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Consumer willingness to pay and farmers' adoption intentions for pesticide-reducing technologies in European orchards

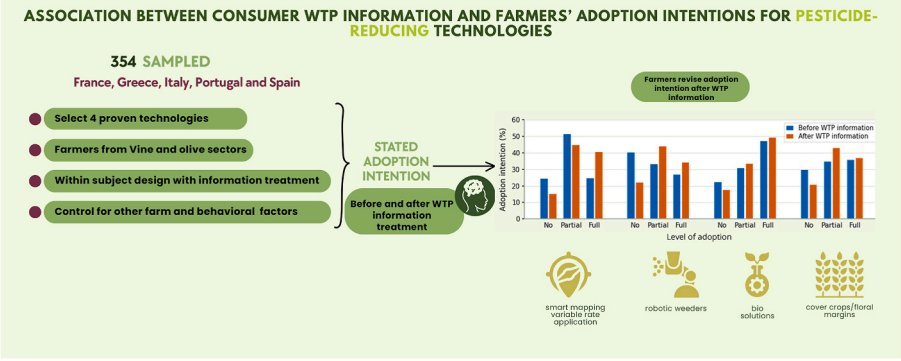
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HIGHLIGHTS

- Market pathway towards pesticide reduction is explored across five EU Mediterranean countries.
- Within-subject survey compares farmers' adoption intentions before and after WTP information.
- Exposure to consumer WTP information is associated with higher adoption intentions.
- The association with consumer WTP information is stronger for capital-intensive technologies.
- Demand-side incentives could support farmers' consideration of pesticide-reducing technologies.

GRAPHICAL ABSTRACT



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ABSTRACT

Reducing synthetic pesticide use remains an EU sustainability objective, yet uptake of pesticide-reducing technologies remains limited in high-input orchard systems. This study examines whether information on consumer willingness to pay (WTP) for products with reduced pesticides is associated with farmers' adoption intentions. We focus on four pesticide-reducing innovations: smart mapping variable rate (VRA) application systems, robotic weeders, bio-based solutions with low sulphur and copper formulations, and cover crops. Evidence is drawn from a structured survey experiment involving 354 olive and vine growers across five European Union countries. Using a within-subject design with randomised presentation order and a Cheap Talk script to mitigate hypothetical bias, we compare farmers' adoption intentions before and after exposure to estimated consumer WTP premiums for wine and olive oil produced with reduced pesticide use. Non-parametric tests and multinomial logit models indicate that consumer WTP information is positively associated with both partial and full adoption intentions across all four technologies, with stronger associations for smart mapping VRA and robotic weeders than for bio-solutions and cover crops. Farm structure and behavioural factors, including perceived costs, subjective norms, and perceived effectiveness of existing pest management practices, exhibited technology-specific

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associations with adoption intentions. Although the study design does not permit causal inference, the findings suggest that consumer-driven market signals could complement existing policy approaches to support the transition towards more sustainable agricultural production.

1. Introduction

The intensification of agriculture over the past half-century has delivered significant crop productivity gains, in part through the widespread use of chemical pesticides. Yet, despite their crucial role in ensuring global food supply, excessive and prolonged pesticide use is linked to several concerns, including biodiversity loss, groundwater contamination, and increased risks of cancer and neurological disorders (Finger, 2024; Skidmore et al., 2023; Zhou et al., 2025). This trade-off between productivity gains and environmental and human health risks has placed pesticide reduction at the centre of global sustainability agendas.[1]

In the European Union (EU), this concern is particularly pronounced, as regional pesticide use remains among the highest globally on a per-hectare basis (FAO, 2023). Despite ambitious policy targets, including the EU Green Deal's objective of reducing pesticide use and associated risks by 50 % by 2030, progress has been limited. The Sustainable Use Regulation (SUR), a key piece of EU legislation introduced in 2022 to operationalise these commitments, faced political resistance and was subsequently withdrawn in 2024 after agreement could not be reached (Finger et al., 2024; Candel, 2022). As a result, responsibility for pesticide reduction has shifted, de facto, toward voluntary action by farmers. This policy impasse raises a central question: in the absence of binding regulatory frameworks to enforce pesticide reduction, what complementary mechanisms may encourage farmers to consider pesticide-reducing practices? This paper explores whether market-based incentives may represent a complementary demand-side mechanism.

This question is especially relevant in pesticide-intensive production systems such as EU orchard agriculture.[2] Perennial crops such as vines and olives account for a substantial share of the EU's total pesticide use (Chen et al., 2022; Martínez Gila et al., 2024; Zachmann et al., 2025). Due to long growing seasons and persistent biological vulnerabilities, these orchards are heavily reliant on chemical inputs to manage pests, weeds, and fungal diseases (Martín-García et al., 2024; Regus et al., 2022), which makes them priority sectors for sustainability transitions and a context in which the trade-off between productivity and environmental objectives is especially acute.

Technological innovation offers a potential pathway to reconcile this trade-off. A range of pesticide-reducing innovations has emerged driven by technological advances and substantial research investment (Dalhaus et al., 2024), including those supported by European research projects under the Horizon Europe programme. Examples include robotic weeders that replace herbicides with autonomous mechanical control, smart variable rate (VRA) application systems that optimise pesticide use via canopy sensing, bio-based fungicides that reduce reliance on synthetic chemicals, and ecological approaches such as cover cropping. Field trials suggest that these technologies can reduce pesticide use, by up to 80 % in some cases, without compromising the effectiveness of pest control (Lytridis and Pachidis, 2024; Salas et al., 2024). Despite their technical viability, adoption among conventional orchard farmers remains limited, as many continue to rely on pesticide-intensive practices embedded in longstanding farm management routines. This gap between technological potential and actual uptake points to constraints that extend beyond agronomic performance.

Existing research on technology adoption has identified a range of explanatory factors, ranging from relative advantage and complexity as outlined in Rogers' diffusion theory (Rogers, 2003), to behavioural determinants such as risk perception, attitudes, subjective norms, and perceived behavioural control (Garmendia-Lemus et al., 2024; Rezaei et al., 2019). More recently, information-based interventions have also been shown to encourage the adoption of sustainable technologies by improving farmers' knowledge or altering perceptions of economic, environmental, and health risks (Chen et al., 2025). However, these studies primarily examine educational or risk-based information. Comparatively little attention has been given to market information that communicates consumer demand for sustainable products.

At the downstream end of the food value chain, there is growing evidence that consumers are willing to pay price premiums for environmentally sustainable products (Grunert, 2011; Lusk et al., 2014; Bazoche et al., 2014), and that such preferences have contributed to the expansion of organic production (Oliveira et al., 2024; Taghikhah et al., 2021). Yet a critical disconnect persists. Whereas consumer willingness to pay (WTP)[3] for sustainable products is well documented (Li and Kallas, 2021), it remains unclear whether, and to what extent, information on these consumer preferences is associated with farmers' adoption intentions for pesticide-reducing technologies that do not require full organic certification. Qualitative evidence suggests that perceived market demand can encourage sustainability transitions (Feliciano, 2022; Struben et al., 2025), but empirical evidence linking consumer-derived market signals with farm-level technology adoption decisions remains limited (Piñeiro et al., 2020).

We attempt to fill this gap by examining how information about consumer WTP premiums is associated with conventional orchard farmers' intentions to adopt a set of validated pesticide-reducing technologies across five major EU producing countries. Three questions guide the analysis: (i) whether WTP information is associated with changes in adoption intentions for pesticide-reducing technologies? (ii) to what extent is consumer WTP information associated with farmers' stated adoption intentions relative to demographic, structural, and behavioural factors? and (iii) how do demographic, structural, and behavioural factors shape these responses.

To address these questions, we conducted a structured, interactive survey of 354 conventional orchard farmers in France, Greece, Italy, Portugal, and Spain. A within-subject panel design was employed in which each farmer's adoption intentions for four validated pesticide-reducing technologies, each varying in terms of cost and technical requirements, were elicited before and after exposure to empirically-derived consumer WTP price premium information. The technologies are: (i) mapping-based variable rate application, (ii) robotic weeders, (iii) bio-solution using low-sulphur and copper-based formulations, and (iv) the use of cover crops for biological pest control. The WTP information was derived from recent research on consumer premiums for olive oil and wine produced with reduced pesticide use (Larvoe et al., 2025a, 2025b). The design allows us to compare each farmer's stated adoption intentions before and after the presentation of market-based

[1] These include, among others, the EU's Farm to Fork Strategy which targets a 50 % reduction in chemical pesticide use and risk by 2030; China's Action Plan to Achieve Zero Growth in Pesticide Use by 2020, aimed at curbing pesticide and fertiliser overuse; and Switzerland's 'Reduction Paths for Pesticides' strategy, which seeks to halve pesticide risks by 2027 relative to a 2012–2015 baseline.

[2] For clarity, the term 'orchard' in this study refers specifically to vine growing (viticulture) and olive growing (oliviculture).

[3] Willingness to Pay is defined as the maximum price a consumer is willing to pay for a particular good or service. It represents the value that consumers place on a product, reflecting their preferences and perceived benefits (Schmidt and Bijmolt, 2020).

information, thereby reducing between-subject heterogeneity, improving comparability of responses, and limiting sample attrition (Bouma et al., 2020). The empirical analysis combines non-parametric Wilcoxon signed-rank tests with a multinomial logit model to assess changes in adoption intentions, while accounting for demographic, structural, behavioural, and country-level factors.

The study makes several contributions to the literature on sustainable agricultural transitions. First, it provides cross-country evidence on adoption intentions for multiple pesticide-reducing technologies in a high-intensity production context. Second, unlike previous information-intervention studies that focus on technical knowledge or risk awareness, this study uses empirically derived consumer WTP information as a market-based signals to examine whether demand-side information is associated with farmers' adoption intentions. Theoretically, it extends existing adoption frameworks by providing empirical evidence on the relationship between downstream consumer preferences and upstream farmers' stated adoption intentions. This pathway remains underdeveloped relative to research focusing on technology attributes, behavioural factors, or public subsidies. The study also provides new evidence on the association between consumer-derived market signals and conventional farmers' stated adoption intentions for incremental sustainability innovations, such as pesticide-reducing technologies, rather than full organic certification. From a policy perspective, the findings inform ongoing efforts under the EU Green Deal to reduce pesticide use, particularly at a time when regulatory proposals have faced substantial political challenges. The findings suggest that clear and credible consumer-derived market signals may complement regulatory approaches.

