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Leveraging blockchain for ecosystem service transparency: enhancing consumer value and sustainability in the beef industry

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Abstract

Blockchain technology has the potential to enhance transparency and traceability in the agrifood sector, particularly in the beef industry. However, its adoption remains limited in many regions, including Europe. This study investigates the role of ecosystem services in sustainable beef production, highlighting the value these services bring not only to the environment but also to the industry and consumers. By using QR codes linked to blockchain-based traceability systems, consumers can access detailed information about the environmental benefits of extensive livestock farming, such as carbon sequestration, biodiversity preservation, and soil health improvement. Based on a representative sample of 1158 Spanish consumers, our study shows that providing ecosystem service information through QR codes significantly increases consumers' willingness to pay a premium for beef products. This finding highlights the growing consumer demand for transparency and sustainability in food systems. The integration of information on ecosystem services into product labeling, facilitated by blockchain and QR codes, presents an opportunity for the beef industry to differentiate itself in a competitive market while promoting more sustainable consumption patterns. This study contributes to the food industry by showing how blockchain-enabled transparency regarding ecosystem services can reshape consumer behavior, thus driving both environmental and economic benefits.

Keywords: QR codes, Beef sustainability, Ecosystem services, Blockchain technology, Food supply chain, Consumer preferences, Traceability systems

Introduction

The sustainability of beef production has become a pressing issue in debates on agrifood systems, as evidenced by a body of literature on this topic that started growing in 2020, with continued interest up to the present (Giganti et al. 2024). The considerable environmental footprint of beef production, which is linked to greenhouse gas emissions, the intensive use of natural resources, and biodiversity loss, has attracted rising criticism (Gerber et al. 2015; Springmann et al. 2016). However, several scholars have emphasized that certain extensive systems, such as those operating in Mediterranean *dehesas* or mountain areas in Spain, not only produce food but also provide key ecosystem services (ES), including carbon sequestration, wildfire prevention, biodiversity conservation, and landscape maintenance (Moreno 2019; Dumont et al. 2019; Manzano and White 2019). In Spain, these systems occupy ecologically valuable areas, many of which are part of the Natura 2000 network, and they play a crucial role in the environmental and socioeconomic sustainability of rural regions (Casasús Pueyo 2023).

ES are defined as "the benefits people obtain from ecosystems" (MEA 2005). These services arise from the positive value that social actors attribute to specific functions or structures in ecosystems, and they are categorized into four types: provisioning, supporting, regulating, and cultural services (MEA 2005). Provisioning services include essential goods (e.g., food, fiber, and medicinal products), while supporting services encompass ecological processes, such as primary production and nutrient cycling, which are directly linked to biodiversity. Regulating services involve carbon sequestration, soil erosion prevention, and natural flood control, whereas cultural services refer to intellectual, inspirational, or recreational activities (Sala et al. 2017). According to Madau et al. (2022), landscape and cultural services are the most highly valued by society, and appreciation of one type of service often implies recognition of other associated services.

Consumers' willingness to pay for ES is critical for supporting the sustainability of extensive beef production systems. Recent research (Contini et al. 2023; Tran et al. 2024) shows that consumers value products associated with environmental and social benefits, yet the ES that create these remain largely invisible or undervalued in the marketplace. This lack of consumer recognition is mainly due to the absence of transparent information about the contributions of extensive livestock production to ecosystem preservation and rural development. Obeng and Aguilar (2018) demonstrated that contextual attributes significantly influence consumer behavior, with specific groups purchasing pasture-raised products in particular places; however, overall familiarity and knowledge of noncommercial ES and payments for environmental services remain low in urban and rural populations. Still, attitudes toward payments for ES tend to be moderately positive and motivated by self-benefit, community benefit, or environmental reasons.

