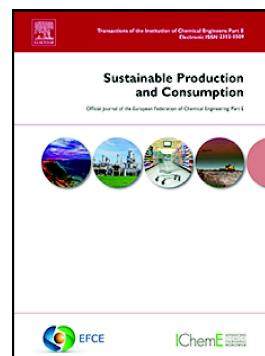


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## Exploring Behavioral Intentions Behind Biochar Technology Adoption in Agriculture

Mariavittoria Perrone<sup>a</sup>, Giordano Ruggeri<sup>a</sup>, Alberto Tosca<sup>b</sup>, Edoardo Verga<sup>b</sup>, Chiara Mazzocchi<sup>\*a</sup>

<sup>a</sup> Department of Agricultural and Environmental Science, Production, Territory, Agroenergy, University of Milan, Via Celoria 2, 20133, Milan, Italy

<sup>b</sup> Fondazione Minoprio, Viale Raimondi, 54, 22070 Vertemate con Minoprio CO

\*Corresponding author: chiara.mazzocchi1@unimi.it

### Abstract

Biochar technology represents a promising solution for sustainable agriculture. It holds great potential for enhancing agricultural performance, enabling carbon sequestration, and promoting sustainable climate change mitigation practices. However, large-scale implementation of the technology remains under development. This study explores the key drivers influencing adoption intentions among Italian farmers through an extended Technology Acceptance Model (TAM). A survey was administered to 131 Italian Farmers. Data collected has been analyzed applying a TAM model in STATA SEM builder. The research results emphasize the central role of Perceived Usefulness and Perceived Ease of Use in shaping intentions, implying that farmers consider biochar technology both valuable and easy to use. Additionally, factors such as social norms, demonstrability of results, economic returns, and climate change awareness have been found significant in influencing farmers' perceptions. Those who are more aware of climate change tend to perceive biochar as more useful, reinforcing the role of environmental consciousness in shaping technology adoption. Economic considerations emerge as particularly influential, underscoring the importance of returns in driving adoption. These findings have important implications for policymakers, agricultural advisors, and technology developers, offering valuable insights for the development of structured initiatives aimed at promoting the adoption and integration of biochar technology.

## Exploring Behavioral Intentions Behind Biochar Technology Adoption in Agriculture

### Abstract

This study examines Northern Italian farmers' intentions to adopt biochar by applying the Technology Acceptance Model and an extended specification tailored to sustainability contexts. A cross-sectional telephone survey of farmers ( $n = 131$ ) was analysed using partial least squares structural equation modelling. We estimate a baseline model that includes perceived usefulness, perceived ease of use, subjective norm, image, job relevance, output quality, and result demonstrability, as well as an extended model that adds climate-change awareness, perceived economic value (price–value), and perceived external control/support.

Across specifications, intention to adopt is positively related to perceived usefulness and perceived ease of use. In the extended model, the economic value proposition emerges as the most salient antecedent of perceived usefulness, with additional contributions from output quality, result demonstrability, and awareness of climate change. By contrast, social-influence pathways (subjective norm, image) are weak or inconsistent.

The exploratory findings suggest that, in a voluntary setting with generally low prior knowledge, farmers' intentions are most consistent with instrumental, value-for-money judgments and the perceived simplicity of implementation, rather than social endorsement. Interpretations are correlational and are bound to a sample of Northern Italian farmers. Practical implications include demonstrating credible agronomic and economic benefits, reducing perceived complexity, and ensuring visible support for early adopters. Future research should validate these patterns longitudinally and in other countries and awareness stages.

### 1. Introduction

In pursuing sustainable and environmentally responsible solutions to address current and future agricultural and environmental challenges, it is essential to understand the factors shaping the perception and acceptance of emerging technologies within the agricultural sector. Agriculture is under pressure to increase productivity while minimising environmental impacts, making the adoption of climate-smart innovations vital for long-term sustainability (Dessart et al., 2019). One such innovation, biochar, has gained increasing attention due to its multiple benefits, such as soil enhancement, organic waste valorisation, and climate change mitigation (Osman et al., 2020). Biochar's appeal lies in its ability to simultaneously improve soil health, recycle organic wastes, and

sequester carbon (Jeffery et al., 2017; Nogués et al., 2023), positioning it as a multi-functional tool in sustainable agriculture. Produced through pyrolysis, a thermochemical process that decomposes organic matter in a low-oxygen environment, biochar is the solid co-product alongside bio-oil and syngas, both of which hold potential for renewable energy generation (Joseph et al., 2021). This co-production of energy products enables biochar systems to enhance farm resource efficiency by generating bioenergy while producing a valuable soil amendment (Woolf et al., 2010). From an agronomic perspective, biochar improves nutrient retention, reduces leaching, enhances microbial activity, and increases water-holding capacity, particularly in degraded soils (Kant Bhatia et al., 2021; Randolph et al., 2017; Zheng et al., 2013). Indeed, meta-analyses have found that biochar can significantly boost crop yields in nutrient-poor, acidic tropical soils (often by ~25% on average), whereas yield effects in temperate, well-fertilised regions tend to be minimal (Jeffery et al., 2017). Furthermore, its long-term stability and capacity to sequester carbon make it a valuable tool in climate-smart agriculture (Lehmann and Joseph, 2015; Paustian et al., 2016; Vaccari et al., 2011). According to Woolf et al. (2010), annual net emissions of carbon dioxide (CO<sub>2</sub>), methane and nitrous oxide could be reduced by a maximum of 1.8 Pg CO<sub>2</sub>-C<sub>eq</sub> yr<sup>-1</sup> (12% of current anthropogenic CO<sub>2</sub>-C<sub>eq</sub> emissions; 1 Pg=1 Gt), and total net emissions over the course of a century by 130 Pg CO<sub>2</sub>-C<sub>eq</sub>, without endangering food security, habitat or soil conservation (Woolf et al. 2010).

The adoption of biochar technology aligns with the principles of the circular economy, where organic waste materials serve as a valuable feedstock for energy production. This process contributes to both carbon sequestration and organic waste management, offering a sustainable solution to multiple environmental issues (Kurniawan et al., 2023). Moreover, biochar has recently gained formal recognition under the European Union (EU) Carbon Removals and Carbon Farming (CRCF) Regulation (EU/2024/3012), positioning it within the broader context of the European Green Deal and the European Union's carbon neutrality goals (European Union, 2024). Similarly, in the United States, new initiatives are emerging to encourage biochar use, such as the adoption of a U.S.–Canada Biochar Protocol in 2024 to generate high-quality carbon credits from biochar projects (Climate Action Reserve, 2024). These policy developments signal institutional support for the use of biochar. However, despite its documented agronomic and environmental benefits, the adoption of biochar among farmers remains limited (Falconi et al., 2024; Latawiec et al., 2017; Ruiz et al., 2013). Empirical studies indicate that awareness and willingness to use biochar are still low in many farming communities. For example, in a Polish survey, only 27% of farmers had heard of biochar, and just 20% were interested in trying it (Latawiec et al., 2017). Many farmers were either unwilling

to adopt biochar or undecided, citing barriers such as a lack of access, uncertain costs, and limited knowledge of its use cases (Latawiec et al., 2017). Similarly, in the United States, the biochar sector is described as fragmented, with key barriers including variable product quality, insufficient market incentives, and inconsistent policy support hindering widespread adoption (Janaranjana and Bandara, 2025). Understanding what drives or hinders the acceptance of biochar within the agricultural sector is therefore essential for closing the gap between its potential and its actual use on farms (Masud et al., 2023).

To explore these dynamics, this study focuses on the Northern Italian agricultural context, where the literature on biochar adoption remains scarce. Northern Italy presents a pertinent case to investigate farmer behaviour regarding sustainable soil innovations, given the country's emphasis on agricultural sustainability but relatively limited awareness of biochar technology to date. Using an extended TAM, a theoretical framework originally proposed by Davis (1989) and widely applied to study technology uptake in agriculture (Canavari et al., 2021; Li et al., 2023; Ling et al., 2023; Savari et al., 2024; Thomas et al., 2023) this research investigates barriers, and motivations influencing Italian farmers' intentions to adopt biochar technology. Furthermore, the paper proposes an extended version of TAM by incorporating new variables considered central to investigating biochar technology acceptance. TAM posits that perceived usefulness and ease of use are primary determinants of technology adoption; here, we extend this model by incorporating additional variables particularly relevant to sustainable agriculture and biochar. In our extended TAM, we include factors as the economic value of the technology and awareness of climate change, as we hypothesise these to be central in shaping biochar acceptance. By integrating these new constructs, the study aims to provide a more comprehensive understanding of farmers' decision-making. In doing so, our work sheds light on the behavioural predictors of

adoption, offering insights for policymakers, extension services, and agricultural stakeholders to craft strategies that encourage the uptake of this promising climate-smart innovation. Ultimately, a better grasp of farmer behaviour and perceptions will help bridge the gap between biochar's proven agronomic benefits and its practical adoption on the ground, contributing to both agricultural sustainability and broader environmental goals (Hounnou et al., 2024; Janiszewska-Latterini et al., 2025).

## **2. Literature review**

Numerous studies document that adding biochar to soil can enhance crop productivity and soil quality while reducing greenhouse gas emissions (Biederman and Stanley Harpole, 2013; Kuppusamy et al., 2016; Randolph et al., 2017). It is particularly effective in degraded and nutrient-poor soils (Laghari et al., 2015; van Zwieten et al., 2010; Zhang et al., 2012), enhancing cation exchange capacity, pH balance, water retention, microbial activity, and nitrogen availability (El-Naggar et al., 2019).

Although historical evidence supports the use of carbonised biomass in soil, the integration of biochar into modern, climate-smart agricultural strategies can be considered an innovation since the technological knowledge, the production process, and best practices for its dual role, as a soil amendment and as a tool for soil carbon sequestration, represent a comparatively recent development in the agricultural landscape. Numerous studies (Kurniawan et al., 2023; Lehmann and Joseph, 2015; Sohi et al., 2010) identify biochar as a viable option for achieving substantial carbon sequestration, underscoring its role in advancing carbon neutrality and supporting circular economy initiatives (Kurniawan et al., 2023).

A body of scientific literature (Lefebvre et al., 2023; Lehmann et al., 2021; Roe et al., 2021; Weng and Cowie, 2025; Woolf et al., 2010) provides estimates of the significant contribution that biochar can offer to carbon sequestration. At the global level, estimations indicate a minimum feasible carbon removal potential of  $\sim 0.17 \text{ Gt C yr}^{-1}$  (and a technical upper bound of  $\sim 0.32 \text{ Gt C yr}^{-1}$ ), with permanence dependent on production methods and system boundaries (Sirén, 2024). Considering that the addition of biochar to the soil enhances tree growth rates, these estimates increase to 0.22 and  $0.42 \text{ Gt C yr}^{-1}$ , respectively (Sirén, 2024). At the European scale, recent reviews report an EU-wide removal potential of  $\sim 133 \text{ Mt CO}_2 \text{ yr}^{-1}$  for biochar. Using the standard stoichiometric conversion of roughly  $2.7 \text{ t CO}_2$  per tonne of biochar (for typical carbon contents), with roadmap projections of approximately  $6 \text{ Mt CO}_2 \text{ yr}^{-1}$  by 2030 and  $\sim 100 \text{ Mt CO}_2 \text{ yr}^{-1}$  by 2040 under accelerated deployment (Chiaramonti et al., 2024; European Biochar Industry, 2024; Roe et al., 2021). For Italy, long-running Tuscany field platforms—among the longest biochar trials in the EU—demonstrate agronomic viability and empirically verified durability of biochar-derived carbon in situ over multi-year horizons, reinforcing permanence assumptions relevant to carbon removal accounting (Chiaramonti et al., 2024). Moreover, an Italian life-cycle assessment of a gasification-to-biochar supply chain estimates a net climate benefit equivalent to  $\sim 1.51 \text{ t of CO}_2$  removed per tonne of biochar applied after upstream and downstream emissions are included, offering a conservative benchmark for potential removals under realistic conditions (Marzeddu et al., 2021).