The remainder of the paper is structured as follows. Section 2 outlines the background of the study, reviewing pesticide-reducing technologies and adoption drivers to identify research gaps that form the basis of our hypotheses. Section 3 details the data, survey approach, and analytical methods. Sections 4 and 5 present the empirical results and discussion, including implications for policy and research limitations. Section 6 concludes with a summary of the main findings.

2. Research background

This section reviews the technological, behavioural, and conceptual foundations of pesticide-reducing innovation adoption in fruit orchards. Section 2.1 outlines the main categories of emerging innovations and their agronomic potential. Section 2.2 synthesises the theoretical and empirical determinants of adoption, focusing on economic, behavioural, institutional, and technical factors. Section 2.3 discusses the role of information in shaping adoption decisions, providing the theoretical context for the consumer WTP information treatment. Section 2.4 identifies a key gap in the literature and presents the study's hypotheses.

2.1. Pesticide-reducing innovations in olive groves and vineyards

A wide range of technologies that reduce pesticide use in modern agriculture have emerged, especially in the case of high-input orchard systems such as vineyards and olive groves. These innovations range from biological and agronomic approaches to advanced, automated and sensor-based technologies that vary in precision, initial investment cost, and complexity. One notable advancement is the use of autonomous robots equipped with artificial intelligence and sensors that detect and eliminate weeds, reducing or even eliminating the need for herbicides such as glyphosate (Upadhyay et al., 2024). In orchard trials, robotic weeders have demonstrated the potential to reduce herbicide use by up to 70 %, or reduce the volume of required herbicides by a factor of 20 compared to conventional spray systems (Zhang et al., 2022), while achieving near-complete weed coverage (Magni et al., 2020; Sportelli et al., 2021). Similarly, cover crops and floral margins serve as natural weed suppressants and attract beneficial insects, enhancing pest control while improving biodiversity and soil health (Cabrera-Pérez et al., 2023).

In the area of precision farming, VRA systems supported by canopy characterisation using technologies such as Light Detection and Ranging (LiDAR), ultrasonic sensors, unmanned aerial vehicles, or satellite imaging, allow for site-specific pesticide application (Campos et al., 2019). These systems have demonstrated pesticide savings of between 40 % and 83 % depending on crop, terrain, and environmental conditions (Garcia-Ruiz et al., 2023; Llorens et al., 2023; Wodzicki et al., 2023). In addition to reducing chemical inputs, VRA enhances application efficiency, minimises drift to off-target areas, and saves costs (Martinez-Guanter et al., 2020).

Biological alternatives, or bio-solutions, including pheromone traps and microbially-derived pesticides, offer targeted pest control with minimal environmental impact. For instance, mass trapping of olive fruit flies (*Bactrocera oleae*) in olive groves has demonstrated effective pest reduction leading to a significant decrease in insecticide use (Kapnas et al., 2025; Noce et al., 2009). These approaches are particularly relevant for integrated pest management (IPM) and for use in small farms with limited access to high-capital technologies.

These innovations vary widely in terms of initial investment cost, complexity, and ease of use. For example, robots and VRA technologies require substantial upfront investment and technical know-how, while bio-solutions and decision-support tools are generally more affordable and user-friendly (Garcia-Ruiz et al., 2023; Pérez-Ruiz et al., 2011). Furthermore, while long-term savings in pesticide use and labour from using advanced technologies may be substantial (Haleeva et al., 2024; Paleari et al., 2024), their implementation may be constrained by higher financial and operational barriers. This highlights the importance of considering different types of technologies when analysing farmers' adoption behaviour, as distinct innovations present varying levels of risk, accessibility, and perceived value.

2.2. Determinants of the adoption of sustainable farm technologies

The study of agricultural innovation adoption has evolved significantly since its early foundations in Rogers (2003) diffusion of innovations theory, which emphasised how specific characteristics such as relative advantage, compatibility, complexity, trialability, and observability, influence the likelihood of adoption. Over time, analytical approaches have become more interdisciplinary and methodologically diverse, integrating behavioural, economic, and institutional perspectives and employing approaches including structural equation modelling, duration analysis, and mixed methods (Karbo et al., 2024; Neves et al., 2022; Olum et al., 2020; Rizzo et al., 2024). Within the growing literature on the adoption of sustainable farming technologies and practices, three broad categories of adoption determinants have emerged beyond the intrinsic characteristics of the technologies.

Among the first and most frequently cited drivers of sustainable technology adoption in agriculture are economic factors. Grounded in rational choice theory, this perspective views farmers as utility-maximising agents who assess innovations based on expected costs, returns, and financial risks (Liebe et al., 2011). Key determinants include profitability, investment costs, market prices, and yield expectations (Rizzo et al., 2024; Rodríguez-Entrena et al., 2014; Srivastav and Das, 2025). For example, high capital requirements often constrain the adoption of technologies such as precision agriculture and organic systems, particularly in olive and vineyard farming. Conversely, subsidies and market demand for sustainable food products significantly enhance adoption likelihood (Genius et al., 2014; Kallas et al., 2010; Zachmann et al., 2024). Farm size is also relevant: larger farms typically have more resources to invest in new technologies but may also face greater opportunity costs and structural inertia (Bolzonella et al., 2020; Ghali et al., 2022). Access to financial support such as credit, green payments, or EU agri-environmental schemes further facilitates adoption, especially when such instruments are well-aligned with the economic realities of the sector (Aznar-Sánchez et al., 2020; Bounadi et al., 2022;

Parra-Lopez et al., 2007).

The second set of factors shaping adoption among farmers involves social, psychological, and institutional influences. These go beyond purely economic reasoning and reflect the role of individual behaviour, peer norms, perceived risks, and broader contextual conditions. Studies under this strand emphasise constructs such as attitudes toward innovation, subjective norms (social pressure), perceived behavioural control, and risk perception as key predictors of adoption behaviour based on theories of reasoned action and planned behaviour, among others (Garmendia-Lemus et al., 2024; Neves et al., 2022; Parra et al., 2022). Extension services and peer networks have proven to be powerful enablers. Informal knowledge exchange, especially in olive-producing regions with less structured institutional support, can play a decisive role in disseminating innovations (Genius et al., 2014; Parra-López and Calatrava Requena, 2005). In contrast, vineyard systems often benefit from formal advisory systems and policy alignment, which facilitates broader diffusion of innovations (Shaw et al., 2011). Institutional factors such as policy clarity, regulatory stability, and certification schemes also matter. Studies in the vineyard sector have found that clear organic labelling policies and irrigation rights can catalyse transitions, while inconsistent regulatory environments can deter investment (Kallas et al., 2010; MacMillan, 2020). Social capital, including membership in producer associations or cooperatives, further enhances adoption by reducing transaction costs and facilitating access to collective knowledge, infrastructure, and niche markets (Ghali et al., 2022; Parra-López et al., 2015).

The third group of factors influencing adoption relates to environmental and technical considerations, which tend to be important for early adopters and environmentally conscious farmers. In the olive sector, producers often cite ecological motivations such as preserving soil health, enhancing biodiversity, and reducing chemical inputs, sometimes placing these concerns above financial returns (Aznar-Sánchez et al., 2020; Parra-Lopez et al., 2007). In vineyards, the perceived health and environmental benefits of reducing pesticide use can also play a key role in driving adoption decisions (Zachmann et al., 2024). However, several barriers remain. Uncertainty about agronomic outcomes and risk aversion can discourage adoption, as seen in the reluctance of vineyard farmers to grow fungus-resistant grape varieties due to concerns over market acceptance and regulatory uncertainty. Similarly, olive growers hesitate to implement soil management practices when the long-term impacts are unclear (Zachmann et al., 2024; Aznar-Sánchez et al., 2020). Technical limitations also present challenges. A lack of knowledge, limited training opportunities, and poor access to practical demonstrations continue to impede the uptake of newer pesticide-reducing technologies (Bolzonella et al., 2020; Sarri et al., 2020). Evidence shows that more participatory approaches to extension, including practical training and demonstration farms, can play a crucial role in overcoming these barriers by strengthening farmers' skills and confidence (Rizzo et al., 2024).

Recent studies on sustainable and precision agriculture technologies suggest that adoption decisions are shaped by the interaction of economic, technical, institutional, and behavioural factors rather than by any single determinant. Evidence from precision spraying systems shows that farm size, investment costs, expected input savings, and economic returns play a central role in determining adoption feasibility (Testa et al., 2025; Tona et al., 2018). Public incentives can further reduce financial barriers and improve the viability of capital-intensive technologies, particularly among smaller farms. At the same time, adoption outcomes often depend on the suitability of technologies to specific production contexts, including crop characteristics, management practices, and operational conditions (Tona et al., 2018). Beyond these structural considerations, behavioural factors such as perceived control, social influences, and environmental motivations have also been shown to influence farmers' willingness to adopt sustainable technologies (Feisthauer et al., 2024). More broadly, research on digital and data-driven farming technologies highlights that technological complexity, skills requirements, organisational readiness, and individual-level factors can represent important barriers to adoption alongside economic constraints (da Silveira et al., 2023).

2.3. Information, behaviour, and technology adoption decisions

Conventional policy approaches used to promote sustainable agricultural practices generally fall into three broad categories: regulatory measures, economic incentives, and information-based instruments (Dessart et al., 2019). Regulatory approaches rely on mandatory standards and compliance requirements, while economic instruments seek to alter behaviour through financial incentives such as subsidies, taxes, or price premiums. Information-based approaches aim to improve decision-making by addressing information gaps and uncertainty.

Behavioural economics extends these approaches by recognising that farmers do not always make decisions solely on the basis of objective profit calculations. Adoption decisions are also shaped by risk perceptions, cognitive biases, social influences, and the way information is presented (Dessart et al., 2019; Streletskaya et al., 2020). Consequently, behavioural interventions have increasingly attracted attention as tools for encouraging more sustainable decision-making. One prominent example is the use of nudges, which seek to influence behaviour by altering how choices are presented without restricting options or imposing substantial economic incentives (Thaler and Sunstein, 2009). In agricultural settings, such interventions may include social norm messages, peer comparisons, or other approaches that make particular behaviours more salient (Kuhfuss et al., 2016; Howley and Ocean, 2022).