The challenge of conveying accurate yet simple environmental information to consumers has been noted (Stampa et al. 2020). This emphasizes the need for environmental education to improve the public's understanding of the benefits of agro-livestock programs for ES. Doing so could foster pro-environmental behaviors and enhance people's willingness to pay for such programs, even among geographically distant consumers. For example, Duncan (2014) documented UK consumers' positive willingness to pay despite limited information, provided payment incentives were properly designed. Aguilar et al. (2018) highlighted environmental attitudes as key drivers of willingness to pay for ecosystem service initiatives aimed at water-related functions. Furthermore, Cubero Dudinskaya et al. (2021) reported substantial variation in red meat consumer preferences across Europe, but national origin and ecological labels were consistently valued. Regarding climate change, the link between it and consumer behavior is complex, with consumers struggling to identify impactful actions (Thøgersen 2021). However, European meat consumers show a willingness to pay premiums of up to 12% for products with reduced carbon footprints (Broeckhoven et al. 2021). This evidence suggests that integrating transparent information on the environment and ecosystem service benefits into food labeling could positively influence purchase decisions and promote more sustainable consumption patterns.

Consumers often lack awareness or understanding of the ES provided by extensive beef production systems, leading to their limited recognition in the market. This gap is largely due to the lack of transparency and traceability along the food supply chain (Herrera 2020; Rodríguez-Ortega et al. 2019). This information asymmetry prevents consumers from adequately identifying and valuing products from farms that deliver ES, which weakens their competitiveness compared to more intensive systems. Scholars have highlighted that the high consumption of red meat—particularly from conventional systems—has significant environmental impacts, including higher greenhouse gas emissions and intensive use of land and water (Willet et al. 2019; Springmann 2024). For this reason, several experts have proposed shifting toward diets with a greater share of plant-based proteins (Godfray et al. 2018; Drewnowski and Conrad 2024; Springmann 2024). However, sustainability varies not only among plant-based foods (Reckling et al. 2016; Parlasca and Qaim 2022), but also across different beef production systems, such as extensive livestock farms (Moreno 2019; Manzano and White 2019). Therefore, improving food labeling and the information available to customers is essential. This will ensure that consumers can make more informed choices and producers who employ more sustainable practices are not disadvantaged.

Blockchain technology has emerged as a promising tool to enhance food traceability, as it offers a decentralized, transparent, and immutable system of data recording throughout the supply chain (Stallone et al. 2021; Domínguez and Roseiro 2020). In the agrifood sector, its application enables the reliable registration of attributes, such as animal origin, management practices, feeding systems, and associated ecosystem benefits, all of which are made accessible to consumers via QR code labels. These smart labels may include data on rotational grazing, the absence of antibiotics, positive biodiversity impacts, or the product's carbon footprint. According to Bandinelli et al. (2023), the use of blockchain can strengthen trust in a product's credibility attributes, but it requires effective communication strategies to avoid increasing the perceived complexity of decision-making for consumers.

According to several studies, blockchain-based traceability enhances consumers' trust and increases their willingness to pay for products with differentiated attributes (Zhang et al. 2022; Dos Santos et al. 2021). However, its acceptance depends on subjective factors, especially perceived usefulness (PU) and ease of use, which are concepts drawn from the technology acceptance model (TAM) (Kim and Woo 2016). It has been shown that acceptance of QR code labeling depends on the cultural context and the perceived value of the information provided. The quality, clarity, and relevance of the data are critical for consumers to recognize its usefulness.

In Spain, empirical evidence regarding the acceptance of traceability technologies in the meat sector reveals notable heterogeneity. While earlier studies (Angulo & Gil, 2007; Mesías et al. 2005) showed low willingness to pay for traceability, more recent research (Eldesouky et al. 2020; García-Torres et al. 2016) points to a growing appreciation for labels associated with organic agriculture, animal welfare, and local origin. Other scholars have confirmed that attributes, such as circular production (Ornelas Herrera et al. 2024), low carbon footprints (Lami et al. 2022), and ES (e.g., wildfire prevention; Lecegui et al. 2023) are well received by specific consumer segments. Lombardi et al. (2017) emphasized the importance of ensuring that the content provided is perceived as relevant, accessible, and trustworthy, as these qualities are essential for effective product differentiation based on informational transparency. This evidence reinforces the need for efficient communication tools.

