoption of treated wastewater in agriculture. The adoption of treated wastewater in agriculture seems constrained by heterogeneous risk perceptions, uneven access to information, and structural differences in farmers' human capital. These interrelated factors constitute major barriers to the diffusion of this practice.

A single strategy could not be sufficient for incentivising the use of wastewater in agriculture. To effectively promote the adoption of this practice, it is crucial to develop multi-faceted strategies that encompass:

1. Training and information campaigns, including outreach on regulations and safety protocols, aimed at mitigating the substantial knowledge gaps prevalent among older and less educated farmers.
2. Evidence-based demonstrations, through pilot projects or case studies, that can show the concrete advantages of using wastewater, thereby alleviating uncertainties among

the most hesitant farmers and fostering networks of pioneering farmers who can act as credible testimonials.

3. Specific economic incentives designed to reassure farmers, such as Product Concerned farmers, who harbour concerns regarding potential impacts on crop quality and market valuation.

Several actors could be involved in implementing this strategy with a different role. The Agricultural Knowledge and Innovation System (AKIS) within the Common Agricultural Policy is the natural frame for this intervention. By linking research institutes, national and regional authorities, extension services, farmers, and farmers' organisations, AKIS promotes knowledge sharing, enhances the flow of information, and supports innovation practices. However, our findings suggest the need to implement targeted informational campaigns that employ appropriate communication strategies to reach different farmer profiles effectively (Regan 2019; Joffre et al. 2019; Li et al. 2022b; Gardezi et al. 2022).

In summary, while the use of wastewater in agriculture represents a concrete approach to contemporary water scarcity, its efficacy will hinge on the capacity to translate technical data into comprehensible messages, enhance the confidence of potential users through concrete evidence, and tailor communication strategies to the distinct needs and concerns of various farmers' groups. Our study suggests the significance of investing across multiple dimensions in a joint and differentiated manner. That can help transform this practice, still perceived as risky by many farmers, into a collective opportunity for a more resilient and sustainable agriculture.

Limitations and future research

This study has some limitations. Firstly, the farmers were contacted mainly through local Producer Organisations (POs), and therefore the sample was a convenience, non-probabilistic sample. That introduces potential biases as the sampling could automatically select the more active farmers. Secondly, the study is based on self-reported information concerning knowledge, perceived risks, innovation attitude and willingness to use treated wastewater. This approach is appropriate for analysing subjective perceptions and attitudes, which represent the core focus of the research. However, self-reported measures may also be influenced by respondents' interpretation of the questions and, to some extent, by social desirability, especially when dealing with environmentally relevant practices. In addition, risk perceptions data have been collected as binary variables. This choice was based on the questionnaire pre-test, which revealed a tendency for farmers to position themselves at the extremes of the Likert scale. Nevertheless, it is evident that risk perception merits a more "nuanced" assessment, and the use of more gradual measurement scales is acknowledged as a potential direction for future research.

The study had an exploratory aim. Future developments of the research could address more robust analysis of relationships and causal links among variables, the relationship between actual and perceived risks, and patterns related to information channels, knowledge, risk perception, and the adoption of sustainable practices.

Supplementary Information

The online version contains supplementary material available at https://doi.org/10.1186/s40100-026-00508-4.

Supplementary Material 1

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Author contributions
A. C.: Conceptualisation, Methodology, Formal analysis, Writing – review & editing. A. T.: Methodology, Investigation, Data curation, Writing – review & editing.

Data availability
The data are available from the corresponding author on reasonable request.

Declarations

Ethics approval and consent to participate
The research protocol has been approved by the ethics committee of the University of Basilicata, in accordance with current University regulations. Information on data protection is reported in https://portale.unibas.it/site/home/riferimenti/protezione-dati.html in "Informativa progetto di ricerca sull'utilizzo delle acque reflue in agricoltura". All participants were informed about the purpose of the study, the voluntary nature of their participation, and their right to withdraw at any time without providing justification. Informed consent was obtained from all participants prior to their involvement in the survey. No personally identifiable information was collected; all responses were anonymized and aggregated for statistical analysis, ensuring participant confidentiality throughout the research process. Data were processed in compliance with the EU General Data Protection Regulation (GDPR, Regulation (EU) 2016/679). Participation involved no physical, psychological, or social risk to respondents beyond that of everyday life, as the survey consisted solely of self-reported questionnaire items regarding perceptions and acceptance of treated wastewater (TWW) use for irrigation.

Competing interests
The authors declare no competing interests.

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