The information treatment employed in this study is informed by these behavioural insights. Rather than changing actual market conditions, farmers were provided with information regarding consumers' WTP for products produced with reduced pesticide use. Such information may influence adoption intentions by increasing the potential market rewards and reducing uncertainty surrounding future economic returns. Previous research suggests that information interventions can affect farmers' perceptions of profitability, risk, and opportunity, thereby influencing technology adoption decisions even in the absence of direct financial support (Chen et al., 2025; Streletskaya et al., 2020). From this perspective, consumer WTP information can be viewed as an information-based behavioural intervention that communicates potential market incentives and encourages farmers to incorporate previously uncertain demand signals into their decision-making process.

2.4. Research gap and hypotheses

Despite significant technological progress in pest and disease management in the orchard sector, their adoption remains relatively limited among Euro-Mediterranean farmers. Structural and behavioural constraints such as initial investment costs, limited technical capacity, uncertain economic returns, and inadequate access to information continue to impede uptake, particularly among small to medium-sized farms. In perennial crop systems such as vineyards and olive groves, where production practices are often inherited and routines deeply embedded, innovation adoption is further shaped by generational dynamics and risk perceptions. These persistent challenges underscore the need for complementary incentives that may reduce perceived risks, enhance expected benefits, and signal economic viability.

The literature reveals a growing array of pesticide-reducing technologies, each with distinct agronomic profiles, effectiveness, and cost structures (Bruno et al., 2021; Crocetti et al., 2023; Garcia-Ruiz et al., 2023). However, despite their proven efficacy, many conventional farmers in the Mediterranean region remain reliant on traditional pesticide-intensive methods (Chèze et al., 2020; Fusar Poli et al., 2025). The disconnect between available innovations and real-world adoption highlights a critical gap: the need to better understand how market incentives, beyond policy subsidies and technical support, could be

associated with farmers' stated adoption intentions.

While previous research has examined supply-side factors such as profitability, policy alignment, and farm structure (Rizzo et al., 2024), few studies have assessed whether exposure to consumer premiums is associated with farmers' stated adoption intentions, and to what extent. This is especially relevant given the EU's faltering regulatory progress on pesticide reduction, which underscores the importance of voluntary and market-driven action. Although previous research suggests that consumer demand has contributed to the growth of organic production (Oliveira et al., 2024; Taghikhah et al., 2021; Wollni and Andersson, 2014), much less is known about the extent to which consumer decisions is associated with farmers' adoption intentions, especially for intermediate sustainability technologies without full organic certification.

This study addresses this gap by examining whether exposure to WTP information is associated with farmers' intention to adopt four field-tested pesticide-reducing innovations: robotic weeders, smart mapping variable rate application, bio-solution with low sulphur and copper formulations, and cover crop, selected for their technical diversity and contextual relevance to Mediterranean orchard systems. The central hypothesis of this study is that exposure to consumer WTP information is associated with higher adoption intentions. While this relationship may reflect changes in perceived economic returns or market uncertainty, these mechanisms are not directly tested in the present study. Our hypothesis is grounded in behavioural economic theory, which posits that market-based incentives may serve as 'nudges' when delivered in ways that may enhance salience, reduce decision complexity, or reinforce social norms (Adkisson, 2008; Puaschunder, 2020).

3. Methods

3.1. Study region and selected sectors

We focus on vineyards and olive groves due to their economic importance, similar canopy structures, comparable pest control practices, and intensity of pesticide use within European agriculture (Gil et al., 2025; Homet et al., 2024; Vasconcelos et al., 2022). The five countries included in this study (France, Greece, Italy, Portugal, and Spain) account for a major share of EU production in both sectors. Spain, France, and Italy together produce more than half of global wine output (OIV, 2025), while Spain, Italy, Greece, and Portugal are leading olive oil producers in the Mediterranean basin, supplying over 90 % of global production (IOC, 2025). Compared with other perennial crops in the EU Mediterranean, these systems combine high economic value, extensive land use, and pesticide-intensive practices due to their high susceptibility to several pests and fungal diseases. This makes both sectors particularly relevant to the EU's sustainability targets under the Green Deal and Farm to Fork strategies.

From an agronomic perspective, the two systems share key features while also exhibiting important differences. Both are perennial crops with long production cycles and continuous exposure to pests and diseases, necessitating repeated pesticide applications. Vineyards are generally more input-intensive, with frequent fungicide use driven by diseases such as downy mildew (*Plasmopara viticola*), powdery mildew (*Erysiphe necator*), botrytis (*Botrytis cinerea*) and pests, such as grape moth (*Eupoecilia ambiguella*) that affect both the yield and quality of grapes (Fouillet et al., 2022). Olive groves, by contrast, face persistent insect and disease pressures, notably the olive fruit fly (*Bactrocera oleae*), olive moth (*Prays oleae*), olive leaf spot (*Spilocaea oleagina*), and black scale (*Saissetia oleae*), with high treatment intensity that varies across regions (González-Ruiz et al., 2024). These shared and contrasting characteristics provide a common basis for comparative analysis of pesticide use in high-value Mediterranean systems.

The four pesticide-reducing technologies we examine are developed for use in both vineyard and olive systems, targeting common challenges such as input optimisation, pest control, and environmental impact reduction. While relevant across both crops, the extent and mode of application may vary with crop-specific pest pressures and management practices. To ensure farm-level applicability, the survey included a screening step in which respondents assessed the suitability of each technology for their operations. Only those for whom the technologies were applicable were included in the adoption experiment.

3.2. Data source and sampling

The study used primary data collected in November 2024 through a structured, interactive survey hosted on Qualtrics©[4] platform. The survey was optimised for mobile, tablet, and desktop use, and made available in the national languages of each participating country. The subjects were primarily conventional vine and olive farmers, recruited through a combination of purposive and snowball sampling. Approximately 80 % of the participants were recruited through focus groups and stakeholder meetings organised within the framework of the EU HORIZON NOVATERRA project across the five participating countries, which seeks to develop innovative integrated strategies to reduce the use and impact of pesticides in Mediterranean vineyards and olive groves (https://www.novaterraproject.eu). These sessions served both as recruitment platforms and as opportunities to foster dialogue with farmers about sustainable practices. Participation was not limited to project members, as invitations were disseminated through local networks, cooperatives, and extension services. The remaining participants were identified through project partners and producer associations, using snowball sampling to reach additional farmers beyond the initial contact networks. While this approach enabled broad outreach, voluntary participation may imply a greater representation of farmers with an interest in sustainability, which should be considered when interpreting the generalisability of the results. Consequently, the sample should not be regarded as statistically representative of conventional orchard farmers in the five study countries, although it captures considerable variation in farm size, farmer age, gender, and orchard type.

We used a stated intention approach given the forward-looking nature of the innovations and the absence of well-established markets for reduced-pesticide products. Such methods are widely applied when observed adoption data are limited or when relevant market conditions have not yet fully formed (Gómez-Valenzuela, 2023). Although stated intentions may not fully translate into actual behaviour, the approach allows for the controlled introduction of market-relevant information, such as willingness to pay, and provides insight into how farmers may respond to these market signals under plausible scenarios. Thus, in line with ex ante policy evaluation practice, stated intentions are interpreted here as measures of behavioural sensitivity to emerging market signals, rather than as predictions of realised technology adoption.

The study received ethical approval from the ethics committees of the relevant institutions involved. All data collection procedures adhered to the EU's General Data Protection Regulation, with strict safeguards implemented to ensure participant anonymity and data privacy. Informed consent was obtained from all participants through signed agreement forms before their participation in the survey.

3.3. Survey structure and experimental design

The survey employed a two-phase within-subject design, summarised in Fig. 1. This design allows each farmer to serve as their own

[4] Qualtrics (https://www.qualtrics.com) is a widely used online survey platform that supports advanced survey logic and multimedia integration. Its use enabled participation across regions, including other farmers not present at focus group or stakeholder meetings where the initial data collection took place. Further, it ensured consistent presentation of the technologies through embedded visual materials, and supported the two-step survey design by allowing respondents to review their initial choices in the second stage.

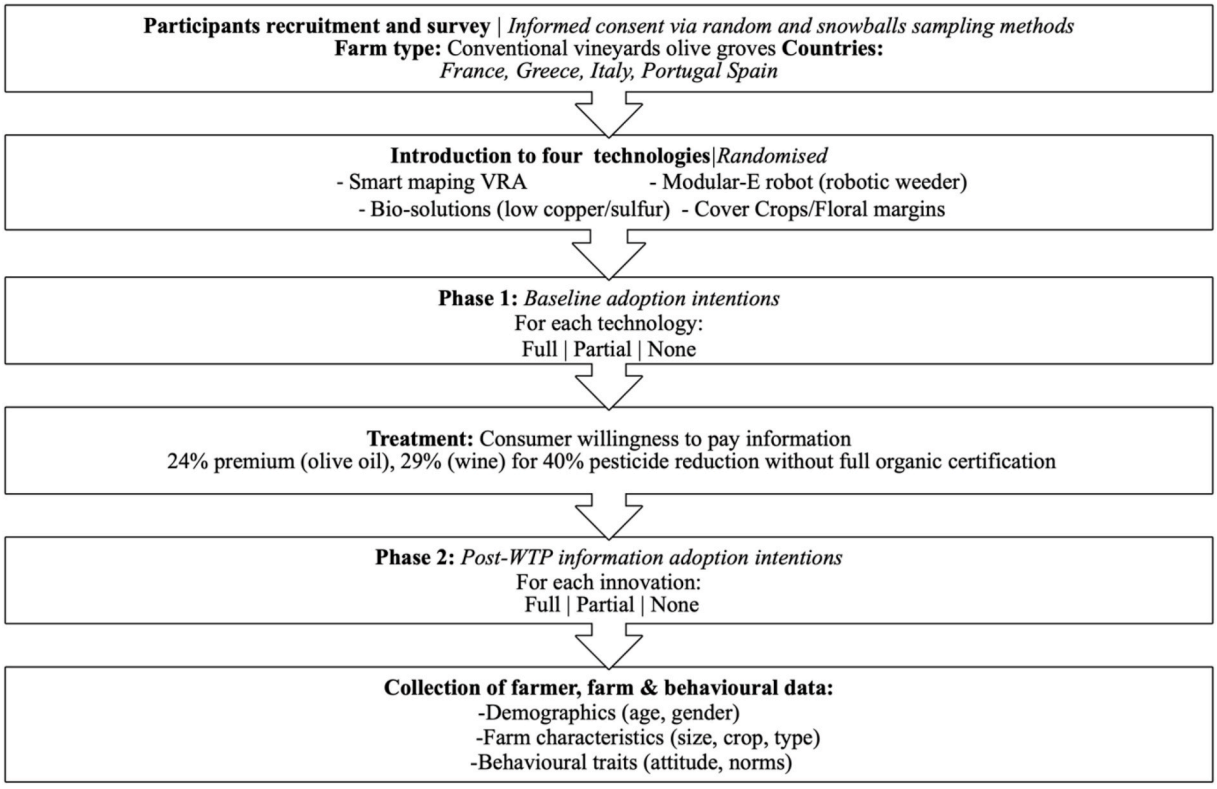


Fig. 1. Summarised steps in the survey implementation.

reference point, improving internal comparability and reducing unobserved heterogeneity in preferences (Thomas et al., 2019). It is particularly suitable for multi-stage decision tasks, as it limits respondent burden and attrition. To support careful responses, participants were reminded of their initial choices in the second phase and encouraged, through a brief script, to provide considered and consistent answers. While some degree of learning or reconsideration may occur, the results are interpreted with caution and do not imply definitive causal effects.