Despite growing recognition of the environmental benefits of extensive beef production systems, these benefits remain undervalued in the market due to limited traceability and consumer awareness. While blockchain has the potential to enhance transparency and communicate ES, little is known about its acceptance among Spanish consumers. Moreover, the use of the TAM to evaluate the consumer response to blockchain-based traceability in the context of sustainable beef production remains underexplored.

Despite the growing interest in sustainable food systems, we have little information regarding how consumers perceive and respond to blockchain-enabled traceability when applied to extensive beef production. While scholars have explored willingness to pay for sustainability attributes in meat products, some authors have pointed out that more research needs to be done to understand how technological factors influence consumer decision-making (Vu et al. 2021; Shahzad et al. 2024). This study fills this gap by using the TAM to examine how the PU and ease of use of blockchain-based traceability impact consumer trust and willingness to pay for extensively produced beef products. By linking food transparency, digital innovation, and sustainability communication, we provide novel insights into how blockchain can enhance market differentiation for extensive livestock systems. Our findings inform both policymakers and industry stakeholders on the role of traceability systems as a strategic tool for promoting environmentally responsible meat consumption.

Given the above, this study contributes to the literature by addressing a gap identified in recent reviews (e.g., Giganti et al. 2024): the lack of empirical evidence on how blockchain technologies can be used to communicate ES to consumers. While blockchain's potential for enhancing sustainability has been acknowledged, few scholars have examined this potential using large-scale consumer data. Based on a nationally representative sample from Spain, our study is one of the first empirical analyses in Europe of how blockchain-enabled QR codes can make ES visible to consumers and influence their willingness to pay (WTP), thus supporting environmental goals and food system transitions.

Literature review and hypothesis development

Sustainability and ES regarding beef sourced from extensive livestock farms

Traditionally, livestock sustainability has been assessed from an environmental perspective, focusing on emissions, water use, or soil erosion. However, a more integrative approach considers ES as a framework for analysis, and it includes the provision of food; regulation of soil, air, and water quality; carbon sequestration; and cultural services (Pogue et al. 2018). Godfray et al. (2018) provided a comprehensive view of the effects of meat consumption, emphasizing its link to chronic diseases and significant environmental pressures, such as greenhouse gas emissions, pollution, and biodiversity loss. Parlasca and Qaim (2022) expanded on this by highlighting the heterogeneity of livestock systems and their socioeconomic contexts, arguing that while meat consumption should be reduced in high-income countries, livestock farming in other regions can represent a vital source of nutrition, employment, and territorial resilience. In particular, they stressed that well-managed extensive systems can deliver relevant environmental and social benefits.

Extensive livestock farming is characterized by the use of local forage resources through grazing, the reliance on breeds adapted to environmental conditions, and the minimization of the use of external inputs, such as feed and energy (Herrera 2020). This practice transforms inedible biomass from uncultivated lands into high-value products, such as meat, milk, and wool, thus contributing to local economies and ecological sustainability. In some cases, this production model involves grazing for both breeding and fattening, either by relying entirely on pastures or by combining the latter with feedlots (Greenwood 2021). In Spain, 89% of suckler cow production is concentrated in *dehesa* areas, the Cantabrian Mountains, and the Pyrenees—regions that host the majority of extensive livestock farms (MAPA 2025). This form of farming typically takes place on land unsuitable for agriculture due to poor soil quality, geographical challenges, or extreme climate (Manzano & White 2019), as described for other countries (Van Zanten et al. 2016; Schader et al. 2015). In Spain, these areas coincide largely with *dehesa* landscapes and mountainous zones, which cover vast portions of the EU's Natura 2000 network for biodiversity protection (Casasús Pueyo 2023; Bernués Jal 2023).