Despite this potential, biochar uptake remains limited globally, as the technology has not yet seen widespread deployment outside of pilot projects and niche uses (Ruiz et al., 2013). In other words, biochar's promise for climate mitigation and soil restoration has so far outpaced its real-world implementation. This gap between potential and practice is attributed to a range of persistent barriers (Pierson et al., 2024).

According to the literature, economic constraints (Jayakumar et al., 2023; Pierson et al., 2024; Shackley et al., 2011), technical complexities (Bilotto et al., 2024), and limited awareness (Latawiec et al., 2017) determine substantial barriers. Biochar production requires a high initial capital investment and specialised technical knowledge, while the pyrolysis process itself presents operational challenges (Cui et al., 2022; Kong et al., 2014). Additionally, farmers' insufficient knowledge of biochar's benefits and applications limits its adoption (Latawiec et al., 2017; Soriano Ynfante et al., 2024). According to Torres-Morales et al. (2023), limited awareness of biochar's benefits may constrain its market potential in Colombia, where the adoption of new agricultural technologies often depends on demonstrated success by others. Other recent empirical studies reveal that knowledge and perception are critical drivers of biochar acceptance. According to Hounnou et al. (2024), who investigated the intention to adopt biochar among cotton farmers in Benin, there is a strong connection between knowledge, perception, and the acceptance of an innovation. Soriano Ynfante et al. (2024), and Latawiec et al. (2017), in their studies on biochar technology acceptance in New Mexico and Poland, revealed that only 65% and 27% of respondents were familiar with biochar. Furthermore, Fridahl et al. (2021) in Tanzania, showed that carbon removal benefits alone are insufficient to drive the technology uptake. Instead, clear, tangible benefits were needed to motivate both smallholders and larger agricultural businesses to adopt biochar systems (Fridahl et al., 2021).

The situation in Italy reflects the global challenges on a domestic scale. Analyses by the Italian Council for Agricultural Research (CREA) indicate that the biochar supply chain in Italy remains underdeveloped (Falconi et al., 2024). Only a limited number of biochar producers are active in the country, and several have ceased operations due to insufficient demand in the agricultural market (Falconi et al., 2024). In fact, some producers have pivoted to alternative outlets (such as pharmaceutical or animal feed applications) in an effort to create value and find stable revenue streams (Falconi et al., 2024). According to CREA's assessment, the main obstacles hindering biochar expansion in Italy are the absence of a stable market and ongoing technical difficulties in production and application. These findings echo the need for greater advisory support and awareness-raising

among Italian farmers regarding biochar. Until a reliable market and knowledge base are established, many businesses have struggled to justify continuing biochar production for soil amendment purposes. The combination of biochar's diverse potential benefits and the significant hurdles in Italy's current market conditions highlights why an exploratory study is needed to understand what would influence Italian farmers' intentions to adopt this technology (Falconi et al., 2024).

This study represents the first application of TAM to biochar adoption by farmers. By extending TAM with context-specific factors, we aim to capture the unique aspects of biochar acceptance in agriculture. TAM's proven ability to illuminate the drivers and barriers of technology acceptance makes it an ideal framework (Canavari et al., 2021). Using an extended TAM allows us to systematically explore the factors influencing whether Italian farmers are willing to implement biochar – a novel practice for soil improvement and carbon sequestration – in their operations. This approach will yield insights into the behavioural mechanisms at play and guide strategies to enhance technology acceptance in sustainable agriculture.

### **3. Methodology**

#### **3.1 Technology Acceptance Model (TAM) and Extended TAM conceptual frameworks**

TAM was originally introduced by Davis (1989) as an adaptation of the Theory of Reasoned Action (Fishbein and Ajzen, 1975), focusing on the determinants of technology use. In its initial form, TAM explains an individual's intention to perform a behaviour (and actual technology use) through two key beliefs: Perceived Usefulness (PU) and Perceived Ease of Use (PEU). PU is defined as the degree to which a person believes that using the technology will improve their job performance or otherwise yield significant benefits in their work. PEU represents the degree to which a person expects that using the technology will be free of effort (Davis, 1989). Davis (1989) demonstrated TAM's predictive capability and argued it could outperform the broader Theory of Reasoned Action as it could be applied across different technological contexts by concentrating on these two constructs. A subsequent version, TAM-2, extends this foundation by incorporating external variables related to social influence (e.g., Subjective Norm, Image) and cognitive instrumental processes (e.g., JR, RD) that shape an individual's perceptions and intentions (Venkatesh and Davis, 2000).

While several established frameworks exist, TAM-2 was selected as the optimal theoretical foundation for this study after careful consideration of the alternatives. Its successful application in

numerous agricultural technology studies confirms its robustness in this domain (Makeel et al., 2025; Marikyan and Papagiannidis, 2024; Thomas et al., 2023). Our research focuses on the individual farmer's voluntary, pre-adoption decision, a context for which TAM-2 is specifically tailored. Unlike the broader Theory of Planned Behaviour (TPB), it offers more diagnostically precise constructs of Perceived Usefulness and Ease of Use, rather than a general 'Attitude' (Ajzen, 1991). It is also better suited than the Unified Theory of Acceptance and Use of Technology (UTAUT), which is primarily designed for organisational or mandatory contexts less relevant to an individual entrepreneur (Venkatesh et al., 2012; Venkatesh and Davis, 2000). Similarly, while Diffusion of Innovations (DOI) theory explains population-level diffusion, TAM-2 provides a more granular psychological model of an individual's belief formation (Rogers, 2003). Furthermore, biochar is a dual-purpose technology with both economic and environmental dimensions. A purely pro-environmental framework, such as the Value-Belief-Norm (VBN) theory, effectively explains sustainability motivations but does not capture the pragmatic, instrumental appraisals critical to a farmer's business decisions (Stern et al., 1999). The flexible and extendable nature of TAM-2 provides an adequate foundation for integrating these diverse drivers (Dai and Cheng, 2022; Ling et al., 2023). Therefore, TAM-2 was chosen as the most parsimonious and powerful theoretical 'backbone' for modelling individual, voluntary, pre-adoption decisions for a complex agricultural innovation. To test our hypotheses and address potential model misspecification, we estimate two models in sequence. First, we test a baseline TAM-2 model that includes the core constructs of Perceived Ease of Use (PEU), Perceived Usefulness (PU), Subjective Norm (SN), Image (IM), Job Relevance (JR), Output Quality (OQ), Result Demonstrability (RD), and Intention to adopt (Intention). Second, we test an extended model that retains this TAM-2 backbone and adds three context-specific constructs: Climate Change Awareness (CCA), Price Value (PV), and Perceived External Control (PEC). This two-step approach allows us to confirm the foundational theory before demonstrating the added explanatory power of our proposed extensions.

The complete diagram of the extended model is presented in Figure 1 and discussed in the following section. We estimated the models using variance-based partial least squares structural equation modelling (PLS-SEM). PLS-SEM is appropriate when the primary goals are theory development and prediction with complex models and moderate samples, and when indicators may deviate from multivariate normality. All latent variables are modelled as reflective composites and estimated with Mode A weights. Model estimation used nonparametric bootstrapping (10,000 resamples) to obtain standard errors and bias-corrected confidence intervals for path coefficients.

### 3.2 Model Extensions to TAM-2

To tailor the TAM to the context of biochar adoption, we made deliberate modifications by excluding two original TAM-2 moderators and introducing three new context-specific constructs. Each change is grounded in theoretical reasoning and prior findings, as detailed below. The complete list of variables included in the research design is presented in Table 1 in Section 3.3.

#### 3.2.1 Removed TAM-2 moderators

TAM-2 includes voluntariness as a moderating variable, defined as the extent to which potential adopters perceive the adoption decision to be non-mandatory (Venkatesh and Davis, 2000). This construct moderates the direct influence of SN on behavioural intention, which TAM-2 theorises occurs primarily in mandatory usage settings. In our study context, adopting biochar is entirely voluntary – there are no external mandates forcing farmers' adoption. Empirical evidence from TAM-2 indicates that SN significantly boosts adoption intentions only under low-voluntariness conditions (i.e. mandatory contexts or compliance settings) and when users lack prior experience (Venkatesh and Davis, 2000). In voluntary settings, SN tends to affect intentions mainly indirectly (via PU or IM), and the direct compliance-driven effect is negligible. Given that Italian farmers face no mandate to use biochar, we omitted voluntariness from our model. This decision aligns with prior TAM applications in voluntary innovation adoption, which often drop the voluntariness construct as it offers little explanatory power outside forced-use scenarios (Ling et al., 2023; Savari et al., 2024).

Similarly, experience (another TAM-2 moderator) was not included. Venkatesh and Davis (2000) found that as users gain experience with a technology over time, the impact of social influence diminishes. Experience in TAM-2 moderates effects such as SN → Intention and IM → PU, indicating that once individuals have substantial firsthand experience, they rely less on others' opinions. In the case of biochar, the innovation is relatively new, and almost none of our respondents had prior experience with its use. Thus, there was neither a theoretical need nor empirical variance to model an experience moderator – all farmers were essentially “novice” with respect to biochar technology. Excluding the experience construct keeps the model parsimonious and is consistent with TAM-2 usage in initial adoption studies (where users have no prior hands-on exposure). In summary, because biochar adoption is a voluntary decision and farmers generally lack prior experience with biochar, the TAM-2 moderators (voluntariness and experience) were deemed unnecessary and are omitted for theoretical parsimony and relevance.

#### 3.2.2 Added context-specific constructs

Beyond the core TAM-2 structure, we integrated three antecedents that are theoretically pertinent to a voluntary, cost-bearing sustainability practice: PV—the user’s benefit–cost appraisal of adoption as formalised in UTAUT2 (Venkatesh et al., 2003; Venkatesh and Davis, 2000); CCA—the knowledge/salience of climate risks and mitigation, expected to raise the instrumental value attributed to climate-smart practices; and PEC—the availability of external enablers (support, infrastructure, subsidies) aligned with facilitating conditions in UTAUT and perceived behavioural control in TPB. These constructs – CCA, PV and PEC – were selected based on literature in technology adoption and the specifics of biochar’s value proposition (Venkatesh et al., 2003; Venkatesh and Davis, 2000).