In Phase 1, all farmers were introduced to four pesticide-reducing innovations[5] that have been validated for Mediterranean orchard systems: (i) Smart mapping variable rate application, which uses satellite imagery of the canopy to optimise spray volume and targeting in real time; (ii) Robots equipped with a Mowit tool (a robotic weeder) for autonomous mechanical weeding; (iii) a bio-solution using low-sulphur and copper-based formulations; and (iv) the use of cover crops and floral margins (hereafter referred to as cover crops) to enhance natural pest control. A detailed overview of each innovation, including associated costs, benefits, and comparison with conventional practices, is provided in Table A1 in the supplementary appendix.

Each innovation was presented through randomised multimedia demonstrations, including explanatory text, field images, and short videos filmed at trial sites. The randomisation of the four technologies was done to reduce any bias from the order in which they were shown to respondents. The selected technologies reflect the diversity of available pesticide-reducing approaches that span across advanced, capital-intensive systems such as robotics and precision spraying, to low-cost ecological solutions such as cover crops. They differ in terms of complexity, technical requirements, and investment needs, making them broadly representative of the current landscape of pesticide-reducing options available to Mediterranean orchard farmers. Their selection and inclusion in the study were guided by demonstrated efficacy, adoption relevance, and practical potential for evaluating market-based incentives.

Following each presentation, farmers stated their adoption intentions for the given innovation using a three-point categorical scale: full adoption, partial adoption, or no adoption, reflecting the extent of adoption within farms (Montes de Oca Munguia et al., 2021). Full adoption was defined as the willingness to implement across the entire farm, while partial adoption referred to implementation on part of the farm, without imposing a fixed proportional threshold. Given the heterogeneity in farm size, technologies, and investment requirements, partial adoption is interpreted as an intermediate stage of adoption, which may range from small-scale experimentation to phased implementation. The scale is therefore intended to capture relative differences in adoption intensity and directional changes in behaviour, rather than precise shares of land use or investment levels. No adoption indicated intention to stick to their prevailing pest management methods (Ruiz-Espinosa et al., 2024). All participants confirmed that the four innovations were suitable for their farms.

To ensure data quality, several screening and quality-control procedures were implemented (Meade and Craig, 2012). Based on pilot-testing data from 25 respondents, a minimum completion time threshold of 9 min was established and responses completed below this threshold were excluded. A total of 6 responses fell below this threshold, with a mean completion time of 6.8 min. Additional exclusions included 12 incomplete responses, 5 respondents located outside the five study countries, and 17 respondents reporting farm-management systems other than conventional farming. In addition to these screening procedures, the survey was designed to support response quality through carefully worded questions and interactive multimedia elements that facilitated respondents' understanding of the technologies presented, maintained engagement, and minimised response fatigue.

To examine the possibility of satisficing behaviour, we analysed

[5] The selected innovations should not be interpreted as an exhaustive or optimal set of pesticide-reducing technologies. Rather, they were chosen based on prior validation, practical feasibility, and documented field trial in Mediterranean orchard systems within the study region.

completion-time patterns and response stability of the final sample (Table A3, Appendix). The mean completion time was 12.77 min (SD = 6.48), while the median completion time was 12.22 min, both exceeding the minimum threshold established during pilot testing. In addition, 46.9 % of respondents revised at least one adoption intention following exposure to the WTP information, whereas 53.1 % provided identical responses across the pre- and post-information stages. Together with the completion-time diagnostics and transition patterns reported in Tables A3, A6 and A7 in Appendix, these results provide no clear indication that very short completion times drove the observed changes, although they cannot rule out satisficing or other response-quality concerns.

3.4. Consumer WTP information treatment in phase 2

After the baseline responses, each farmer was shown information about consumer WTP premiums using clear, accessible visual examples of product labelling to mimic how such premiums could be communicated in real retail settings. The information treatment was designed to provide farmers with an empirically derived indication of potential market demand rather than to predict realised farm-gate price premiums. Specifically, the premium information was drawn from two earlier consumer valuation studies conducted within the same Horizon Europe NOVATERRA project, which estimated that consumers were willing to pay approximately 29 % more for conventional wines and 24 % more for olive oils produced with a 40 % reduction in pesticide use relative to conventional production across the same five Mediterranean countries (Larvoe et al., 2025a, 2025b). The present study extends this research by examining whether these consumer-derived market signals are associated with conventional orchard farmers' stated adoption intentions. These estimates are further supported by evidence that consumer willingness to pay for reduced pesticide use accounts for a substantial share of the premium associated with organic wine (Larvoe and Kallas, 2025). Accordingly, the information treatment should be interpreted as an evidence-based market signal presented to farmers rather than as an assumption about realised farm-gate prices, which will depend on price transmission through the supply chain, processing margins, and contractual arrangements (Kinnucan and Zhang, 2015).

Farmers were then asked to re-state their adoption intentions for each of the four innovations after being presented with the consumer WTP information. To minimise experimenter demand effects, the post information adoption question was framed in a neutral manner and did not invite respondents to revise or improve their earlier choices. Instead, farmers were asked to state their current adoption intention after reviewing the information, using the following question: *"Considering the information on the prices that consumers are willing to pay for products with reduced pesticide use, what is your intended level of adoption for each innovation*?" The baseline and post-treatment responses were collected within a single survey session, with the information presented immediately after the initial questions, ensuring temporal consistency and within-subject coherence while preventing attrition. The before-and-after structure allows us to estimate within-subject differences in adoption intentions associated with exposure to consumer WTP information. While this design does not allow full causal attribution in the absence of a control group, it provides insights into how farmers revise their decisions when exposed to potential demand-driven incentives.

To minimise potential hypothetical social desirability bias, where participants overstated or understated their intentions due to the absence of real consequences, a brief 'Cheap-Talk' script was implemented before the first and second rounds of responses. Farmers were asked to carefully read and reflect on the following statement: *'I am aware that in hypothetical situations, people may overstate or understate their true intentions because there is no real cost involved. However, in this case, I pledge to state my true intention that reflects the importance of the innovation to my actual pest management decisions.'* Past research suggests that such scripts help align stated intentions more closely with real-world behaviour, improving the internal validity of stated preference designs (Penn and Hu, 2019; Xhakollari et al., 2025).

3.4.1. Control variables

In addition to innovation-specific adoption responses, the survey gathered comprehensive data on farmer demographics, farm structure, and key behavioural traits. Demographic variables included age and gender, while structural characteristics captured farm size and orchard type (vineyard or olive grove). Behavioural dimensions included perceived costs of innovation, perceived effectiveness of current pest control methods, and subjective norms reflecting peer and social influences. Farm size serves as a proxy for resource availability and operational scale, and orchard type distinguishes between systems with potentially different market and agronomic pressures. Age provides insight into experience and generational orientation, while gender, understood here as the socially constructed roles, behaviours, and identities associated with being male or female, may be associated with differences in decision-making. Perceived cost captures financial concerns that may deter adoption, and perceived effectiveness of current methods reflects satisfaction with existing practices. Subjective norms indicate the degree to which social expectations shape adoption behaviour. These variables were included as controls in the econometric models, with their expected associations summarised in Table 1. Their inclusion allowed us to account for demographic, structural, and behavioural factors when examining the association between market incentives and adoption intentions.

Table 2 presents summary statistics for the final sample of surveyed farmers, after excluding ineligible and low-quality responses. The final sample consisted of 354 farmers, with the largest shares from Spain (38.1 %) and Portugal (34.7 %). The sample comprised 76.6 % males, with over half of the respondents aged 45 years or older, consistent with the ageing demographic characteristic of the European farming population. Regarding production systems, 76.7 % of the respondents were engaged in viticulture, while 23.3 % were into olive cultivation.

Table 1
Summary of variables and their expected association with adoption intention.

Factor	Expected association	Reference
Market incentive		
Consumer WTP premium	(+) Consumer WTP information may signal potential market value and be positively associated with adoption intentions	El Bakali et al. (2023) Zimmermann et al. (2024), Kakkavou et al. (2024)
Demographics		
Gender	(+) Men often show higher adoption of innovations, as they tend to take more risk	Olum et al. (2020), Castellini et al. (2025)
Age	(+) Older farmers are more experienced and more receptive	Olum et al. (2020)
Structural factors		
Farm size	(+) Larger farms can absorb risks and costs better	Ma and Rahut (2024) Kernecker et al. (2020)
Type of orchard (vineyards)	(+) Vineyards face higher market pressure for sustainability	Kernecker et al. (2020)
Behavioural Factors		
Perceived cost of innovation	(−) High perceived cost discourages adoption	Rizzo et al. (2024)
Effectiveness of the current methods	(−) Satisfaction with the status quo reduces motivation to change	Rodríguez-Barillas et al. (2024)
Subjective norm	(+) Peer influence promotes uptake	Li et al. (2023)

Table 2
Background of participants (n = 354).