Extensive livestock systems usually rely mainly on green water—rainwater stored in soil or plants—which helps reduce pressure on scarcer water resources, such as groundwater and surface water (Gerbens-Leenes et al. 2013). When pastures are well managed, their water retention capacity can also improve (Machmuller et al. 2015), which is especially important in a country, such as Spain, which has irregular rainfall patterns. Extensive livestock farming also supports biodiversity and helps conserve multifunctional landscapes, such as *dehesas*, which are essential habitats for emblematic species, such as the Iberian lynx (Pulido et al.. 2014). Additionally, it contributes to preventing forest fires by controlling shrub encroachment and regenerating soil through the continuous interaction between grazing and vegetation (Fernández-Lugo 2014; Manzano-Baena and Salguero-Herrera 2018) as well as through carbon sequestration (Martínez et al. 2012; Ministerio para la Transición Ecológica y el Reto Demográfico 2022; Escribano et al. 2024; Schils et al. 2022). In *dehesas* managed with rotational grazing, the maintenance of a balance between trees and pastures can reduce greenhouse gas emissions per unit of product (Reyes-Palomo et al. 2022). In one study, the average carbon sequestration rate of *dehesa* systems was 1.36–5.09 t CO_2eq ha^{-1}·$year^{-1}$, depending on soil type, vegetation cover, and pasture management, which led to negative net emissions in some cases (Reyes-Palomo et al. 2022). Extensive livestock farming also helps retain population in rural areas, promotes local economic development, enables the production of healthy food that is compatible with animal welfare standards, and preserves traditional cultural practices (Díaz-Gaona 2013; Zabalza et al. 2021).

In contrast, the abandonment of grazing causes landscape homogenization, which contributes to biodiversity loss and the reduction of the water available for human consumption. Also, the expansion of fire-prone plant communities increases the risk and virulence of forest fires, especially in the Mediterranean (Rodríguez-Ortega et al. 2019; Varela et al. 2020).

If sustainability is an aspect of meat that is considered by the customer (Eldesouky et al. 2020), it is important to enable customers to consciously choose high-quality beef that can offer ES. To achieve this, it is crucial to distinguish extensive livestock products in the market to enable consumers to make informed purchases. By raising consumer awareness and promoting informed choices, extensive livestock farmers can improve the economic viability of their farms and better address the challenges presented by climate change. As stated by Parlasca and Qaim (2022), sustainable meat consumption strategies can be effective only when consumers are informed and incentivized to make environmentally responsible choices. The implementation of animal welfare standards and extensive production certification creates the opportunity to access the market segment of customers willing to pay more for foods that respect the environment, have low (or neutral) emissions, and promote ES (Herrera 2020).

Food traceability systems and QR codes

Opara and Mazaud (2016, p. 243) described traceability as "the collection, documentation, maintenance, and application of information related to all processes in the supply chain in a way that assures the consumer of the origin and life history of a product."

Food supply chain traceability builds a kind of information chain that provides feedback on food safety, food processing, food sales, customer information, etc. (Karlsen et al. 2013). Several scholars have demonstrated consumers' preferences and willingness to pay for mandatory and voluntary labeling programs associated with credibility attributes regarding traceability guarantees and beef origin evidence (Alfnes 2004; Alfnes and Rickertsen 2003; Dickinson et al. 2005). In many cases, these programs are a result of consumers' increased concerns (Tsakiridis et al. 2021).

Technological development has significantly improved the current value of traceability (Badia-Melis et al. 2015). There are many types of traceability systems. One is QR codes, which allow stakeholders to quickly and easily track food products and detect problems with them, as well as drastically reduce human errors, as manual operations are not necessary (Karlsen et al. 2013). Moreover, QR codes are readable even in small formats or with some physical damage, and they can be read with common devices (Tarjan et al. 2014). Furthermore, Tran et al. (2024) have found that blockchain-based QR codes improve consumer understanding of and trust in product authenticity, leading to stronger purchasing intentions. Finally, Contini et al. (2023) have demonstrated that blockchain technology enhances consumer preferences for credence attributes, thus reinforcing sustainability and transparency in food systems.