Biochar is widely promoted as a climate-smart innovation due to its carbon sequestration and mitigation potential. We posit that farmers’ awareness of climate change issues influences their perception of biochar’s usefulness. In general, CCA refers to an individual’s understanding of the causes, impacts, and the need for mitigation of climate change. High CCA often correlates with pro-environmental attitudes and openness to low-carbon innovations. Prior studies confirm the importance of this factor: for example, Ling et al. (2023) found that farmers’ awareness of climate change can act as an external driver that positively influences their utility perceptions of low-carbon farming practices, thereby increasing willingness to adopt such practices (Ling et al., 2023). In our model, we incorporate CCA as an external predictor of PU. The rationale is that a farmer aware of climate risks and mitigation strategies may find greater value in biochar – not only for improving farm productivity but also as a climate action tool. This hypothesis is supported by evidence that purely “climate” benefits alone do not guarantee adoption unless farmers recognise and value those benefits. For instance, a Tanzanian study noted that the benefits of carbon sequestration were insufficient to motivate the uptake of biochar unless farmers perceived clear advantages (Rogers et al., 2022). By including CCA, we capture this cognitive link: farmers who are more aware of climate change are expected to attribute a higher value to biochar’s environmental benefits, thereby bolstering its PU.

Economic considerations are a pivotal adoption factor in agriculture. Price value represents the perceived trade-off between the benefits of a technology and the financial costs of adopting it. We introduced PV to explicitly account for farmers’ cost-benefit evaluations of biochar. This addition is theoretically grounded in adoption research. Venkatesh et al. (2012) incorporated a similar price value construct in the UTAUT2 model, showing that when users face monetary costs, the net value (benefits minus costs) significantly affects their intention to adopt (Venkatesh et al., 2012). In

farming contexts, the literature consistently shows that economic viability is a major driver (or barrier) of technology uptake. Biochar implementation requires upfront investment (e.g. in pyrolysis equipment or purchasing biochar) and entails operational costs. If farmers do not perceive a positive payoff – through improved yields, input savings, or new revenue streams – they are unlikely to adopt the practice. Indeed, economic constraints are frequently cited as a top barrier to biochar adoption. By modelling PV, we capture whether a farmer believes “biochar is worth it” financially. Our PV construct encompasses perceptions of potential revenue or cost savings from biochar use (e.g. improved soil productivity, reduced fertiliser needs) and even the prospect of earning carbon credits for sequestered carbon. This reflects the emerging opportunities in carbon markets where farmers could monetise biochar’s climate benefits. In sum, including Price Value allows the model to reflect a farmer’s economic motivation: a favourable cost-benefit perception should enhance biochar’s PU (and by extension, adoption intention). This extension is well supported by diffusion theory (relative advantage) and prior TAM extensions that emphasise financial return as a key component of PU in agricultural innovation adoption.

PEC was included to represent the influence of external support structures, such as government policies, subsidies, or technical assistance, on biochar acceptance. The concept is analogous to “facilitating conditions” in the Unified Theory of Acceptance and Use of Technology (UTAUT) and to the control beliefs from the Theory of Planned Behaviour (TPB). It gauges the degree to which individuals believe that an enabling infrastructure exists to support their use of the technology (e.g. access to resources, knowledge, or incentives) (Canavari et al., 2021). The decision to include PEC was informed by both theoretical considerations and the practical realities of biochar adoption. Theoretically, TAM3 and related models recognise that if users perceive strong external support, they feel more capable of adopting the innovation (greater control), which can boost either ease or usefulness. In our case, we hypothesise that PEC primarily influences PU. A farmer who is aware of supportive measures – for instance, a subsidy program, extension services for biochar training, or favourable regulations – may regard biochar as more useful or advantageous to adopt. The literature on agricultural technology adoption underscores this point: when growers expect public policy support or technical help, it encourages them to adopt new practices (Canavari et al., 2021). For example, a study of Italian farmers adopting precision irrigation found that the availability of organisational resources and external support significantly improved perceived ease of use and adoption rates (Canavari et al., 2021). In the biochar context, external control might include the presence of cost-share programs, carbon credit schemes, or informational support that lowers the

hurdles to using biochar. We also draw on (Canavari et al., 2021), who incorporated the PEC into a TAM-based model of sustainable farming technology adoption, finding that expected external support positively impacted farmers' perceptions of technology.

By including PEC, our model acknowledges that biochar uptake is not only a function of personal beliefs but also of the broader enabling environment. A positive perception that “the necessary external help is available” can enhance a farmer’s confidence in the technology’s value, thereby indirectly fostering stronger acceptance (notably, TAM-2 originally did not account for such external facilitation factors; however, given the importance of policy incentives and infrastructure in sustainable agriculture, integrating PEC offers a more holistic view of biochar adoption drivers).

Our extended model retains the core strengths of TAM-2 while adapting it to the sustainability domain of biochar. We removed voluntariness and experience because these moderators pertain to contexts (mandatory use and long-term usage) that do not apply to our study of voluntary, early-stage adoption (Venkatesh and Davis, 2000). At the same time, we introduced CCA, PV, and PEC to capture salient influences on farmers’ decision-making that the standard TAM-2 would miss. These additions are firmly rooted in prior research: farmers who are more climate-conscious tend to recognise the added usefulness of a climate-friendly innovation (Ling et al., 2023); those who perceive a favourable cost-benefit are more inclined to adopt technologies with uncertain profitability; and those who sense strong external support face fewer barriers and thus view the innovation more favourably (Canavari et al., 2021). By justifying each model modification with established theory and empirical findings, we ensure that our extended TAM framework is not an ad-hoc assortment of variables, but a theoretically coherent model. This approach strengthens the study’s explanatory power and relevance: it acknowledges well-documented barriers to biochar adoption (economic and knowledge constraints) and leverages insights from sustainability adoption literature to explain why Northern Italian farmers might accept or reject biochar technology.

### 3.3 Hypothesis Formulation

Figure 1. Extended TAM-2 Framework to investigate the Intention to Adopt biochar technology in the agricultural sector. Solid lines represent the base TAM-2, while dashed lines highlight the extended TAM-2 with the introduction of three new variables: PEC, CCA, PV.

Biochar adoption in farming hinges on whether producers expect the practice to deliver tangible agronomic or economic gains and whether it can be implemented with manageable effort. In the TAM/TAM-2 methodologies (Davis, 1989; Venkatesh and Davis, 2000), we conceptualize PU as

farmers' belief that biochar improves enterprise performance—through soil fertility and water retention, yield stability or quality, input savings, and potentially monetizable carbon benefits—and PEU as their expectation that biochar can be sourced, dosed, applied, and managed without undue complexity (e.g., compatibility with machinery, handling and learning requirements). Consistent with TAM (Caffaro et al., 2020; Jimenez et al., 2020; Kamara et al., 2019; Yeo and Keske, 2024), we expect both beliefs to raise behavioural intention to adopt biochar (H1: PU → Intention, positive; H2: PEU → Intention, positive) and easier practices to be considered more useful (PEU → PU).

*H1: Perceived Usefulness has a significant positive impact on farmers' Intention to adopt biochar technology.*

*H2.1: Perceived Ease of Use has a significant positive impact on farmers' Intention to adopt biochar technology.*

*H2.2: Perceived Ease of Use has a significant positive impact on farmers' Perceived Usefulness of biochar technology.*

Social influence in agricultural communities can shape beliefs about a novel practice. SN refers to the perceived social pressure an individual feels to perform or not perform a particular behaviour (French and Raven, 1959). In the context of farmers' adoption of biochar technology, SN refers to the social pressures or influences farmers perceive from others in their community, such as fellow farmers or trusted advisors. Positive SN can reinforce biochar's PU by aligning the adoption with community expectations and values.

*H3: Subjective norms have a significant positive impact on farmers' Perceived Usefulness of biochar technology.*

Image (IM) could be defined as “the degree to which the use of an innovation is perceived to enhance one's status in one's social system” (Moore and Benbasat, 1991), and it acts as a mediating variable in the relationship between SN and PU (Venkatesh and Davis, 2000). In this study, IM examines whether farmers perceive biochar use as a means to enhance their social standing—either within their professional community or among final consumers—thereby influencing its PU through social recognition. Being a mediating variable, IM involves two distinct relationships: (1) the influence of SN on IM, and (2) the effect of an enhanced image on the PU of the technology. We therefore posit that stronger perceived expectations will heighten PU directly (H3: SN → PU, positive) and raise image (H4.1: SN → IM, positive), and that a stronger image will translate into higher PU (H4.2: IM → PU, positive) as status signals act as cues to instrumental value.

*H4: Image plays a positive mediating role between Subjective Norms and Perceived Usefulness.*

*H4.1: Subjective Norms have a significant and positive impact on Image.*

*H4.2: Image has a significant and positive impact on Perceived Usefulness.*

TAM-2 further models cognitive-instrumental cues that help users judge whether a technology “pays its way”. For biochar, RD refers to the observability and communicability of outcomes (e.g., monitored input savings or visible improvements in soil tilth). If farmers recognize visible improvements such as increased yields, better soil quality, or reduced input costs after using biochar, these tangible results could support their PU. Furthermore, RD may also involve scientific validation or community-based evidence, such as neighbours sharing successful outcomes or data confirming biochar’s effectiveness. JR captures the degree to which biochar is perceived as beneficial onto the farm’s production system (crop mix, soil constraints, irrigation regime). We expect clearer and more communicable results to be associated with greater PU (H5: RD → PU, positive), and higher perceived relevance to the farm’s tasks to do likewise (H6: JR → PU, positive). In line with TAM-2’s performance-quality logic, we also estimate OQ (H7: OQ → PU, positive) to capture perceived quality of outcomes under biochar use.

*H5: Result Demonstrability has a significant positive impact on farmers’ Perceived Usefulness of biochar technology.*

*H6: Job Relevance has a significant positive impact on farmers’ Perceived Usefulness of biochar technology.*

*H7: Output Quality has a significant positive impact on farmers’ Perceived Usefulness of biochar technology.*

Because biochar is both a production and a climate-smart innovation adopted voluntarily and at cost, we extend the PU formation block with three contextual predictors grounded in established acceptance frameworks (Canavari et al., 2021; Dai and Cheng, 2022; Li et al., 2023; Ling et al., 2023; Rezaei-Moghaddam and Saeid, 2010; Savari et al., 2024; Taheri et al., 2022).

PEC captures perceived availability of enabling resources and support (e.g., extension advice, reliable supply, subsidy schemes, access to carbon markets) (Canavari et al., 2021; Dai and Cheng, 2022; Venkatesh et al., 2003). In our context, the variable aims to assess whether individuals are inclined to seek financial or technical support and perceive such assistance as enhancing the utility of biochar technology. Mirroring facilitating-conditions/control-beliefs mechanisms, stronger perceived support should enhance the technology’s instrumental value (H8: PEC → PU, positive).

In general, CCA refers to the individuals' capacity to understand and recognise the various aspects of climate change (Lawrance et al., 2022). In our study, this variable was based on previously validated Ling et al. (2023) psychometric scale, where CCA denotes the extent to which respondents recognise the challenges posed by climate change, as well as the potential benefits of mitigation strategies. In the case of biochar, since the technology represents a useful tool for climate change mitigation and farm sustainability in general, a higher CCA may correlate with positive PU. In sustainability contexts, environmental cognition shifts what "useful" means by foregrounding resilience and carbon benefits, so greater awareness should be associated with greater PU (H9: CCA → PU, positive).