Variable	Sub-category	Sample	Percentage
Country	Greece	31	8.8 %
	France	29	8.2 %
	Italy	36	10.2 %
	Portugal	123	34.7 %
	Spain	135	38.1 %
Gender	Male	271	76.6 %
	Female	72	20.2 %
	Non-binary/Not declared	11	3.1 %
Age of farmers	18-34 years	56	15.7 %
	35-44 years	65	18.4 %
	45-54 years	101	28.6 %
	55-64 years	90	25.3 %
	65+ years	42	12.0 %
Orchard type	Vineyard	272	76.7 %
	Olive grove	82	23.3 %

3.5. Analytical approach

3.5.1. Wilcoxon signed-rank test

We use the Wilcoxon signed-rank test to assess changes in farmers' adoption intentions before and after exposure to consumer WTP information. This non-parametric test evaluates the equality of paired observations, such as before-and-after measurements, and is particularly suited for ordinal data, which do not meet assumptions of interval scaling or normal distribution (MacFarland and Yates, 2016). In our case, we compared within-subject changes across three adoption categories: no adoption, partial adoption, and full adoption. For each innovation, we test the null hypothesis (H_0) that there is no difference in the median adoption intentions before and after the exposure to WTP information. The alternative hypothesis (H_1) is that the median adoption intentions differ between the two time points. This approach provides a within-subject assessment of whether farmers' stated adoption intentions differ before and after exposure to consumer WTP information.

3.5.2. Multinomial logistic model

To estimate the associations between consumers' WTP information and farmers' adoption intentions for pesticide-reducing technologies, we employ a Multinomial Logit (MNL) model (Borooah, 2002; Winship, 2003). The MNL was selected because the study aims to estimate separate associations for partial and full adoption relative to no adoption without imposing the proportional-odds assumption of an ordered response model. Although the three adoption categories have an inherent ordinal interpretation, the MNL specification allows the associations with partial and full adoption to differ rather than constraining them to follow a common ordered structure. This distinction is relevant because partial adoption may represent experimentation or phased implementation, whereas full adoption represents a substantially different level of commitment. As a robustness check, we also estimated mixed-effects ordered logit models that account for the repeated observations within farmers.

Formally, the probability that farmer i chooses an adoption category $j \in \{1$ (partial adoption), 2 (full adoption)$\}$ relative to the base category $j = 0$ (no adoption) is given by:

$$\text{Prob}(Y_i = j) = \frac{\exp\left(\beta_j' X_i\right)}{1 + \sum_{k=1}^{J} \exp\left(\beta_k' X_i\right)} \text{ for } j \in \begin{Bmatrix} 1, 2 \end{Bmatrix} \quad (1)$$

where β_j' is a vector of coefficients estimated for the corresponding explanatory variables x_i, which include: x_1 (market incentives), x_2 (farm size), x_3 (farm type), x_4 (gender), x_5 (Age), x_6 (cost perception), x_7 (method effectiveness), and x_8 (subjective norm). In addition to the consumer WTP premium variable, these controls reflect structural and behavioural factors commonly cited in the adoption literature. A detailed description of each variable, along with summary statistics, is provided in Table A2 of the appendix.

The estimated coefficients in the MNL quantify the change in the log relative probability of a farmer choosing adoption category (partial or full adoption) relative to the base category (no adoption), associated with a one-unit change in an explanatory variable. This can be expressed as:

$$\ln\left(\frac{P(Y_i = j)}{P(Y_i = 0)}\right) = \beta_j X_i \quad (2)$$

where $P(Y_i = j)$ is the probability that farmer i chooses adoption category j, where $j = 1$ denotes partial adoption, $j = 2$ denotes full adoption, and $P(Y_i = 0)$ is the probability of choosing no adoption, the base category. To aid interpretation, the coefficients are exponentiated to obtain the relative risk ratio (RRR):

$$RRR = e^{\beta_j} \quad (3)$$

The RRR expresses the multiplicative change in the relative risk of choosing adoption category $j \neq 0$ rather than no adoption for a unit increases in the explanatory variable. An RRR greater than one indicates a higher relative likelihood of choosing the given adoption category over no adoption, an RRR less than one indicates a lower relative likelihood, and an RRR equal to one indicates no change in the relative likelihood.

The multinomial logit model was estimated using the *mlogit* command in Stata 19. The base category for the dependent variable is no adoption (0), and results are reported for partial adoption (1) and full adoption (2). The model was estimated using maximum likelihood with robust standard errors clustered at the farmer level.

3.5.3. Robustness checks in estimation

Given the uneven distribution of observations across countries and crop types, we adopt a pooled MNL model to ensure robust estimation and to maintain statistical power. Estimating separate models by country or orchard type would risk unreliable and non-comparable coefficients for smaller subsamples. The pooled model leverages the full dataset while accounting for heterogeneity through fixed effects for country and crop type. To account for systematic differences across countries, we include country-specific dummy variables in the model, with France serving as the reference category. These controls capture country-level differences in farmers' adoption intentions while preserving comparability of the estimated associations across technologies.

To test the reliability of our estimation results, we conducted several robustness checks. First, we assessed potential multicollinearity among the explanatory variables in the MNL model by computing the variance inflation factors (VIFs). All VIF values were below the accepted threshold of 2.50 – most below 1.50, with a maximum of 2.23 – indicating no serious multicollinearity concerns and supporting the stability and reliability of the coefficient estimates (Midi et al., 2010). Second, we evaluated overall model fit for each model using likelihood ratio tests, comparing our full specification to nested alternatives. The results consistently favoured the full model, indicating that the inclusion of the selected covariates significantly improved explanatory power. Third, we tested the independence of the irrelevant alternatives (IIA) assumption using the Hausman-McFadden test (Hausman and McFadden, 1984). The results showed no significant violations, supporting the appropriateness of the MNL specification for our three-category adoption outcome. Finally, as a robustness check for potential response-quality concerns, we re-estimated the MNL models after excluding the fastest 5 % of survey completions (18 respondents). The estimated WTP RRRs were similar after excluding the fastest 5 % of respondents, and the WTP information variable remained positive and statistically significant for all four technologies (Table A8).

4. Results

4.1. Descriptive statistics

Table 3 compares farmers' adoption intentions before and after exposure to consumer WTP information. For all four technologies, the share of farmers indicating partial or full adoption increased following the presentation of the price premium. The largest changes occurred in robotic weeders: full adoption rose from 26.8 % to 34.2 %, while no adoption dropped from 40.1 % to 22.0 %. Smart mapping VRA systems saw a 15.8 percentage point increase in terms of full adoption (from 24.6 to 40.4 %) and a 9.3 point decline in terms of no adoption.

Bio-solutions and cover crops showed more modest changes. The share of farmers willing to fully adopt bio-solutions rose slightly, from 46.9 to 49.2 %. In the case of cover crops, full adoption increased from 35.6 to 36.7 %. The marginal increases may reflect high initial acceptance, suggesting that baseline adoption intentions were already near their ceiling.

Table A4 in appendix presents additional evidence of how farmers' adoption intentions changed following exposure to consumer WTP information. Unlike Table 3, which used a three-category scale, adoption intention was recoded into a binary measure: willing to adopt (either partially or fully) versus not willing to adopt. Across all four technologies, the proportion of farmers willing to adopt was higher in the post information responses, with the largest changes observed for robotic systems, which rose by 18.1 percentage points. This binary comparison corroborates the results in Table 3, indicating stronger responses for high-cost technologies.

Figs. 2 and 3, as well as A1 and A2 (*see* supplementary appendix), provide graphical illustrations of these patterns more clearly, showing consistent upward movement in both partial and full adoption intentions across all innovations. These descriptive patterns indicate higher adoption intentions following exposure to consumer WTP information across all four innovations. Importantly, the observed changes are not uniform across technologies. Larger changes in adoption intentions are observed for innovations with higher upfront costs and greater technical complexity, whereas changes are more modest for lower-cost or more familiar practices. This pattern indicates that the magnitude of the observed changes differs across technologies.

Table 3
Farmers' adoption intentions before and after the WTP information treatment (n = 354).

Innovation	Level of adoption intention	Before WTP information (%)	After WTP information (%)	Difference (%)
Smart mapping variable rate application	No adoption	24.3	15.0	−9.3
	Partial adopters	51.1	44.6	−6.5
	Full adoption	24.6	40.4	+15.8
Robotic weeders	No adoption	40.1	22.0	−18.1
	Partial adoption	33.1	43.8	+10.7
	Full adoption	26.8	34.2	+7.4
Bio-solution	No adoption	22.3	17.5	−4.8
	Partial adoption	30.8	33.3	+2.5
	Full adoption	46.9	49.2	+2.3
Cover crop and floral margins	No adoption	29.7	20.6	−9.1
	Partial adoption	34.7	42.7	+8.0
	Full adoption	35.6	36.7	+1.1
Total		354	354	

4.2. Wilcoxon signed-rank tests

Table 4 presents the results of the Wilcoxon signed-rank test, which indicates statistically significant differences in adoption intentions before and after exposure to WTP information. Adoption intentions changed positively across all four technologies, although the magnitude of the changes varied. In the case of smart mapping VRA and robotic weeders, z-values were 7.74 and 8.53 respectively ($p < 0.001$), indicating significant increases in adoption intentions. Bio-solution and cover crops also showed significant changes, with z-values of 4.69 and 5.83 respectively ($p < 0.001$). The positive rank sums indicate that all non-zero changes were in the direction of higher adoption intentions after exposure to the WTP information. Similar results are recorded using the binary measure of adoption intention (*see* Table A4 in the appendix). These results reject the null hypothesis of no change in adoption intentions and indicate an increase following exposure to consumer WTP information. Notably, although farmers were free to revise their responses in either direction following the information treatment, no respondent reported a lower adoption category for any of the four technologies. Consequently, the Wilcoxon signed-rank tests yielded no negative ranks, with all observed changes consisting of either upward transitions or unchanged responses.

To further investigate the source of the observed changes, we constructed transition matrices comparing adoption intentions before and after exposure to consumer WTP information (see Tables A6 and A7 in Appendix). Across all technologies, changes were exclusively upward, with no farmer moving to lower adoption categories. For Smart mapping VRA, 33.7 % of farmers initially reporting no adoption moved to full adoption, while a further 4.7 % moved to partial adoption. Similarly, for robotic weeders, 45.1 % of non-adopters revised their intentions upward, with 33.1 % moving to partial adoption and 12.0 % to full adoption. By contrast, upward transitions were less common for bio-solutions and cover crops, where only 21.5 % and 30.5 % of initial non-adopters changed their intentions, respectively. These smaller increases coincided with relatively higher baseline adoption levels, with 77.7 % of respondents already indicating partial or full adoption for bio-solutions and 70.3 % for cover crops prior to receiving the WTP information. This pattern suggests that farmers' adoption intentions vary across technologies.