Willingness to pay more for traceability information via QR codes

The TAM is derived from earlier models proposed by Ajzen and Fishbein (1980), and it was developed to explain the factors that determine users' acceptance of a technology (Davis 1989; Davis et al. 1989). Technology acceptance refers to a person's willingness to employ a technology for the tasks for which it is designed (Byun et al. 2018)—in our case, the use of QR codes to access beef traceability information. The model presented below draws on this theoretical framework and includes new variables that are relevant to beef consumption, such as previous consumption experience.

On the one hand, the perceived information provided through QR codes, especially when supported by blockchain technology, enhances the consumer's perception of product credibility and safety. Scholars have shown that when customers receive detailed and reliable information, their perceptions of the product's usefulness become stronger (Chen and Huang 2013). This relationship is particularly significant in food traceability contexts, where consumers cannot directly verify product quality and safety. Blockchain-based QR codes offer verifiable data regarding the production process and environmental impact of an item, thus strengthening customers' perceptions of its value (Bandinelli et al. 2023). Therefore, we propose the following hypothesis (H):

H1: Perceived information through the QR codes (PI) positively affects perceived usefulness of the QR codes (PU)

On the other hand, according to the TAM, ease of use directly impacts PU (Davis 1989). In the context of blockchain-based QR codes, consumers are more likely to perceive these tools as useful if they are easy to navigate and understand (Shin et al. 2012). Recent empirical studies in the agrifood sector have shown that user-friendly blockchain interfaces lead to greater consumer confidence and perceived benefit (Bandinelli et al. 2023). Similarly, PI has a direct and positive influence on PU. This relationship has been tested in food traceability contexts (Chen and Huang 2013). Therefore, ease of use is added to the TAM as an antecedent of PU as follows:

H2: Perceived ease of use (PEOU) positively affects PU.

PU is one of the strongest predictors of attitudes toward technology adoption (Venkatesh and Davis 2000). In the food sector, consumers who perceive that QR codes provide valuable information on safety, sustainability, and product origin are more likely to develop positive attitudes toward their use (Lombardi et al. 2017). Hence, we hypothesize the following:

H3: PU positively affects attitude toward use (ATT).

In the technological context at hand, consumers are more inclined to adopt technologies that they find effortless to use (Davis 1989). The possibility of scanning QR codes and receiving comprehensive traceability data without technical difficulties improves customers' attitudes toward these tools (Bandinelli et al. 2023). Therefore, we propose the following:

H4: PEOU positively affects ATT.

In addition, and according to the TAM, a positive attitude toward a technology influences the behavioral intention to use it (Venkatesh and Davis 2000). In food traceability studies, consumers with favorable attitudes toward QR codes have been shown to possess stronger intentions to use them for obtaining product information (Lombardi et al. 2017). Thus, we hypothesize the following:

H5: ATT positively affects intention to use the QR codes (BI).

Furthermore, we must consider the impact of BI on WTP. The behavioral intention to use a traceability system directly translates into the willingness to pay for products with enhanced traceability (Obeng and Aguilar 2018). Consumers value transparency and are willing to pay premium prices for products that assure safety, sustainability, and environmental responsibility through reliable traceability systems (Broeckhoven et al. 2021). Hence, we propose the following:

H6: BI positively affects WTP_QR.

Finally, as previously mentioned, the consumer experience (CEXP) variable is included as a moderator in the relationship between ATT and BI. According to Park et al. (1994), consumer experience can be understood as the information regarding consumption that is stored in customers' memories when they consume or evaluate consumption behavior; this information can affect their judgment and capacity to think (Swaminathan 2003). Consumer choice and decision-making vary as a function of consumer knowledge, and greater consumer knowledge leads to higher-quality decision-making (Swaminathan 2003). Customers with prior knowledge or usage experiences of traceability systems are more likely to translate favorable attitudes into concrete intentions and rely on these technologies (Yuan et al. 2020). Therefore, we hypothesize the following:

H7: CEXP moderates the relationship between ATT and BI.