Finally, PV reflects farmers' benefit–cost appraisal in a voluntary, cost-bearing setting (Venkatesh et al., 2012); a favourable value-for-money judgment should be associated with greater PU (H10: PV → PU, positive), consistent with value mechanisms formalised in extended acceptance models.

*H8: Perceived External Control has a significant positive impact on farmers' Perceived Usefulness of biochar technology.*

*H9: Climate Change Awareness has a positive and significant impact on perceived usefulness.*

*H10: Price Value has a positive and significant impact on perceived usefulness*

### **3.4. Data collection and survey structure**

Data collection was conducted via telephone interviews targeting agricultural entrepreneurs throughout Italy. This approach was selected for its practicality and effectiveness compared to face-to-face or online methods, as telephone interviews often yield high response rates and engagement levels (Fricker et al., 2005; Szolnoki and Hoffmann, 2013). Contacts of agricultural entrepreneurs were obtained with the assistance of various local consortia and professionals<sup>1</sup>. A multi-step consent process was followed to ensure participants were fully informed. Potential participants were first contacted to determine their willingness to take part in the survey. Those who expressed initial interest were subsequently sent an email providing comprehensive information about the study's objectives, the voluntary nature of their participation, and the procedures in place to ensure the anonymity and confidentiality of their responses. Finally, verbal informed consent was formally

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<sup>1</sup> Fondazione Patrimonio Ca' Granda  
 Consorzio per la tutela del Franciacorta  
 Co.pro.vi. Societa' Cooperativa Consorzio Difesa Pavia  
 CIB – Consorzio Italiano Biogas  
 FELCOS – Associazione di Comuni per lo Sviluppo Sostenibile

reconfirmed with each participant at the beginning of the telephone interview before any questions were asked. All participants consented to the use of their fully anonymised data for research and publication purposes.

The questionnaire is structured in three sections; the full version of the survey can be found in Section S1 of the Supplementary Information (SI). The first section introduced biochar technology, providing essential information to participants who might not be familiar with its use and benefits. This part also detailed the types of investment involved, whether individual or through consortia, offering a broad understanding of the financial aspects related to biochar technology implementation.

The second section collected detailed socioeconomic data about the farmers and their farming operations. It included a self-assessment question where respondents rated their knowledge of biochar technology on a scale from 1 to 10, allowing for an assessment of their familiarity and understanding of the subject.

The third section comprised 32 items designed to measure the constructs of the TAM, organised according to the model's variables (as shown in Table 1). Each item was crafted based on prior research with minor adjustments to better suit the specific context of biochar technology. For each item, respondents were asked to indicate their level of agreement with each statement on a scale from 1 (strongly disagree) to 5 (strongly agree), a standard measure in psychometric surveys. The questionnaire was administered in Italian; the items presented in Table 1 have been translated into English. Before any construct items were presented, all participants received a standardised, neutral description of biochar (including its production process and agronomic and environmental effects) to ensure that pre-adoption beliefs were formed based on common information rather than idiosyncratic prior knowledge. In line with TAM/TAM-2's role in modelling pre-adoption intentions and beliefs (Davis, 1989; Venkatesh and Davis, 2000), this design permits respondents to evaluate perceived usefulness, ease of use, and job relevance without prior hands-on experience.

A small pilot survey ( $n = 30$ ) with farmers was used to check comprehension, wording, and response burden. Beyond reporting basic reliability, we collected qualitative feedback about the clarity of wording, ambiguous terms, and the length of the survey. Based on this evidence, we made minor wording refinements, clarified instructions, and adjusted the sequence of a few items to improve flow. No new items were added, and no constructs were removed; the content coverage of each construct was preserved.

We assessed the reflective measurement model using established criteria. Indicator reliability was examined via standardised loadings (target  $\geq 0.70$ ). For internal consistency, we report both Cronbach's alpha ( $\alpha$ ), Composite Reliability (CR/Dillon–Goldstein's  $\rho$ ) and interpret them jointly. Alpha is widely used in TAM research but assumes (essential) tau-equivalence and is sensitive to scale length, whereas CR relaxes that assumption by leveraging estimated loadings; reporting both aligns with current guidance in variance-based SEM (Hair et al., 2011). Beyond Cronbach's  $\alpha$  and composite reliability, we report a congeneric reliability index ( $\rho_A/\omega$ ) for reflective constructs, computed from a one-factor analysis of each scale's polychoric correlation matrix (principal-factor extraction) (Flora and Curran, 2004). This index does not assume tau-equivalence and complements  $\alpha$  for short, congeneric scales (Raykov, 1997). In variance-based SEM, this serves the same role as Dijkstra–Henseler's  $\rho_A$ —a reliability index consistent with reflective measurement in PLS (Dijkstra and Henseler, 2015).

Convergent validity was assessed with Average Variance Extracted (AVE), adopting the AVE  $\geq 0.50$  heuristic (Fornell and Larcker, 1981). For discriminant validity, we report the heterotrait–monotrait ratio (HTMT) with a conservative 0.85 benchmark (Henseler et al., 2015), alongside the Fornell–Larcker criterion (AVE exceeding inter-construct correlations) (Fornell and Larcker, 1981). To diagnose collinearity, we inspected VIFs among indicators and structural predictors; values below  $\sim 5$  indicate no problematic multicollinearity in PLS-SEM (Hair et al., 2011).

**Table 1. Psychometric scale items for each variable, including question formulation and references.**

Components	Items		Alpha	CR	$\rho_A/\omega$	AVE	Reference
Perceived Usefulness PU	pu1	The production of biochar would improve my production process.	0.84	0.89	0.84	0.67	Davis (1989); Venkatesh and Davis (2000)
	pu2	The production of biochar would create positive opportunities for my farm.					
	pu3	The production of biochar would create new opportunities for my business.					
	pu4	The production of biochar would help my farm to become more efficient.					
Perceived Ease of Use PEU	peu1	Biochar could be easily produced on my farm.	0.60	0.77	0.68	0.53	Davis (1989); Canavari (2021)
	peu2	The production of biochar would not require a very high effort for my farm.					
	peu3	Acquiring skills for biochar production on my farm would be quite simple.					

	peu4	The biochar production technology is clear and understandable.					
Subjective Norm SN	sn1	If the current technological landscape suggested adopting biochar in my company, I would do so.	0.82	0.89	0.91	0.73	Venkatesh and Davis (2000)
	sn2	If my consultants recommended adopting biochar technology on my farm, I would do so.					
	sn3	If most of my fellow farmers produced biochar, I would also adopt this technology.					
Image IM	im1	The image of my farm would be positively influenced by the use of biochar technology.	0.76	0.86	0.79	0.68	Venkatesh and Davis (2000)
	im2	The image of my brand would be positively influenced by the production of biochar.					
	im3	Farmers who implement biochar technology could gain more public recognition than those who do not.					
Result Demonstrability RD	rd1	I could easily demonstrate the advantages of biochar technology.	0.86	0.91	0.87	0.78	Venkatesh and Davis (2000); Canavari (2021)
	rd2	I could communicate to my stakeholders the benefits of using biochar technology.					
	rd3	I believe I would have no trouble explaining to others the benefits and disadvantages of biochar production.					
Job Relevance JR	jr1	In my work, the use of biochar technology is common.	0.70	0.88	0.82	0.79	Kim (2008); Venkatesh and Davis (2000);
	jr2	In my job, the use of biochar technology is relevant.					
	jr3	In my job, the use of biochar technology is important.					
Output quality OQ	oq1	I believe that the quality of my products could improve thanks to the production of biochar.	0.71	0.86	0.92	0.76	Venkatesh and Davis (2000)
	oq2	N					
Perceived External Control PEC	pec1	I would leverage public policies supporting the production and use of biochar.	0.87	0.92	0.88	0.80	Venkatesh et al., (2003); Canavari (2021)
	pec2	I could request financial public support necessary to invest in biochar production.					
	pec3	I could request technical public support for the use of biochar technology.					
Price Value PV	pv1	The additional profits from selling energy would be useful for my company.	0.89	0.93	0.90	0.76	Dai and Cheng (2022) Venkatesh et al. (2012)
	pv2	The additional profits from selling carbon credits would be positive for my company.					
	pv3	The valorisation of agricultural waste could have a positive economic impact on my agricultural business.					
	pv4	The additional profits from selling biochar would be positive for my company.					
Climate Change Awareness CCA	cca1	Thanks to its properties, biochar is one of the climate change mitigation solutions available to the agricultural sector.	0.84	0.90	0.89	0.76	Ling et al. (2023)
	cca2	Biochar used as a soil amendment and as a carbon dioxide storage solution, represents a technology that is useful given the current climate change challenges in agriculture.					
	cca3	In a climate change context, biochar, due to its soil amendment properties and thanks to the possibility of renewable energy					

		production (syngas and bio-oil), will have a positive impact on the sustainability of my farm.					
Intention to Adopt INTENTION	int	I intend to adopt biochar technology in the future (within 5 to 10 years).					Venkatesh and Davis (2000)

## 4. Results

### 4.1 Descriptive statistics

The final study population comprised entirely farmers from Northern Italy. An initial pool of 212 farmers was contacted by telephone, resulting in 131 fully completed interviews (a response rate of approximately 62%). Table 2 summarises the socioeconomic data obtained from these respondents. Overall, the average age stood at 44.07 years (SD = 12.72). Among them, 16.03% were under 30, 31.30% were aged 31–40, 22.14% were 41–50, and 30.53% were over 50, indicating a well-distributed age profile. In terms of education, 57.25% held a university degree, 34.35% were high-school graduates, 4.58% had earned a Ph.D., and 3.82% had completed middle-school education. Their average farming experience was 20.98 years (SD = 12.89). Information collected on knowledge of biochar technology reveals a generally low to moderate level of awareness among respondents. Most participants (50.38%) rated their knowledge between 1 and 3, indicating minimal familiarity with the subject, and a fraction (12.98%) reported a higher level of knowledge (7-8) of the technology; no individuals responded with a 9 or higher score. Our sample aligns with Falconi et al. (2024), confirming a generally limited expertise in biochar technology. Regarding farm size, the sample showed relatively even distribution in both cultivated land area and annual economic revenues. Viticulture emerged as the leading production type (48.09%), followed by rice and cereals (25.19% combined). A comprehensive breakdown of sociodemographic variables such as age groups, gender, education level, years of experience, farm size, farm revenues, and main production types is available in Table 2.