4.3. Factors associated with adoption intentions

Tables 5a and 5b report the results from multinomial logit models estimating the likelihood of partial and full adoption relative to no adoption for each of the four pesticide-reducing technologies. Robust standard errors were estimated to account for repeated observations from the same farmer. Across all models, the Wald chi-square statistics are highly significant ($p < 0.001$), indicating that the explanatory variables jointly explain variation in adoption intentions. The pseudo-R^2 values are comparable to those commonly reported for multinomial logistic regression models of behavioural choice (McFadden, 1973). To aid interpretation, relative risk ratios are obtained by exponentiating the estimated coefficients (see Equation (3)). These estimates should be interpreted as conditional associations within the study design rather than as causal effects. As a further robustness check, mixed-effects ordered logit models with farmer-level random effects were estimated to account for the repeated nature of the observations. The results are reported in Supplementary Table A9. The WTP information coefficient remained positive and significant where the models converged. The multinomial logit model was retained as the primary specification because it distinguishes between partial and full adoption intentions.

4.3.1. Association between consumer WTP information and adoption intentions

In the full adoption results (Table 5b), exposure to consumer WTP premiums is associated with a higher relative likelihood of adopting

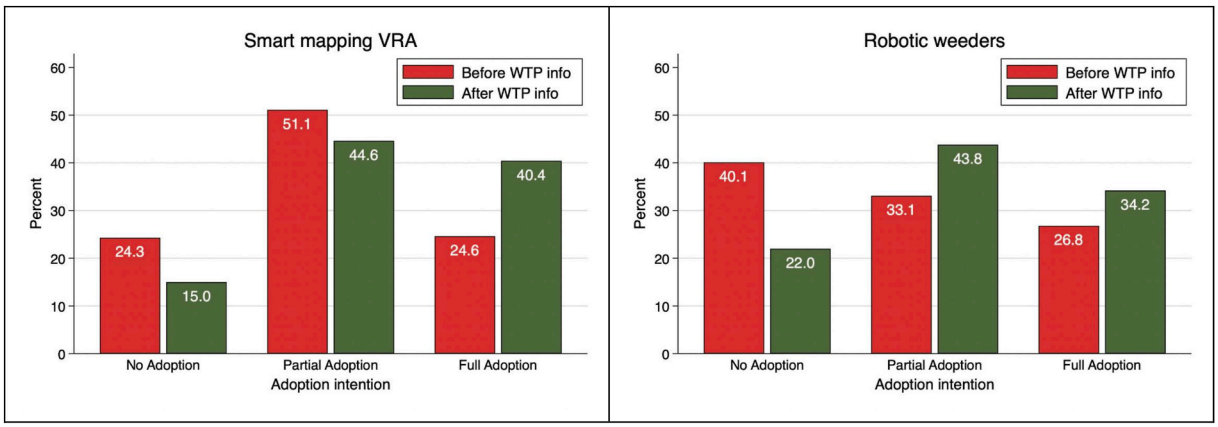


Fig. 2. Adoption intention before and after information treatment for *smart mapping VRA* (left) and *robotic weeders* (right).

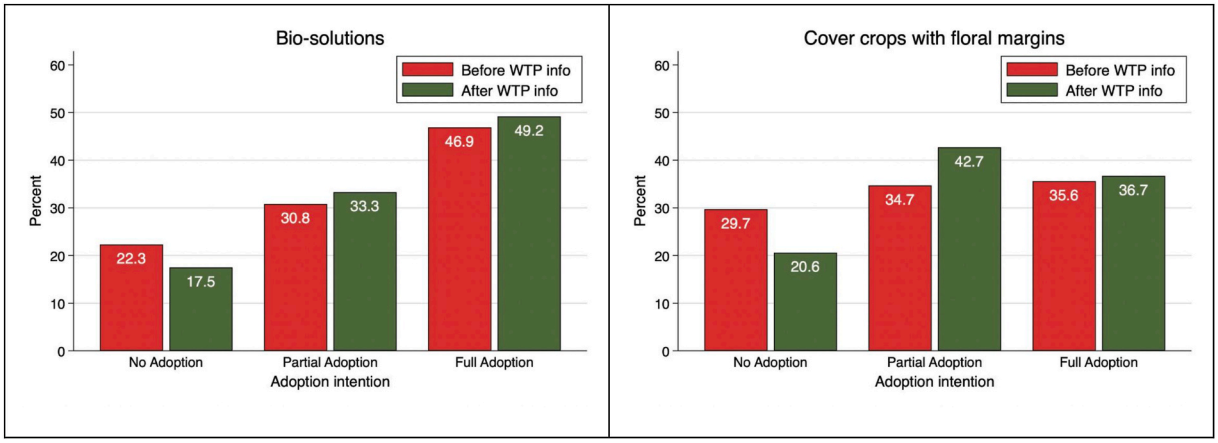


Fig. 3. Adoption intention before and after information treatment for *bio-solutions* (left) and *cover crops* (right).

Table 4
Results of the Wilcoxon signed-rank test.

Metrics	*Smart mapping VRA*	*Robotic weeder*	*Bio-solution*	*Cover crops*
Number of observations	354	354	354	354
Sum of positive ranks	19,470	23,214	7557	11,475
Sum of negative ranks	0.00	0.00	0.00	0.00
Sum of zero ranks	43,365	39,621	55,278	51,360
z-value	7.74	8.53	4.69	5.83
Prob > |*z*| = *p-value*	*0.0000*	*0.0000*	*0.0000*	*0.0000*

Note: All p-values are less than 0.001. A positive z-value indicates that the distribution of adoption intentions increase after exposure to consumer WTP information. The sum of positive ranks is the cumulative rank of observations with positive paired differences.

smart mapping VRA by a factor of 2.79 ($p < 0.01$) and robotic weeders by 2.35 ($p < 0.01$). This pattern may be consistent with the view that transparent market signals are associated with greater consideration of capital-intensive technologies. With regard to partial adoption (Table 5a), the relative likelihood of reporting partial adoption intentions was higher for smart mapping VRA and robotic weeders, with RRRs of 1.42 ($p < 0.01$) and 2.45 ($p < 0.01$), respectively. These results suggest that farmers' stated intentions regarding partial adoption are also associated with the presentation of consumer WTP information. The association remained positive and statistically significant for both partial and full adoption across all four technologies. However, the magnitude of the association was relatively larger for smart mapping VRA and robotic weeders compared to bio-solutions and cover crops.

While the stronger associations observed for the VRA and robotic systems may reflect their higher capital requirements, they should be interpreted with caution. Lower baseline adoption levels for these technologies, as reported in Section 4.1, leave greater scope for increases in adoption intentions, whereas higher initial adoption rates for bio-solutions and cover crops may limit further increases. The observed differences may therefore reflect a combination of baseline conditions and differences in the estimated associations across technologies.

The results are consistent with the hypothesis that exposure to consumer WTP premiums is positively associated with higher adoption intentions, especially for innovations that involve higher upfront investment. However, the study design does not allow us to establish whether the WTP information alone accounts for these positive associations, independently of other factors.

4.3.2. *Other factors associated with adoption intentions*

The associations reported for control variables should be interpreted descriptively, as these variables are not exogenous and are included primarily to control for observable heterogeneity rather than to support causal inference (Hünermund and Louw, 2023).

Farmer-level characteristics showed limited association with adoption intentions compared to consumer WTP premiums. Age was not significantly associated with either partial or full adoption across any of the four technologies. Gender was not significantly associated with adoption intentions for most technologies, except for bio-solutions, for

Table 5a
Multinomial logit estimates for partial adoption intentions for pesticide-reducing innovations.

Variable	Smart mapping VRA		Robotic weeders		Bio-solution		Cover crops	
	Coefficient (SE)	RRR	Coefficient (SE)	RRR	Coefficient (SE)	RRR	Coefficient (SE)	RRR
WTP information	0.351*** (0.096)	1.421	0.894*** (0.117)	2.446	0.331*** (0.091)	1.393	0.582*** (0.101)	1.789
Gender (male = 1)	−0.479 (0.366)	0.620	0.083 (0.299)	1.087	0.380 (0.353)	1.462	−0.073 (0.304)	0.930
Age	−0.018 (0.016)	0.982	−0.006 (0.014)	0.994	−0.001 (0.017)	0.999	−0.010 (0.015)	0.990
Farm size	0.004 (0.009)	1.004	−0.002 (0.006)	0.998	0.004 (0.010)	1.004	0.005 (0.008)	1.005
Farm type (vineyard = 1)	−0.639* (0.375)	0.528	−0.048 (0.293)	0.953	−0.824** (0.376)	0.438	0.018 (0.327)	1.018
Current method effectiveness	−0.051 (0.216)	0.950	0.092 (0.157)	1.096	−0.182 (0.200)	0.834	−0.312 (0.192)	0.732
Subjective norm	−0.041 (0.098)	0.960	0.064 (0.092)	1.066	0.040 (0.108)	1.041	0.110 (0.103)	1.117
Perceived cost	−0.246 (0.187)	0.782	−0.155 (0.150)	0.856	0.089 (0.192)	1.093	−0.145 (0.186)	0.865
Country (reference = France)								
Greece	−0.883 (0.678)	0.413	0.826 (0.596)	2.283	0.640 (0.682)	1.896	0.896 (0.632)	2.451
Italy	−0.492 (0.698)	0.611	1.108* (0.567)	3.029	−0.245 (0.645)	0.782	0.979 (0.654)	2.661
Portugal	−1.148** (0.570)	0.317	0.933* (0.478)	2.542	0.003 (0.529)	1.003	0.530 (0.503)	1.698
Spain	−0.592 (0.572)	0.553	1.177** (0.478)	3.243	0.125 (0.531)	1.133	0.755 (0.497)	2.128
Constant	4.552*** (1.463)	94.823	−0.786 (1.183)	0.456	0.858 (1.323)	2.359	1.564 (1.302)	4.780

Note: Tables 5a and 5b presents outputs from the same multinomial logit model estimated separately for each technology.