Moreover, the results obtained by Chung et al. (2010) and Sun and Zhang (2006) indicate the robustness of the pathways from PEOU to PU and from PU to BI. Additionally, the model includes external factors and antecedents that affect the two key variables PEOU and PU (Chung et al. 2010). Thus, in subsequent works, another important component in innovative technology contexts has been shown to be PI and its relationship with consumers' intention to use a new system (Amoako-Gyampah 2007). This is derived from credibility as it provides extra information, and it is especially important in the case of food products in contexts where consumers cannot accurately assess product safety. Traceability systems are highly informative and are considered valuable for consumers' purchasing decisions (Mora and Menozzi 2008). In this sense, a higher degree of information regarding meat can give a higher degree of perceived benefit from the technology (Polyorat and Buaprommee 2016) (Fig. 1).

Methodology

Questionnaire and sample design

A questionnaire was prepared to investigate certain sociodemographic (and meat-product consumption) aspects and the variables in the model described above; as far as possible, already tested scales were used (see Table 1). All the scales (except those pertaining to the sociodemographic and meat consumption concepts and the willingness to pay more) were measured with 5-point Likert-type scales. We conducted a pretest with individuals who were regular meat consumers and who had different sociodemographic characteristics to represent diverse consumer profiles, thus ensuring the validity and reliability of the pretest. This process allowed us to correct possible errors and biases, and it led to a reduction in the number of items initially proposed, which resulted in the final questionnaire. After initial validation, the data was collected through an online survey using the contracted panel services of Qualtrics. The sample consisted of 1,558 consumers from mainland Spain; it ensured broad regional coverage, but it excluded the Balearic Islands, Canary Islands, Ceuta, and Melilla due to their distinct market conditions. To ensure sample representativeness, quotas based on age distribution were applied, with some flexibility during data collection. Additionally, only respondents who reported consuming meat either at home or outside the home were included. A detailed breakdown of the sample's regional representation is available in the Appendix. The data was collected over 1 month (July 2021). Of the 1158 participants, 584 were women (50.40%), and 574 were men. The majority of the respondents (75.5%) were aged between 30 and 64 years; 21.3% were under 30, and 3.2% were over 65. Most of the respondents (69.2%) reported living in households with a monthly income between 2000 and 3000 euros, and in 61.1% of