**Table 2. Socio-demographic characteristics of the sample**

Variable	Classification	Frequency	Percentage
Age	Under 30	21	16.03%
	31-40	41	31.30%
	41-50	29	22.14%
	Above 50	40	30.53%
Gender	Female	18	13.74%
	Male	113	86.26%
Education	Junior high school	5	3.82%

	High school/Technical secondary school	45	34.35%
	University degree	75	57.25%
	PhD	6	4.58%
Years of Experience	Less than 10 years	35	26.72%
	10-20 years	41	31.30%
	21-30 years	27	20.61%
	Above 30 years	28	21.37%
Biochar Knowledge	Score from 1 to 3	66	50.38%
	Score from 4 to 6	48	36.64%
	Score from 7 to 8	17	12.98%
Farm size	Less than 2 ha	8	6.11%
	Between 2 and 10 ha	38	29.01%
	Between 11 and 30 ha	30	22.90%
	Between 31 and 50 ha	9	6.87%
	Between 51 and 100 ha	15	11.45%
	Over 100 ha	28	21.37%
	No answer	3	2.29%
Farm revenues (2022)	Under €50,000	23	17.56%
	Between €51,000 and €70,000	8	6.11%
	Between €71,000 and €100,000	11	8.40%
	Between €101,000 and €200,000	14	10.69%
	Between €201,000 and €300,000	14	10.69%
	Between €301,000 and €400,000	11	8.40%
	Between €401,000 and €500,000	3	2.29%
	Over €500,000	38	29.01%
	I don't know / Prefer not to answer	9	6.87%
Main sector of Production	Apiculture	1	0.76%
	Cereals	15	11.45%
	Floriculture	3	2.29%
	Fruits	3	2.29%
	Olives	4	3.05%
	Horticulture	9	6.87%
	Rice	18	13.74%
	Viticulture	63	48.09%
	Animal husbandry	13	9.92%
	Other	2	1.53%

#### 4. Structural model results

All indicators loaded positively on their intended constructs (all the loadings and reliability coefficients can be found in Table S1 in the SI). In the baseline TAM-2, standardised loadings ranged from 0.63 to 0.93 (most  $\geq 0.70$ ). Internal consistency was assessed jointly via Cronbach's  $\alpha$ , composite reliability (CR/ $\rho_c$ ), and  $\rho_A$ . With the exception of PEU ( $\alpha \approx 0.60$ ), all  $\alpha$  were  $\geq 0.70$ ; PEU's CR  $\approx 0.77$  and AVE  $\approx 0.53$  nonetheless meet recommended thresholds, with standardised loadings in

the 0.63–0.78 range. Discriminant validity is supported by both Fornell–Larcker and HTMT (conservative cutoff 0.85). We therefore retain PEU and rely on CR/ $\rho$ A alongside  $\alpha$  for inference. Internal consistency was acceptable when evaluated jointly via Cronbach’s  $\alpha$  and composite reliability (CR/Dillon–Goldstein’s  $\rho$ ): aside from PEU ( $\alpha=0.551$ ), all  $\alpha$  were  $\geq 0.70$ ; all CR were  $\geq 0.76$  (range  $\approx 0.77$ – $0.92$ ). For PEU, the congeneric reliability ( $\rho$ A/ $\omega$ ) was acceptable, and all indicators loaded on the intended factor; accordingly, we retain PEU but interpret PEU-related effects cautiously. Convergent validity was supported for every construct. The extended TAM-2 showed the same pattern (all CR  $\geq 0.70$ ; all AVE  $\geq 0.50$ ). Fornell–Larcker discriminant validity was satisfied in both models: each construct’s  $\sqrt{\text{AVE}}$  exceeded its inter-construct correlations; equivalently, squared inter-factor correlations were below the corresponding  $\sqrt{\text{AVEs}}$ . HTMT (conservative cutoff 0.85) was also inspected and remained below the threshold for all constructs. The full Fornell–Larcker table (Table S2, S4) and the HTMT matrix (Table S3, S5) are provided in the SI.

**Table 3. TAM-2 and Extended TAM-2 Models**

Path	TAM-2 (Base Model) ( $\beta$ )	Extended TAM-2 Model ( $\beta$ )
Perceived Usefulness (PU) $\rightarrow$ Intention	0.416***	0.415***
Perceived Ease of Use (PEU) $\rightarrow$ Intention	0.315***	0.316***
Output Quality (OQ) $\rightarrow$ PU	0.331***	0.228**
Perceived Ease of Use (PEU) $\rightarrow$ PU	0.195**	0.086
Image (IM) $\rightarrow$ PU	0.142•	0.055
Subjective Norm (SN) $\rightarrow$ IM	0.293***	0.293***
Result Demonstrability (RD) $\rightarrow$ PU	0.118	0.179*
Subjective Norm (SN) $\rightarrow$ PU	0.115	0.095
Job Relevance (JR) $\rightarrow$ PU	0.001	-0.049
Perceived External Control (PEC) $\rightarrow$ PU	—	-0.07
Climate Change Awareness (CCA) $\rightarrow$ PU	—	0.151*
Price Value (PV) $\rightarrow$ PU	—	0.438***
R <sup>2</sup> for Perceived Usefulness	0.46	0.594
R <sup>2</sup> for Intention	0.352	0.352
Q <sup>2</sup> for Perceived Usefulness	0.302	0.393
Q <sup>2</sup> for Intention	0.284	0.284

**Figure 2. Graphical representation of model results. The coefficients displayed represent both Base model and Extended Model.**

#### 4.1 Baseline TAM-2 (PLS-SEM)

The first column of Table 3 reports the structural estimates for the baseline specification. Intention is jointly and positively predicted by PU ( $\beta = 0.416$ ,  $p < 0.001$ ) and PEU ( $\beta = 0.315$ ,  $p < 0.001$ ). The

direct SN → Intention link is not significant ( $\beta = -0.031, p = 0.743$ ). On the belief side, PEU → PU is positive and significant ( $\beta = 0.195, p < .05$ ). Among cognitive-instrumental antecedents of PU, OQ shows a clear association ( $\beta = 0.331, p \leq .001$ ), while RD is small and indeterminate ( $\beta = 0.118$ ), and JR is near zero ( $\beta = 0.001$ ). The social-influence chain is present in its initial path (SN → IM:  $\beta = 0.293, p = 0.001$ ), whereas the subsequent path from IM → PU ( $\beta = 0.142, p = 0.082$ ) and the direct path from SN → PU ( $\beta = 0.115, p = 0.152$ ) are not statistically reliable. Model-level diagnostics indicate moderate explanatory and predictive power:  $R^2(\text{PU}) = 0.489, R^2(\text{Intention}) = 0.367, R^2(\text{IM}) = 0.086$ ; blindfolding yields  $Q^2(\text{PU}) = 0.302, Q^2(\text{Intention}) = 0.284, Q^2(\text{IM}) = 0.058$ . Multicollinearity is low (all VIF  $\approx 1.00$ – $1.75$ ). Bootstrap tests of mediation show that the SN → PU → Intention indirect effect is small and non-significant ( $\beta_{\text{ind}} \approx 0.048, p \approx 0.20$ ). Total-effects decomposition confirms that PEU's total impact on Intention is mostly direct (total  $\beta \approx 0.396$ ), with OQ contributing indirectly via PU (OQ → Intention<sub>ind</sub>  $\approx 0.138$ ).

#### 4.2 Extended TAM-2

The extended model retains the TAM-2 backbone and adds CCA, PV, and PEC as antecedents of PU (Table 3). For the three context-specific antecedents (PV, CCA, PEC), convergent validity was satisfactory (CR  $\geq 0.70$ ; AVE  $\geq 0.50$ ; loadings mostly  $\geq 0.75$ ) and discriminant validity held (HTMT  $< 0.85$ ; Fornell–Larcker satisfied). Full loadings and HTMT matrices are provided in the SI (Table S1, S5).

Two core TAM-2 routes are identical to the baseline: PU → Intention ( $\beta = 0.415, p < 0.001$ ) and PEU → Intention ( $\beta = 0.316, p < 0.001$ ) remain strong and positive, while SN → Intention is again not significant ( $\beta = -0.031, p = 0.743$ ). Knowledge-based multi-group/moderation tests show no amplification of these paths among higher-knowledge farmers. Given that several social links have low achieved power ( $\leq \sim 0.20$ – $0.35$ ), we classify them as inconclusive/latent rather than evidence of no effect and avoid over-interpretation. On the PU equation, the added domain-specific predictors are salient: PV is the largest antecedent ( $\beta = 0.438, p < 0.001$ ), followed by OQ ( $\beta = 0.228, p = 0.008$ ), RD ( $\beta = 0.179, p = 0.026$ ), and CCA ( $\beta = 0.151, p = 0.029$ ). In this richer specification, PEU → PU attenuates and becomes non-significant ( $\beta = 0.086, p = 0.282$ ), and PEC → PU is small and negative ( $\beta = -0.070, p = 0.350$ ). The social-influence first leg is unchanged (SN → IM:  $\beta = 0.293, p = 0.001$ ), whereas IM → PU ( $\beta = 0.055, p = 0.470$ ) and SN → PU ( $\beta = 0.095, \text{n.s.}$ ) remain small.

Relative to the baseline, explanatory and predictive performance for PU improves:  $R^2(\text{PU}) \approx 0.59$  ( $\Delta R^2 \approx +0.13$ ) and  $Q^2(\text{PU}) = 0.393$ ;  $R^2(\text{Intention}) = 0.367$  remains essentially unchanged. Multicollinearity stays low (all VIF  $\leq 1.84$ ). Bootstrap mediation quantifies the indirect contributions

to Intention through PU: PV shows the largest indirect effect (PV → Intention  $\approx$  0.182), followed by OQ ( $\approx$  0.095), RD ( $\approx$  0.074), and CCA ( $\approx$  0.062); the SN-mediated route remains small and non-significant. Table 4 consolidates the hypothesis tests: H1 and H2 (PU and PEU → Intention) are supported; H2.1 (PEU → PU) is supported in the baseline but not in the extended model; H4.1 (SN → IM), H5 (RD → PU), H8 (CCA → PU), and H9 (PV → PU) are supported in the extended model; H3 (SN → PU), H4.2 (IM → PU), H6 (JR → PU), and H7 (PEC → PU) are not supported. The corresponding hypothesis tests for the baseline model are available in the SI (Table S6).

**Table 4. Hypotheses tests — Extended TAM-2 (PLS-SEM, bootstrap)**

Hypothesis	Path	$\beta$ (standardised)	p-value	Verdict	Predictors for DV	Effect Size ( $f^2$ )	Achieved Power	Predictors for DV
H1	PU → Intention	0.415	< 0.001	Supported	2	0.172	> 0.99	Excellent Power
H2	PEU → Intention	0.316	< 0.001	Supported	2	0.100	0.97	Excellent Power
H2.1	PEU → PU	0.086	0.282	Not supported	9	0.007	0.15	Very Low Power
H3	SN → PU	0.095	> 0.100	Not supported	9	0.009	0.18	Very Low Power
H4.1	SN → IM	0.293	0.001	Supported	1	0.086	0.95	Excellent Power
H4.2	IM → PU	0.055	0.470	Not supported	9	0.003	0.08	No Power
H5	RD → PU	0.179	0.026	Supported	9	0.032	0.51	Low Power
H6	JR → PU	$\sim$ 0.000	> 0.100	Not supported	9	0.002	0.07	No Power
H7	OQ → PU	0.228	0.010	Supported	9	0.052	0.73	Adequate Power
H8	PEC → PU	-0.070	0.350	Not supported	9	0.005	0.12	Very Low Power
H9	CCA → PU	0.151	0.029	Supported	9	0.023	0.38	Low Power
H10	PV → PU	0.438	< 0.001	Supported	9	0.192	> 0.99	Excellent Power

*Notes.* Standardised coefficients; two-tailed bootstrap p-values (10,000 resamples). **Predictors for DV** is the number of predictor variables for the corresponding dependent variable in the structural model. **Effect Size ( $f^2$ )** is a measure of the path's local effect size, used as input for the power analysis. **Achieved Power** is the post-hoc statistical power ( $1-\beta$ ), calculated using G\*Power. It represents the probability of detecting an effect of the observed magnitude, given  $N=131$  and  $\alpha=0.05$ .