Table 5b
Multinomial logit estimates for full adoption intentions for pesticide-reducing innovations.

Variable	Smart mapping VRA		Robotic weeders		Bio-solution		Cover crops	
	Coefficient (SE)	RRR	Coefficient (SE)	RRR	Coefficient (SE)	RRR	Coefficient (SE)	RRR
WTP information	1.026*** (0.131)	2.791	0.854*** (0.103)	2.350	0.299*** (0.066)	1.349	0.403*** (0.071)	1.497
Gender (male = 1)	0.067 (0.381)	1.070	0.295 (0.351)	1.343	0.704** (0.348)	2.022	−0.123 (0.345)	0.885
Age	0.012 (0.016)	1.012	0.005 (0.015)	1.005	0.026 (0.017)	1.027	0.012 (0.017)	1.013
Farm size	0.015* (0.009)	1.015	−0.001 (0.007)	0.999	−0.003 (0.009)	0.997	−0.010 (0.009)	0.990
Farm type (vineyard = 1)	−0.651* (0.364)	0.522	0.040 (0.306)	1.040	−0.325 (0.379)	0.723	0.074 (0.340)	1.076
Current method effectiveness	−0.205 (0.252)	0.814	−0.117 (0.229)	0.889	−0.079 (0.208)	0.924	−0.625** (0.273)	0.535
Subjective norm	0.112 (0.096)	1.118	0.174* (0.097)	1.190	−0.002 (0.107)	0.998	0.226** (0.105)	1.254
Perceived cost	0.045 (0.190)	1.046	−0.035 (0.195)	0.966	0.310* (0.183)	1.364	0.511** (0.206)	1.667
Country (reference = France)								
Greece	−0.296 (0.782)	0.744	0.716 (0.623)	2.047	0.998 (0.694)	2.713	0.369 (0.696)	1.446
Italy	−0.133 (0.735)	0.875	0.653 (0.588)	1.922	0.234 (0.649)	1.264	0.761 (0.658)	2.141
Portugal	−0.450 (0.654)	0.638	0.578 (0.499)	1.783	0.383 (0.562)	1.467	0.486 (0.534)	1.625
Spain	0.288 (0.655)	1.334	0.289 (0.503)	1.335	0.736 (0.555)	2.088	0.502 (0.526)	1.652
Constant	0.085 (1.616)	1.089	−1.156 (1.247)	0.315	−2.204 (1.355)	0.110	−0.831 (1.455)	0.436
Pseudo R^2	0.0621		0.0382		0.0356		0.0516	
Wald χ^2 (24)	113.26		100.09		55.44		69.58	
Prob > χ^2	0.0000		0.0000		0.0003		0.0000	
Observations (n)	708		708		708		708	

Notes: The dependent variable is adoption intention (0 = no adoption [reference outcome], 1 = partial adoption, 2 = full adoption). Robust standard error (SE) clustered at the farmer level are reported in parentheses. RRR = Relative Risk Ratio. *, **, and *** indicate statistical significance at the 10 %, 5 %, and 1 % levels, respectively.

which male farmers had a higher relative likelihood of full adoption than female farmers (*RRR = 2.02, p < 0.05*).

Similarly, structural characteristics such as farm size and orchard type showed relatively limited associations with adoption intentions. Farm size was not significantly associated with partial adoption of any technology. For full adoption, however, larger farms were more likely to adopt smart mapping VRA (*RRR = 1.02, p < 0.1*). This may reflect the greater financial and technical capacity of larger farms to invest in cost-intensive precision spraying technologies such as smart mapping VRA. Farm type was also significantly associated with partial and full adoption intentions for smart mapping VRA, as well as partial adoption of bio-solutions. These findings should be interpreted with caution, as the higher proportion of vineyard farmers in the sample may have reduced the robustness of comparisons between orchard types.

Behavioural factors were also associated with adoption intentions. Subjective norms, reflecting perceived peer influence, were positively associated with full adoption intentions for both robotic weeders (*RRR = 1.19, p < 0.1*) and cover crops (RRR = 1.25, p < 0.05). In contrast, perceived effectiveness of current pest control practices was negatively associated with full adoption intentions for cover crops, indicating lower relative likelihood of full adoption among farmers reporting higher perceived effectiveness of their current pest-control practices. Interestingly, perceived cost was positively associated with the full adoption of bio-solutions and cover crops. This pattern may indicate that farmers expressing greater cost concerns are more likely to consider less capital-intensive technologies.

4.3.3. Differences in countries

Country was included as a control variable to account for differences in adoption intentions across the five study countries, with France serving as the reference category. Although a few country coefficients reached statistical significance for specific technologies, these patterns were neither consistent across technologies nor central to the study objectives. Given the relatively small sample sizes for some countries, particularly France, Greece, and Italy, these coefficients should be interpreted cautiously and are not intended to support strong cross-country comparisons.

Overall, the empirical results are consistent with the study

hypotheses. Exposure to consumer WTP information was positively associated with both partial and full adoption intentions across all four technologies. In contrast, the associations for farm characteristics and behavioural factors varied across technologies, indicating that farmers' stated adoption intentions reflect the combined role of market signals, farm structure, and behavioural considerations rather than any single determinant.

5. Discussion

This study provides new empirical evidence on the association between consumer-derived market signals and farmers' stated adoption intentions for pesticide-reducing innovations in two of the EU's most pesticide-intensive perennial cropping systems, namely olive groves and vineyards. Examining hypotheses linking adoption intentions to consumer WTP information, farm characteristics, and behavioural factors, we find that exposure to consumer WTP information is positively associated with both partial and full adoption intentions across all four technologies. The magnitude of this association, however, differs across technologies, with stronger associations observed for the more capital-intensive innovations, namely smart mapping VRA and robotic weeders. These associations remain statistically significant after accounting for demographic, structural, behavioural, and country-level factors. Overall, the findings suggest that positive market signals by consumers may complement existing policy approaches by supporting farmers' consideration of pesticide-reducing innovations. Given the recent slowdown in regulatory progress towards pesticide reduction within the EU, market-based mechanisms deserve greater attention as complementary instruments for supporting sustainability transitions in high-input farming systems.

The findings provide empirical support for the proposition that demand-side market signals are associated with farmers' stated adoption intentions. Across all four technologies, consumer WTP information was positively associated with both partial and full adoption intentions, although the magnitude of the association was greater for smart mapping VRA and robotic weeders than for bio-solutions and cover crops. The stronger associations observed for smart mapping VRA and robotic weeders should be interpreted cautiously. One possible explanation is that these technologies had lower baseline adoption intentions than bio-solutions and cover crops, leaving greater scope for increases following exposure to consumer WTP information. At the same time, the positive associations observed for bio-solutions and cover crops indicate that consumer-derived market signals may also encourage consideration of lower-cost technologies, although the magnitude of the association was smaller.

These findings are consistent with previous evidence that expected economic returns and information are associated with farmers' technology adoption decisions (Chen et al., 2025; Rizzo et al., 2024; Trujillo-Barrera et al., 2016). However, unlike earlier information-intervention studies that examined technical, environmental, economic, or health information, the present study focuses specifically on consumer-derived market signals. The results therefore extend existing evidence by suggesting that information about consumers' WTP for products with reduced pesticide use is also positively associated with farmers' stated adoption intentions. These findings align with earlier research on the role of economic considerations in farmers' technology choices (Trujillo-Barrera et al., 2016) and the relevance of information for adoption decisions (Chen et al., 2025). The findings are also consistent with studies of organic agriculture showing that consumer demand and price premiums are associated with the uptake of sustainable production systems, particularly in the wine and olive sectors (Darnhofer, 2005; Di Vita et al., 2019; Eti, 2025). These findings together suggest that transparent market information based on consumer preferences may encourage greater consideration of pesticide-reducing innovations when farmers perceive a credible opportunity to recover part of the additional costs associated with more sustainable production practices.

5.1. Control variables

Although consumer WTP information showed the most consistent association with adoption intentions, several farm, structural, and behavioural characteristics were also associated with farmers' stated adoption decisions. These relationships, however, varied across technologies, suggesting that the importance of individual factors depends on the characteristics of the innovation being considered.

Among the farm characteristics, larger farm size was positively associated only with the full adoption of smart mapping VRA. This finding is consistent with previous research suggesting that larger farms are generally better positioned to absorb the financial and technical demands of precision agriculture technologies and to realise economies of scale from their adoption (Kernecker et al., 2020; Ma and Rahut, 2024; Testa et al., 2025). Farm type was also associated with adoption intentions for smart mapping VRA and, to a lesser extent, bio-solutions, although these relationships should be interpreted cautiously given the unequal representation of vineyards and olive farms in the sample. By contrast, age showed no significant association with adoption intentions for any of the four technologies, while gender was associated only with the full adoption of bio-solutions, where male farmers showed a higher relative likelihood of adoption. The estimated associations for demographic characteristics were generally less consistent than those observed for WTP information.

Behavioural factors showed more technology-specific associations. Subjective norms were positively associated with full adoption intentions for robotic weeders and cover crops, consistent with earlier research highlighting the role of peer influence and social learning in the adoption of sustainable farming practices (Blasch et al., 2022; Li et al., 2023). In contrast, farmers reporting greater confidence in the effectiveness of their current pest control practices were less likely to indicate full adoption of cover crops, suggesting that satisfaction with existing management practices may reduce the perceived need to adopt sustainable approaches.

An unexpected finding concerns the positive association between perceived cost and the full adoption of bio-solutions and cover crops. Although this relationship appears counterintuitive, it remained robust after re-estimating the models using farmer-level clustered standard errors. One possible explanation is that respondents expressing general concerns about production costs may view these technologies as relatively affordable compared with more capital-intensive innovations. However, this interpretation should be treated with caution, as the possibility that unobserved factors contribute to this relationship cannot be excluded.

Overall, the findings suggest that farmers' adoption intentions are associated with market incentives, farm characteristics, and behavioural considerations, with the relative importance of these factors differing across technologies.