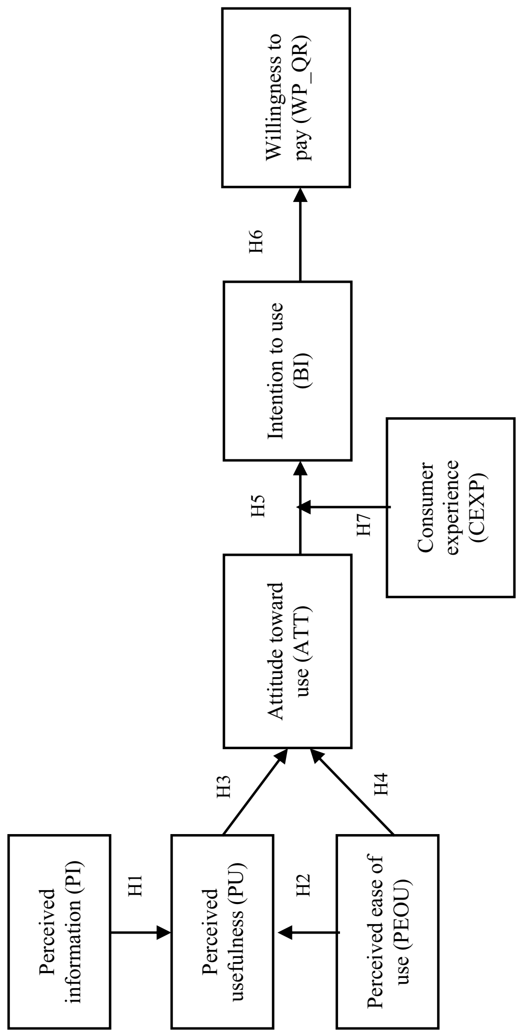

Fig. 1 Proposed model and hypotheses. Source: own elaboration

Table 1 Items used in the questionnaire

Construct	Items	References
Perceived information through the QR codes (PI)	QR_PI1: The QR code for the food traceability system provides a lot of detailed information about the food QR_PI2: The QR code for the food traceability system provides a lot of information that helps me in my decision	Kim and Woo (2016)
Perceived usefulness of the QR codes (PU)	QR_PU1: For me, the QR code for the food traceability system has great value QR_PU2: Using the QR code for the food traceability system saves me a lot of time	
Perceived ease of use of the QR codes (PEOU)	QR_PEOU1: The QR code for the food traceability system is easy to use QR_PEOU2: The QR code for the food traceability system is easy to understand	
Attitude toward use (ATT)	QR_ATT1: I find the QR code for the food traceability system positive QR_ATT2: The use of the QR code for the food traceability system is a good idea QR_ATT3: It makes sense to use QR code for the food traceability system	
Intention to use the QR codes (BI)	QR_BI1: I will use the QR code for the food traceability system in the future QR_BI2: I will recommend using the QR code for the food traceability system to my friends	
Willingness to pay (WP_QR)	What additional percentage would you be willing to pay for the product?	Own elaboration
Consumer experience (CEXP)	CEXP1: I know and understand the regulations concerning food traceability CEXP2: I have experience of purchasing food with traceability information	Yuan et al. (2020)

Source: own elaboration

cases, all household members were employed. More than 600 of the participants had a higher education degree (bachelor's degree, diploma, or graduate degree), while 362 had attended only compulsory secondary education. Regarding purchasing behavior, in 92.61% of the households, all the members consumed beef (See Table 5, Appendix).

To assess the impact of blockchain-based traceability on consumer WTP, we conducted a between-subjects experiment with random assignment. The participants were divided into two conditions: (1) a control group, who viewed a tray of beef fillets without a QR code, and (2) a treatment group, who viewed an identical tray but with a QR code linking to blockchain-based traceability information on sustainable farming practices and ES. Prior to exposure, all the participants in the treatment group were shown a standardized explanation specifying that the QR code was linked to a blockchain-based traceability platform that provided detailed and verified information on the product's origin, production practices, and environmental certifications. An illustrative example of the traceability sheet (see Figure A1) was also presented to visually convey the type of data accessible through the QR code. This design ensured that any differences in WTP were attributable solely to the presence of the QR code, while random assignment minimized potential bias. The information contained in the QR code is available in Figure 3 of the Appendix.

Blockchain description

In this study, processes, materials, and resources were used for the implementation of a blockchain network designed to increase the intrinsic value of meat products sourced from farms, as part of the framework of the SOSTVAN operational group, which has been financed by the National Rural Development Program of the Ministry of Agriculture, Fisheries and Food in Spain and the European Agricultural Fund for Rural Development. This network was achieved by enhancing the information regarding the traceability and origin of the product. The blockchain network allowed for the control of feeding, prophylaxis, and animal welfare during the cows stays at the various entities belonging to the project. The cryptography methods used for data encryption on the blockchain network maintained the system integrity and provided the necessary confidentiality for the data; they also allowed its accessibility to authorized third parties.

The blockchain network was based on the Ethereum system with the client Hyperledger Besu. Among other advantages, Besu allows the creation of chains of authorized blocks in such a way that only certain nodes can participate in the network, which restricts its use to selected accounts. Only authorized nodes and users can access the network, and third parties are not allowed to access the restricted transactions.