### 4.3 Model Diagnostics and Robustness Checks

Blindfolding yielded positive  $Q^2$  values for endogenous constructs, indicating out-of-sample predictive relevance. Cross-validated effect sizes ( $q^2$ ) were consistent with the structural results (e.g., PU→Intention  $q^2 \approx$  0.18; PEU→Intention  $q^2 \approx$  0.06). We inspected model-implied vs. empirical correlation residuals and found no localised patterns of large residuals; multicollinearity checks (VIF  $\leq$  1.84) and inspection of cross-loadings did not flag misspecification.

Given our moderate sample size ( $N=131$ ), we performed a post-hoc sensitivity analysis to assess statistical power using the inverse square-root method, as recommended for PLS-SEM (Kock and Hadaya, 2018). For a statistical power of 80% at a level of 0.05, the minimum detectable path coefficient is  $N \geq (2.486/|\beta| \min)^2 \approx 163$ . Our results show that the model's core predictive paths are well above this threshold and thus sufficiently powered. For example, Price Value  $\rightarrow$  Perceived Usefulness ( $\beta=0.438$ ), Perceived Usefulness  $\rightarrow$  Intention ( $\beta=0.415$ ), and Perceived Ease of Use  $\rightarrow$  Intention ( $\beta=0.316$ ) all demonstrate robust effects. Conversely, several ancillary relationships, particularly those found to be non-significant, have effect sizes far below this threshold. This indicates that the study is exploratory in its nature, as it does not guarantee sufficient power to definitively rule out a small effect for these paths. Therefore, while our main findings are robust, the non-significance of these secondary links must be interpreted with caution, a point we elaborate on in the limitations section.

Moreover, we conducted a detailed post-hoc power analysis for each structural path. Using G\*Power, we calculated the achieved power for each relationship based on the observed effect size, a sample size of 131, and an  $\alpha$  of 0.05. The results, presented alongside the hypothesis tests in Table 4, provide a nuanced view of the model's robustness. The analysis confirms that the study was sufficiently powered to detect the model's core, significant relationships. The key paths determining adoption intention (PU  $\rightarrow$  Intention and PEU  $\rightarrow$  Intention) and the strongest antecedent of usefulness (PV  $\rightarrow$  PU) all demonstrate excellent achieved power ( $>0.95$ ). Other significant paths, such as OQ  $\rightarrow$  PU, show adequate power (0.73). Crucially, the analysis also quantifies the low statistical power for the ancillary paths that were found to be non-significant. For instance, the study had only an 18% probability of detecting an effect for SN  $\rightarrow$  PU and an 8% probability for IM  $\rightarrow$  PU. This provides strong quantitative support for our conclusion that the non-significance of these weaker relationships should be interpreted with caution, as it may reflect an insufficient power rather than a true null effect.

To empirically test whether low a priori knowledge of biochar undermined model validity—particularly for social-influence pathways—we conducted a knowledge-based multi-group analysis. We split the sample into a Low-knowledge group ( $n = 66$ ; self-rated knowledge 1–3) and a Higher-knowledge group ( $n = 65$ ; self-rated knowledge 4–8) and used a permutation test (1,000 permutations) to assess differences in the structural paths. The results, which are detailed in Table S5 of the SI, show no statistically significant differences ( $p < 0.05$ ) for any path, including SN  $\rightarrow$  IM,

IM → PU, and SN → Intention. The core relations—PV → PU, PU → Intention, and PEU → Intention—are stable across groups.

In addition, several social links exhibit low achieved power in our design (e.g., IM → PU and SN → PU, Table 4), so their non-significance is treated as inconclusive/latent rather than “no effect.” We therefore report these paths for transparency but avoid strong claims pending higher-powered replication.

To assess whether Intention depends directly on broader antecedents (as in TPB/UTAUT), we re-estimated the TAM-2 and extended models, adding SN→Intention, IM→Intention (baseline), and SN/IM/CCA/PV/PEC→Intention (extended), keeping measurement blocks and bootstrap settings unchanged. The augmented specifications produced modest gains in explanatory and predictive power— $R^2(\text{Intention})$  rose from 0.367→0.416 in the baseline and 0.367→0.423 in the extended model;  $Q^2(\text{Intention})$  increased from 0.284→0.322 (baseline) and 0.283→0.300 (extended). Across both augmented models, PU→Intention and PEU→Intention were positive and significant; SN→Intention and IM→Intention were small and non-significant; CCA→Intention and PV→Intention were also non-significant in the extended model. Given the small incremental fit and unchanged core predictors, we retain the parsimonious TAM-2 structure in the main text and report the augmented results (Table S8) in the SI for completeness.

To assess robustness, we re-estimated the baseline and extended TAM-2 models by adding the age and education of the entrepreneur (AGE, EDU), and the prior knowledge of biochar (Prior\_knowledge) as exogenous controls (once to Intention only, and once to both PU and Intention). Results (Table S9, SI) are presented in the core substantive effects—PEU → Intention and PU → Intention—remain stable in magnitude and significance across specifications ( $\beta_{\text{PEU} \rightarrow \text{INT}} \approx 0.29\text{--}0.32$ ,  $p < 0.001$ ;  $\beta_{\text{PU} \rightarrow \text{INT}} \approx 0.42\text{--}0.43$ ,  $p < 0.001$ ). Adding controls yields only marginal gains in explained variance for Intention ( $\Delta R^2 \approx +0.009$ ), and none of the controls significantly predict Intention ( $|\beta| \leq 0.088$ ,  $p \geq 0.236$ ). Where controls are allowed to predict PU, AGE shows a small negative association with PU in the baseline variant ( $\beta = -0.173$ ,  $p = 0.009$ ), but this does not translate into Intention. Blindfolding indicates positive predictive relevance for Intention in all control-augmented models ( $Q^2 \approx 0.27$ ), reinforcing that the main attitudinal predictors (PU, PEU) account for the bulk of adoption intentions in this sample.

**Table 5. Summary of the overall fit indices**

Assessment block	Metric (criterion)	TAM-2 (Base)	Extended TAM-2
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<b>Measurement adequacy</b>	Indicator loadings (target $\geq 0.70$ )	0.63–0.93 (most $\geq 0.70$ )	0.63–0.93 (most $\geq 0.70$ )
	Cronbach's $\alpha$ (report with CR)	0.551–0.860 (PEU $\alpha=0.551$ )	$\geq 0.70$ (PEU $\alpha=0.551$ )
	Composite Reliability, CR/pc ( $\geq 0.70$ )	0.77–0.92	$\geq 0.70$
	AVE ( $\geq 0.50$ )	min = 0.528	min $\geq 0.50$
<b>Discriminant validity</b>	Fornell–Larcker ( $\sqrt{AVE} > r$ )	Satisfied	Satisfied
	HTMT (conservative $< 0.85$ )	All $< 0.85$	All $< 0.85$
<b>Explanatory power</b>	R <sup>2</sup> (Perceived Usefulness)	0.489	0.594
	R <sup>2</sup> (Intention)	0.352	0.367
<b>Predictive relevance (blindfolding)</b>	Q <sup>2</sup> (Perceived Usefulness)	0.302	0.393
	Q <sup>2</sup> (Intention)	0.284	0.294
<b>Cross-validated effect sizes (blindfolding)</b>	q <sup>2</sup> : PU $\rightarrow$ Intention	$\approx 0.18$	$\approx 0.18$
	q <sup>2</sup> : PEU $\rightarrow$ Intention	$\approx 0.06$	$\approx 0.06$
<b>Multicollinearity (structural)</b>	Max VIF among predictors	$< 1.75$	$< 1.84$

## 5. Discussion

All interpretations below are correlational and conditional on the specified TAM-2 models. Given the cross-sectional and self-reported nature of the data, we do not make causal claims. We highlight four consistent patterns from the structural estimates (Table 3). First, within our cross-sectional design, intention is most strongly associated with PU and also positively associated with PEU, consistent with an instrumental and feasibility-driven logic.

Second, when the model is contextualised, economic value shows the largest association with usefulness—price value outweighs classic cognitive-instrumental cues (e.g., OQ, JR), indicating that Northern Italian farmers judge biochar through a net-benefit lens that integrates agronomic gains with revenue/cost opportunities (e.g., savings, coproducts, carbon credits). While the importance of economic factors is intuitive, our model's primary contribution lies in quantifying the overwhelming dominance of PV in the farmer's decision-making calculus. In an early diffusion, voluntary setting, our results suggest that a credible economic case is not merely ancillary but a practical precondition for many respondents to view biochar as useful (i.e. "value matters" in a very literal sense) (Latawiec et al., 2017). This dominance of the economic factor is plausible for several reasons salient in farm investment decisions. First, biochar adoption entails substantial up-front costs and operational complexity (equipment purchase, application labour, learning curve), while

agronomic benefits can be uncertain and lagged (Omokaro et al., 2025). Early adopters often face a delay before soil improvements or yield gains materialise, and any potential initial yield decline can deter farmers (as observed with cotton growers in Benin who were discouraged by a short-term yield drop) (Janiszewska-Latterini et al., 2025). Second, farmers operate under liquidity and risk constraints; even modest ambiguity in the cost–benefit calculus can dramatically lower the perceived utility of an innovation (Hounnou et al., 2024). Third, market incompleteness and institutional gaps – such as limited access to carbon credit monetisation, thin local markets for biochar, and uncertain offtake or pricing for biochar and co-products – make private returns less transparent (Janiszewska-Latterini et al., 2025; Omokaro et al., 2025). This helps explain why a “usefulness” narrative becomes persuasive only when underpinned by a clear value-for-money proposition in contexts (Janiszewska-Latterini et al., 2025; Latawiec et al., 2017).

Third, pro-environmental cognition appears secondary: CCA shows a small positive association with PU that we interpret cautiously due to limited sensitivity for small effects; this pattern is consistent with the view that environmental salience can enhance perceived instrumental value.

Fourth, social influence pathways are weak at this stage: SN is positively associated with IM, but neither translates into higher usefulness or intention, which is consistent with a voluntary, pre-diffusion context in our data. We classify these links as latent/inconclusive rather than absent, given achieved-power levels.

Robustness checks support these readings. Augmenting the intention equation with direct paths from broader antecedents marginally increases explained variance but leaves the core PU/PEU predictors unchanged; the only added signal is a direct link from PEC to intention, consistent with the idea that enabling conditions raise willingness to act even if they do not alter beliefs about usefulness. This PEC → Intention link is reported as a supplementary, exploratory specification; it was not part of the main pre-specified TAM-2 structure and should be interpreted with caution given design sensitivity. Multi-group tests based on prior knowledge reveal no structural differences, and the addition of demographic/knowledge controls does not alter the substantive effects. Overall, the evidence suggests a pragmatic adoption logic: make benefits credible and salient, keep the practice straightforward, and strengthen the value proposition—social endorsement and status cues have little traction until visibility and experience are established.