5.2. Theoretical implications

This study makes several contributions to the literature on sustainable technology adoption. First, it extends existing adoption frameworks by incorporating demand-side market signals into a body of literature that has traditionally focused on innovation characteristics (Rogers, 2003) and behavioural determinants (Ajzen, 1991). Previous studies have primarily emphasised technological attributes such as relative advantage, compatibility, and complexity, together with behavioural factors including attitudes, subjective norms, perceived behavioural control, and risk perceptions (Dessart et al., 2019; Thompson et al., 2022; Vrain and Lovett, 2016). By contrast, our findings indicate that information on consumers' WTP for products with reduced pesticide use is positively associated with farmers' stated adoption intentions across all four technologies, with stronger associations observed for more

capital-intensive innovations. This suggests that credible market signals may complement existing behavioural and innovation-based explanations by increasing the perceived economic value of adopting more sustainable production practices.

Second, although consumer WTP for environmentally sustainable food products has been widely investigated (Li and Kallas, 2021), relatively few studies have examined whether such market signals are associated with producers' adoption decisions regarding sustainable technologies. Our study contributes to addressing this gap by linking downstream consumer preferences with upstream production intentions. In doing so, it extends previous information-intervention research by showing that consumer-derived market signals may be positively associated with farmers' adoption intentions for pesticide-reducing technologies. This complements earlier evidence that information relating to technical, environmental, economic, health, and safety considerations can encourage the adoption of sustainable technologies (Chen et al., 2025).

Finally, the findings reinforce the view that technology adoption reflects the interaction of economic, structural, and behavioural factors rather than any single determinant. While consumer WTP information showed the most consistent association with adoption intentions, technology-specific associations were also observed for farm size, subjective norms, perceived effectiveness of existing pest management practices, and perceived costs. Overall, the results suggest that demand-side market signals should be viewed as a complementary component of existing sustainable technology adoption frameworks rather than as a substitute for the economic, structural, and behavioural factors that continue to shape farmers' decisions.

5.3. Practical implications

The findings have practical implications for policymakers, industry stakeholders, and actors across the agri-food value chain seeking to accelerate pesticide reduction in European agriculture. At a time when regulatory progress towards pesticide reduction has slowed, the results suggest that consumer-derived market signals may complement existing policy instruments by supporting farmers' consideration of pesticide-reducing innovations. However, these findings should be interpreted in relation to stated adoption intentions rather than realised adoption behaviour.

One practical implication concerns the communication of market incentives to producers. The findings suggest that transparent and credible communication of consumer WTP information may be relevant to market-based approaches to pesticide reduction. Certification and labelling schemes that communicate verified reductions in pesticide use could provide one means of transmitting market signals along the value chain. Similar to organic and fair-trade certification, such schemes may help producers access differentiated markets while providing consumers with clearer information regarding production practices (Janssen and Hamm, 2012; Marion et al., 2023). For producers unable or unwilling to pursue full organic certification, reduced-pesticide labelling could offer an intermediate pathway towards more sustainable production, particularly where the costs and administrative requirements of organic certification remain prohibitive (Hauck et al., 2021).

The successful implementation of such approaches, however, depends on credible governance arrangements. Reliable verification systems, transparent pesticide-use metrics, independent auditing, and effective price transmission mechanisms are essential to maintain consumer confidence and to ensure that market premiums reach producers. Without these supporting institutions, the incentive created by consumer demand may be weakened and the potential benefits of certification or labelling schemes may not be fully realised.

The findings also suggest that market-based incentives should not be viewed in isolation. Farmers' adoption intentions remained associated with farm characteristics and behavioural factors alongside consumer WTP information, indicating that economic constraints, technical capacity, and existing management practices may also shape technology adoption decisions. Consequently, policies that combine market incentives with investment support, advisory services, extension programmes, and coordinated supply-chain initiatives could be considered alongside regulatory measures. Processors, retailers, cooperatives, and certification bodies may also contribute by incorporating reduced-pesticide standards into procurement strategies and strengthening the transmission of consumer demand to farm-level decision-making.

5.4. Limitations and future research

While this study offers important insights into the association between consumer-driven market incentives and farmers' adoption intentions regarding pesticide-reducing innovations, several limitations should be acknowledged. First, the analysis relies on stated intentions rather than observed behaviour. Although measures were taken to mitigate hypothetical bias, including the use of a 'Cheap Talk' script, empirically estimated willingness to pay data, and video demonstrations to enhance realism, we acknowledge that farmers' stated intentions do not always translate into actual behaviour (Byfuglien et al., 2025). In addition, the three-point adoption scale does not capture variation in the extent of partial adoption, which may range from small-scale trials to broader phased implementation, and should be interpreted accordingly. Future research could strengthen these findings by employing revealed preference methods or field-based experiments to assess whether stated intentions translate into actual adoption decisions over time.

Second, as the sample was partly recruited through project stakeholders and sustainability-oriented networks, it may not be representative of conventional orchard farmers in the five study countries. As such, this recruitment strategy may overstate adoption intentions relative to the broader farming population, and the findings should therefore be interpreted with appropriate caution. Similarly, although the study controlled for demographic, structural, and behavioural factors, unobserved heterogeneity may still influence farmers' adoption decisions. Differences in regional agronomic conditions, institutional environments, or prior exposure to innovation could moderate the association between market signals and farmers' adoption decisions, and further research could explore these contextual dynamics more explicitly using larger and more geographically balanced samples.

Third, the market incentive examined in this study is based on estimates of the premium that consumers are willing to pay for wines and olive oils with reduced pesticide use. In actual market settings, however, the share of this premium received by farmers may differ due to processing costs, retailer margins, and existing contractual arrangements. This is particularly relevant for processed products such as wine and olive oil, where farm-gate prices often capture only a limited portion of the final consumer price. As a result, the assumption that farmers receive 29 % or 24 % more for a 40 % reduction in pesticide use should be interpreted as indicative rather than realised. Accordingly, the estimated association between this incentive and adoption intentions should be understood within the context of these assumptions. Future research could examine how supply chain structures, market governance, and certification systems affect the extent to which consumer price premiums are transmitted to producers. It would also be useful to explore alternative framings of market incentives, including the use of ranges that reflect uncertainty in premium realisation and market variability.

Another notable limitation of this study is the absence of a control group in the experimental design. Although the transition matrices in Appendix A6 show that no farmer revised their adoption intention downward after receiving the WTP information, the reasons for this pattern cannot be established from the transition data alone. It may reflect respondents' responses to the information, but it may also be due to experimenter demand effects, particularly given the uniformly positive information signal and its alignment with the study objective (Zizzo, 2010). For this reason, the observed changes should be interpreted as

associations rather than causal effects. In addition, differences in baseline adoption levels across technologies may constrain the magnitude of observed changes, particularly for options with already high initial adoption intentions, and should be considered when interpreting differences in adoption intention responses. Furthermore, as the study does not include direct measures of potential mediators such as perceived profitability, market uncertainty, or social signalling, it is not possible to identify the specific mechanisms through which WTP information may have influenced responses, consistent with established limitations in causal mediation analysis (Imai et al., 2011). Future studies could strengthen causal inference by incorporating randomised control groups or field-based designs.

Finally, while the potential market incentive offers a useful lens for understanding farmers' adoption intentions, it simplifies the broader decision context in which adoption occurs. In practice, farmers face structural constraints, including high upfront investment costs, access to finance, technical capacity, and institutional and regulatory conditions, particularly for capital-intensive technologies. Market-based incentives may help offset some of these costs over time, but are unlikely to be sufficient on their own. As such, the results should be interpreted as reflecting how price signals may be associated with adoption considerations at the margin, rather than as a standalone driver of pesticide reduction. Framing effects, even when grounded in realistic scenarios, may therefore influence stated behaviour in ways that overestimate actual uptake.

Despite its limitations, this study offers an important empirical contribution to understanding how demand-side premiums may shape supply-side sustainability transitions. The study provides a foundation for future research, including experimental validation, longitudinal assessments of realised adoption behaviour, and deeper examination of the institutional and market conditions shaping farmers' responses to consumer-driven market incentives. The findings provide a basis for examining the long-term viability of certification schemes that reward reduced pesticide use and the institutional conditions needed to translate consumer WTP a premium into more sustainable production practices.

6. Conclusion

This study examined the association between consumer WTP for products with reduced pesticide use and farmers' stated adoption intentions for pesticide-reducing innovations in Mediterranean vineyards and olive groves. Using a structured within-subject survey experiment involving 354 conventional farmers across France, Greece, Italy, Portugal, and Spain, the study assessed whether exposure to consumer WTP information was associated with farmers' stated intentions to adopt four pesticide-reducing technologies. The findings indicate that consumer-derived market signals are positively associated with both partial and full adoption intentions across all four technologies, although the association was stronger for the more capital-intensive innovations. These results suggest that transparent market information may complement existing economic and behavioural factors shaping farmers' technology adoption decisions, particularly where producers face barriers to full organic conversion.

The findings have important implications for the design of policies and market mechanisms aimed at supporting more sustainable pest management in vineyards and olive groves. Given the mixed progress towards the EU's pesticide-reduction targets, consumer-derived market incentives may be considered alongside regulatory and investment-based approaches by strengthening the economic rationale for adopting pesticide-reducing innovations. However, translating consumer demand into farm-level incentives requires credible market institutions, effective price transmission, and transparent mechanisms, such as certification and labelling schemes. Such schemes would reduce information asymmetries by communicating certified pesticide-reduction practices to consumers while enabling producers to receive part of the premium consumers place on reduced pesticide use. These market-based instruments should therefore be viewed as complementary to broader policy measures, including advisory services, investment support, and coordinated supply-chain governance.

The findings should be interpreted in light of the study design. The analysis is based on stated adoption intentions within a before-and-after framework without a control group and therefore identifies associations rather than causal effects. Nevertheless, by linking consumer-derived market signals with farmers' adoption intentions across multiple pesticide-reducing technologies, this study provides new empirical evidence on the potential role of demand-side incentives in sustainable technology adoption. In doing so, it contributes to the understanding of how consumer preferences, when effectively transmitted through markets and supported by appropriate institutional arrangements, may help encourage the transition towards more sustainable production at the farm level.

CRediT authorship contribution statement

Noah Larvoe: Writing – review & editing, Writing – original draft, Methodology, Formal analysis, Data curation, Conceptualization. **Dela-Dem Doe Fiankor:** Writing – review & editing, Writing – original draft. **Zein Kallas:** Writing – review & editing, Validation, Supervision, Funding acquisition.

Declaration of competing interest

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

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jclepro.2026.149820.

Data availability

Data will be made available on request.

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