## 5.1 Theoretical Implications

The strong influence of PU and PEU on adoption intention corroborates the fundamental propositions of TAM. This consistency with prior theory (Davis, 1989; Venkatesh & Davis, 2000) reinforces TAM's validity in agricultural innovation domains: even for a sustainability-focused, agronomic practice like biochar, farmers are more likely to adopt if they think it will enhance their job performance and be free of effort (Dai and Cheng, 2022). Our study thus contributes to the robust body of evidence (Caffaro et al., 2020; Thomas et al., 2023) that the core tenets of TAM hold true across diverse technologies and contexts. More importantly, we contribute by extending TAM-2 with context-specific factors, revealing new insights about technology acceptance in sustainable agriculture. The inclusion of Price Value proved especially illuminating. In line with the Unified Theory of Acceptance and Use of Technology 2 (UTAUT2), which formalised price value as a key construct when users bear costs (Venkatesh et al., 2012), our results indicate that Northern Italian farmers' behavioural intentions are strongly associated with economic calculus. This mirrors findings in other recent TAM extensions (Dai and Cheng, 2022). Our work finds that economic considerations are not merely ancillary in sustainable technology adoption – they are central. By embedding the cost–benefit dimension (PV) into TAM-2, we account for a larger share of variance in PU and highlight that, in our sample, a favourable value proposition is often associated with higher perceived usefulness. This aligns with broader adoption literature emphasising relative advantage and profitability as critical drivers (Pierson et al., 2024). Within our design, we extend TAM-2's "cognitive instrumental" pathway by demonstrating that perceived value (benefits minus costs) serves as a potent cognitive criterion, alongside traditional beliefs about OQ or JR. Indeed, PV overshadowed classic TAM-2 antecedents like OQ, RD, and JR – a finding that suggests TAM-based frameworks in agriculture should explicitly account for the economic utility of innovations to remain predictive.

While the CCA → PU signal is small and not design-powered, making its theoretical reading exploratory, the integration of CCA also offers theoretical implications. We found that Northern Italian farmers with greater awareness of climate change issues tended to rate biochar as more useful, presumably because they recognise its environmental co-benefits. By embedding CCA as an external antecedent to PU, our extended model acknowledges that the "usefulness" of an innovation is evaluated not only in economic or performance terms, but also in relation to an individual's environmental values and knowledge. Theoretically, this suggests that TAM can be successfully enriched by constructs from the Value-Belief-Norm and similar frameworks when studying eco-innovations. Our study thus contributes to the TAM-2 literature by indicating an

effective blend of utilitarian and normative predictors: PU itself may partly derive from alignment with broader value-driven goals (in this case, mitigating climate change). This insight might inform future extensions of TAM in contexts such as renewable energy, climate-smart farming, or conservation technologies, where users' environmental awareness or moral norms could critically shape perceived utility (Savari et al., 2023)

A noteworthy theoretical finding is the limited role of SN and IM in our context. Social influence (e.g. SN and IM) can affect technology adoption, often through shaping PU (people think a technology is more useful if respected others expect them to use it, or if using it confers social status) (Canavari et al., 2021; Savari et al., 2024). However, we observed no significant direct or indirect effect of subjective norm on biochar adoption intentions. This result is consistent with TAM-2's contention that in voluntary adoption settings, the direct influence of subjective norm tends to be negligible (Venkatesh and Davis, 2000). Our respondents faced no mandate to use biochar, and indeed, the decision is entirely discretionary – under such conditions, farmers appear to rely on their own judgment of the innovation rather than social pressure. The finding aligns with studies of other voluntary agricultural innovations where peer influence was only indirect. For example, a recent TAM-based study on green farming in China found that “social network” influences were fully mediated by PU, with no direct effect on adoption behaviour (Dai and Cheng, 2022). In our model, we observed that the SN had a positive effect on IM (farmers who felt more social pressure experienced a slightly greater status benefit from biochar). However, critically, this heightened image did not translate into higher PU, as TAM-2 would typically predict. One possible explanation is the very early stage of biochar awareness and use, where only a minority of peers are familiar with the practice (~50% of the sample rated their biochar knowledge as 1–3 out of 10), resulting in a lack of a strong normative influence. Farmers in our sample may not yet perceive a strong normative climate around biochar, which aligns with the weak social-influence estimates observed. This divergence from the TPB (which treats social norm as a direct determinant of intention) is theoretically significant: it suggests that for nascent, niche innovations, TAM's emphasis on individual cognition over social influence is particularly apt. Over time, if biochar use becomes more visible in farming communities, the effects of social conformity may grow – a possibility supported by Rogers' diffusion theory, which suggests that later adopters are often influenced by witnessing others' success (Rogers, 2003). For now, our findings challenge models like UTAUT that assign a strong role to social influence. In short, our results are consistent with the view that - in the pre-

adoption phase of a complex sustainable technology - social influence pathways may remain latent until a critical mass of users and demonstrable results emerge (Torres-Morales et al., 2023).

Another theoretical insight lies in the non-significance of PEC in our extended model. We hypothesised PEC (analogous to “facilitating conditions” or perceived behavioural control) as an antecedent to PU, expecting that if farmers feel external support is available (such as grants and technical assistance), they will deem biochar more advantageous. Surprisingly, PEC did not significantly raise PU – in fact, its coefficient was negative (though not significant). There are a few ways to interpret this. It is possible that Italian farmers currently do not perceive strong external support for biochar, and thus variations in PEC were minimal or meaningless. The literature suggests that facilitating conditions matter more when a technology is available and support is accessible (Venkatesh et al., 2003); however, in our case, formal support (aside from recent EU policy signals) is scarce. This aligns with recent analyses by Falconi et al. (2024), who describe Italy’s biochar sector as underdeveloped, lacking a stable market or institutional backing. Under such conditions, simply including PEC in the model may have limited value – one cannot appreciate a facilitator that isn’t really there. Another interpretation arises from our supplementary analysis: when we allowed PEC to directly influence adoption intention (akin to TPB’s perceived control → intention link), it showed a significant positive effect (reported here cautiously, as it was not pre-specified and is not design-powered for small effects). This suggests that farmers who believe external help would be available are more willing to adopt (even if that belief didn’t inflate biochar’s PU). Theoretically, this suggests that external enablers might bypass appraisals of cognitive usefulness and instead bolster farmers’ confidence to act. Such a pattern aligns with TPB and UTAUT, where facilitating conditions are believed to facilitate adoption, particularly when users transition from intention to implementation. In a TAM framework, we initially modelled PEC conservatively (as an indirect factor via PU), but our results invite future researchers to consider a dual role: external support can make a technology seem easier or less risky to adopt, even if it doesn’t change one’s perception of the technology’s intrinsic benefits. Our findings contribute to refining the theoretical understanding of “perceived control” in innovation adoption, suggesting that its influence might be more pronounced on the behavioural willingness side than on the usefulness belief side, at least in the case of an innovation like biochar, where tangible support (such as subsidies and supply chains) is still only in early stages of development. We advise that extended TAM-2 models in agriculture consider carefully how contextual enablers are operationalised, as an available subsidy program may not necessarily make

biochar appear more productive, yet could help reduce the psychological barrier to experimentation.

## 5.2 Practical and Managerial Implications

Our results suggest practical guidance for policymakers, agricultural extension services, and firms aiming to promote biochar (or similar sustainable technologies) in the Northern Italian farming sector. PU showed the strongest association with intention in our models; therefore, interventions may be more effective if they convincingly communicate and, if possible, demonstrate biochar's benefits for farm performance. This means moving beyond abstract environmental rhetoric to concrete agronomic value. For example, messaging might emphasise how biochar can improve soil fertility, increase yield or quality, reduce input costs (like fertilisers or water), or generate new income streams. Field trials and pilot projects could be useful: enhancing RD in real local conditions may boost farmers' perceptions of usefulness (consistent with the direction of the RD → PU estimated in our data, though not design-powered). Extension programs might establish demonstration plots or "biochar showcase farms" where neighbours can observe yield improvements or resilience gains. Such tangible evidence can address scepticism noted in other contexts – as Fridahl et al. (2021) observed in Tanzania, carbon benefits alone did not motivate uptake; farmers needed to see direct on-farm advantages (Fridahl et al., 2021). Ensuring that early adopters experience and publicise positive outcomes can create a virtuous cycle: it will not only elevate perceived usefulness for others but eventually build normative pressure as well, making biochar appear a proven innovation rather than an experimental idea.

Economic incentives and support could be the second pillar of an adoption strategy, given the prominent role of PV in our findings: as managers of agricultural enterprises, farmers' decisions tend to be guided by considerations of economic viability. For a population with relatively low initial awareness, such as the one in our study, our findings suggest that promotional strategies might usefully prioritise communicating a clear and compelling price-value proposition to strengthen the perception of cost-benefit. One approach is to reduce costs through subsidies or cost-sharing programs for purchasing pyrolysis equipment, sourcing biochar materials, or applying biochar, which could enhance the perceived net value. Indeed, in exploratory specifications, higher perceived external support showed a positive association with intention to adopt. Offering low-interest loans or grants for on-farm biochar units (perhaps as part of climate-smart agriculture funding) could be effective. Another approach could be to increase the benefits by enabling farmers

to capture the multi-faceted value biochar can provide. This could involve developing markets and certifications for biochar and its co-products. For example, facilitating carbon credit opportunities for biochar usage (as now recognised under the EU Carbon Removal Certification Framework and emerging U.S.–Canada biochar protocols), which could translate climate mitigation into revenue for farmers, subject to program design and local conditions. If a farmer knows that applying biochar not only may boost yields but also earn them tradable carbon credits or qualify them for sustainability labels (and price premiums) on their products, the perceived economic payoff will rise. Our survey items for PV explicitly mentioned potential profits from selling biochar-related products (energy and carbon credits), and strong agreement with these items is associated with a higher PU. Thus, entrepreneurs and cooperatives in the biochar supply chain should work to integrate biochar into the circular economy in a way that rewards the farmer – whether through waste-to-biochar services (turning farm residues into biochar), revenue-sharing models, or certification schemes. The recent growth of the biochar market suggests opportunities here: Janaranjana and Bandara (2025) note that California’s policy support and biomass resources have spurred biochar adoption in the U.S., whereas elsewhere, the lack of market incentives has been a barrier. Policymakers may consider temporary incentive programs (similar to those for solar panels or biogas in the past) to kick-start a self-sustaining biochar market. In parallel, efforts to standardise biochar quality and application guidelines can reduce uncertainty for farmers and ensure that when they do invest in biochar, they get reliable results – thereby reinforcing the perception of “usefulness” and “value for money.”

Tailored communication and training also emerge as important implications. Because PEU showed a direct effect on intention, it may be important to ensure that farmers do not view biochar as overly complex or labour-intensive. Providing training opportunities and developing accessible, user-oriented materials on how to produce (or source) biochar, apply it to soil, determine optimal application rates, and implement safety measures could help address this perception. Agricultural extension services and local consortia can play a key role in disseminating this knowledge.

Notably, more than half of our respondents reported very limited prior awareness of biochar. Although the survey included a brief introductory explanation to mitigate this, in real-world contexts, such knowledge gaps may represent a barrier to adoption—farmers often appear hesitant to adopt practices they do not fully understand. Accordingly, efforts to strengthen awareness and technical literacy could represent an important enabling condition for a broader uptake. This could involve field days, workshops, and inclusion of biochar in agricultural curricula or certification programs for sustainable farming. The content should aim to demystify biochar (improving

perceived ease) and also connect it to farmers' existing practices (improving job relevance). For instance, showing how biochar can be integrated into manure management or combined with compost could make it feel more immediately relevant to livestock farmers or organic growers, respectively. If farmers perceive biochar as fitting naturally into their production system (high job relevance), they might find it more useful. Additionally, leveraging peer networks and progressive farmers as champions may help. Although in our study the SN was not yet a strong factor, farmers often trust information from other farmers. Identifying a few innovative local farmers to trial biochar and then share their experiences (through farm visits or testimonial videos) can indirectly build social normative momentum and reduce risk perception.

Finally, the finding that PEC is not significantly associated with PU yet shows a positive relationship with the willingness to adopt, which may highlight the practical importance of improving the visibility and accessibility of support measures. There may already be pilot subsidy schemes or EU grants for climate-friendly practices that include biochar, although farmers may not always be aware of these opportunities or may perceive them as administratively burdensome. Governments and agricultural agencies could usefully consider ways to increase the clarity and reach of any biochar-related incentives. For example, if a regional authority offers a rebate for soil amendments that sequester carbon, this information might be most effectively communicated through farmer associations, accompanied by clear, concise application guidance. Likewise, explicitly referencing biochar in climate action plans or soil health initiatives may help convey a sense of institutional endorsement. When farmers perceive that "the necessary external help is available," they are more confident to venture into a new practice.

On the flip side, the absence of a stable market or policy support, as noted by Italian researchers (Falconi et al., 2024), may contribute to uncertainty or hesitation. Pragmatically, therefore, fostering an enabling environment could be at least as important as persuading individual farmers. This might include developing supply chains (so farmers know where to buy quality biochar or how to produce it cooperatively), promoting awareness and understanding of existing certification frameworks, particularly the new EU CRCF Regulation (EU/2024/3012), and aligning biochar adoption with broader sustainability programs (so that adopting farmers can gain recognition or financial reward). In summary, to translate our findings into action: make biochar obviously beneficial, make it economically attractive, make it simple, and make it supported. By doing so, stakeholders could address the key levers of acceptance identified in our model. In effect,

promoting biochar should focus on “the tangible and the practical” – tangible benefits and practical feasibility – which our research shows are the decisive factors for farmers in this region.

### 5.3 Limitations and Future Research

While this study offers valuable insights, it is not without limitations. A first limitation is the cross-sectional nature of our data, which captured farmers’ perceptions at one point in time. Causal inferences must therefore be made with caution. Although our results align well with theory, longitudinal studies are needed to confirm the temporal ordering (for example, does an increase in PU over time lead to higher adoption rates?). Future research could track the same farmers over the coming years as biochar initiatives develop, to see how evolving experiences and information alter their acceptance predictors. A related point is that we measured intention to adopt rather than actual adoption behaviour. Intention is a strong predictor of behaviour in many models, but the two are not identical. Our findings assume that removing the identified attitudinal barriers would lead to adoption, but external realities (e.g., biochar availability, weather events, and farm financial shocks) will also influence actual uptake. Studies that observe real adoption decisions (perhaps in a pilot program where some farmers are given the opportunity to use biochar) would be a valuable next step to validate our extended TAM-2 framework in practice.

Second, the generalisability of our findings is constrained. Our study is an in-depth analysis of a specific group—Italian farmers with low prior awareness of biochar—in a particular socio-economic context. While findings cannot be generalised to other regions, we clarify that our study was designed to be agnostic to specific crops or farming systems, focusing instead on the foundational behavioural intentions toward biochar as a general concept. Nonetheless, the results are context-bound and require replication in other populations. We focus on agricultural entrepreneurs in Northern Italy, and while we achieved a decent sample size ( $n=131$ ) covering diverse farm types, this is not a very large sample. Some smaller effects might have gone undetected, partly due to limited statistical power. Our post-hoc power analysis suggested that detecting small path coefficients would require a larger sample (perhaps  $\sim 160$  for certain links). Future studies with more respondents could verify whether the non-significant factors in our model truly have no effect or were too subtle to discern here.

Third, our study is intentionally focused on the behavioural attitudes towards adoption and, as such, does not quantify the material sustainability impacts (e.g., carbon sequestration, nutrient cycling) that would result from this adoption. While we frame biochar as a sustainability innovation

by citing its quantified potential in the literature, our empirical analysis remains confined to the farmers' decision-making process. We acknowledge that a full picture requires integrating these behavioural insights with methodologies like life-cycle assessment and techno-economic analysis. Future research should use the findings from this study to inform more realistic and socio-technically grounded scenarios for such assessments. For example, the strong identified influence of Price Value could serve as a key parameter in techno-economic assessments and policy scenarios, and the findings could help create adoption projection curves that are behaviourally plausible, rather than purely technical.

Moreover, the Northern Italy context – with relatively high education levels among farmers, an EU policy backdrop, but low existing awareness of biochar – might differ from other countries. Cultural factors and farming systems vary; for instance, farmers in countries with strong cooperative extension services or in collectivist cultures might exhibit a greater role of social norms or external advice in adoption decisions. We encourage researchers to replicate our extended TAM-2 model in other regions (e.g. Eastern Europe, developing countries in Africa/Asia, or North America) to compare the determinants of biochar acceptance. As one example, Hounnou et al. (2024) studied cotton farmers in Benin and emphasised knowledge and perception as keys to biochar adoption – it would be interesting to see if the heavy weight of economic factors we found is universal or more pronounced in certain economic contexts. Comparative studies could also explore whether CCA plays a larger role in countries already experiencing severe climate impacts, or conversely, if in regions where economic margins are thinner, price value is an even stronger requisite.

Another limitation is our reliance on self-reported perceptions gathered via surveys, which can be subject to biases. Farmers might have provided socially desirable answers (e.g., overstating climate awareness) or may not have had a fully accurate foresight of how they'd behave in a real adoption scenario (intention-behaviour gap). We mitigated this by ensuring anonymity and clarifying that there were no right or wrong answers, but biases cannot be completely eliminated. Future research might incorporate more objective measures or experimental designs. For instance, an experimental game or choice experiment could present farmers with a realistic adoption scenario (with varying costs, benefits, and supports for biochar) to see how they choose – this could validate the importance of price value and other factors in a simulated decision-making environment.

Additionally, because our respondents generally had limited prior knowledge of biochar, their perceptions were partly based on the brief description we provided. Although this mirrors a real-world situation of first exposure, it means their PU and PEU judgments were somewhat

speculative. As farmers gain actual experience with biochar (even at small-scale trials), those perceptions may adjust. Research that includes an experience factor – either by surveying farmers who have already tried biochar, or by re-interviewing our sample after some have possibly experimented with it – would shed light on how the TAM dynamics evolve from pre-adoption to post-trial. According to Venkatesh and Davis (2000), experience can diminish reliance on social influence and refine ease-of-use perceptions; in our case, if some Italian farmers begin using biochar, one could test whether ease of use becomes less influential (because once they learn, it's no longer a question) and whether RD increases in impact (because they can now see results firsthand).

We also acknowledge that our model, while extended, is still not exhaustive. Together, our predictors explained approximately 35% of the variance in adoption intentions – a respectable figure, but leaving ample room for other influences. Future research should investigate additional factors that may enhance the explanatory power. One candidate is risk perception or uncertainty, which we did not include directly. Biochar adoption likely involves perceived risks (Will it work on my soil? Am I wasting money? Could it have negative side-effects?). Dai and Cheng (2022) found that risk perception moderated the TAM relationships for green farming technology, implying that a high perceived risk could weaken the effect of perceived benefits on adoption. Incorporating a risk construct could be insightful: perhaps farmers with greater risk aversion require an even higher price value or external assurance to intend adoption. Another set of factors relates to personal values and innovativeness. For instance, farmers with strong environmental ethics or a conservation identity might adopt biochar even if the short-term economic payoff is marginal – capturing such value-based motivations might require integrating elements of the Value-Belief-Norm theory or adding constructs like “environmental attitude” or “personal norm” (as Savari et al. 2023 did for pro-environmental behaviours). Likewise, individual innovativeness or openness to new technology could differentiate respondents: our model treats the sample as homogeneous in this regard, but in reality, “early adopters” might systematically weigh things differently (perhaps less constrained by price, more influenced by image or novelty). Segmenting the analysis by adopter categories or using a multi-group analysis for different farm types (e.g., small traditional farms vs. larger tech-oriented farms) could uncover nuanced differences in what drives adoption. A multi-group test comparing low-knowledge and higher-knowledge farmers revealed no structural path differences, indicating that our model is robust across varying awareness levels. However, as the overall knowledge baseline rises, new dynamics could emerge.

We did not conduct interviews or focus groups in this study. While added moderation and multigroup test checks and conservative interpretation reduce over-reach, qualitative work is needed to validate *how* social signals translate into PU/Intention (e.g., peer visibility, trust channels). Future mixed-methods designs should integrate cognitive interviews and farmer/extension focus groups.

Finally, considering the system-level context is important for future work. Our research took the perspective of individual decision-makers, yet the adoption of innovations like biochar often involves system and network factors. For example, the role of cooperatives, supply chain actors, and policy frameworks might be studied using approaches beyond individual behavioural models. A fruitful direction could be to integrate TAM with the Technology-Organisation-Environment (TOE) framework or diffusion of innovation theory to examine how organisational readiness or regional policy intensity interacts with farmer perceptions. We found that the lack of market and policy support in Italy is a perceived barrier; measuring those contextual variables (e.g., density of biochar suppliers in an area, presence of carbon farming pilot programs) and linking them to both perceptions and adoption rates could provide a more holistic understanding. In essence, bridging micro-level attitudes with macro-level conditions would help identify leverage points for scaling up adoption.

## 6. Conclusions

This study provides an initial, context-specific view of Northern Italian farmers' acceptance of biochar using an extended TAM-2 estimated via PLS-SEM. Across specifications, intention to adopt is positively associated with PU and PEU. In the extended model, the economic value proposition emerges as the most salient antecedent of PU, with additional positive links from OQ, RD, and CCA. By contrast, social-influence routes (SN, IM) remain weak in this early-diffusion, voluntary setting. The findings highlight the importance of a credible value proposition and straightforward implementation, while broader social endorsement may become more relevant as visibility increases.

## 7. Declarations

Ethics declaration. This study did not involve any interventions, human trials, or the collection of any sensitive personal data. All data has been collected anonymously.

Informed consent was obtained from all individual participants included in the study.

All participants have consented to the submission and publication of anonymised data.

Competing interests. The authors declare no competing interests.

Data Availability. The de-identified survey dataset is available from the authors upon reasonable request for research purposes. Access will be granted under a data-use agreement that preserves respondent confidentiality and complies with applicable data-protection regulations. Please contact the corresponding author for further inquiries.

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## Transparency statement

In the preparation of this manuscript, the authors used OpenAI's ChatGPT to assist with drafting, language refinement, and revision. The use of ChatGPT was limited to improving clarity, grammar, and readability. All conceptual content, analysis, and interpretations were developed independently by the authors. AI-generated suggestions were critically reviewed and validated to ensure accuracy, coherence, and academic integrity.

## Declaration of Interest Statement

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.

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