The data stored in the blockchain consisted of various indicators that provided information about the traceability and environmental sustainability of the beef. These indicators varied depending on the specific link of the beef supply chain under consideration. At the farm level, the stored data included information about the farm's carbon footprint, landscape quality, habitat diversity, tree status, sustainable pastoralism practices, emissions, and carbon sequestration. Regarding feed, the system held information about its composition, carbon footprint, and any existing quality certification. For each individual animal, details such as ID number, birth date, birth weight, race, gender, farm of origin, lactation data, medical treatments received, animal welfare data, and information about the slaughterhouse (sacrifice date, carcass weight, rating, halal status, etc.) were stored (Fig. 2).

To ensure the complete traceability of the animals and the feed included in the platform, it was necessary to track each step, from the time of transfer to slaughter Entities that were registered as approved slaughterhouses were tasked with notifying the platform when they received a group of animals. At this point, the platform logged the animals' movement and arrival at the slaughterhouse; then, the entity invoked the platform's API. This allowed the entity managing this process to generate a QR code that identified the final product the customer would receive at the points of sale and distribution. By scanning the QR code, the customer obtained access to an online traceability portal containing the gathered information.

In our questionnaire, the participants were shown a QR code as an image, which, when clicked, provided access to blockchain-verified information about the origin of the beef and the ES provided by the relevant farm.

Results

Analysis of the underlying structures of the proposed concepts

To check whether the concepts in the proposed theoretical model were unidimensional, an exploratory factor analysis of the principal components with Varimax rotation was performed, selecting those with eigenvalues greater than 1 (Hair et al. 2004) (Table 2). All the constructs were found to be unidimensional, as only one factor was extracted from the scales. In all the cases, the variance extracted was greater than 50%, which meant that acceptable values were reached. Regarding the reliability of the constructs, which was measured by Cronbach's alpha, all the constructs exceeded the threshold established in the literature (0.7) (Cronbach 1970; Nunnally and Bernstein 1978), the lowest result being 0.713 (PI construct).

- Content validity: This was validated by using scales already tested and contrasted in previous studies and by reviewing the literature.
- Convergent validity: This was verified based on the following three criteria used in the literature: (1) the variance extracted from the constructs exceeds 50% (Fornell and Larcker 1981), (2) the factor loadings are greater than 0.5 (Steenkamp and Geyskens 2006), and (3) the composite reliability is greater than 0.8 (Nunnally and Bernstein 1978). The fulfillment of these criteria showed that there was convergent validity in all the cases.
- Discriminant validity: The correlation between pairs of constructs was found to be less than 0.8 (Bagozzi and Yi 2012). Only the correlation between ATT and BI slightly exceeded this value, but the wording of the items reflected that these two concepts were different. In addition, the square root of the variance extracted from each construct was higher than the correlations between this construct and any other construct, according to Real et al. (2006). Hence, there was discriminant validity in all the constructs.

Contrast of the hypotheses proposed in the model

Once the underlying structures proposed in the model were obtained, a series of linear regressions were performed, the results of which are summarized in Table 3. All the hypotheses were supported by very good R^2 percentages, especially considering that this is a descriptive and exploratory study, without a predictive purpose (except in the case of H6, which had an R^2 of 10.1%). Thus, PU (H1; $R^2 = 53.9\%$; $p < 0.000$) was explained

Table 2 Variance extracted, Cronbach's alpha, and composite reliability

Factor	KMO	Variance extracted (%)	Root variance extracted	Cronbach's alpha	Composite reliability
PI	0.500	78.241	0.8845	0.713	0.878
PEOU	0.500	82.367	0.9075	0.786	0.903
PU	0.500	80.888	0.8994	0.761	0.894
ATT	0.738	78.807	0.8877	0.866	0.917
BI	0.500	85.137	0.9227	0.825	0.920
CEXP	0.500	81.759	0.9042	0.777	0.899

Source: own elaboration

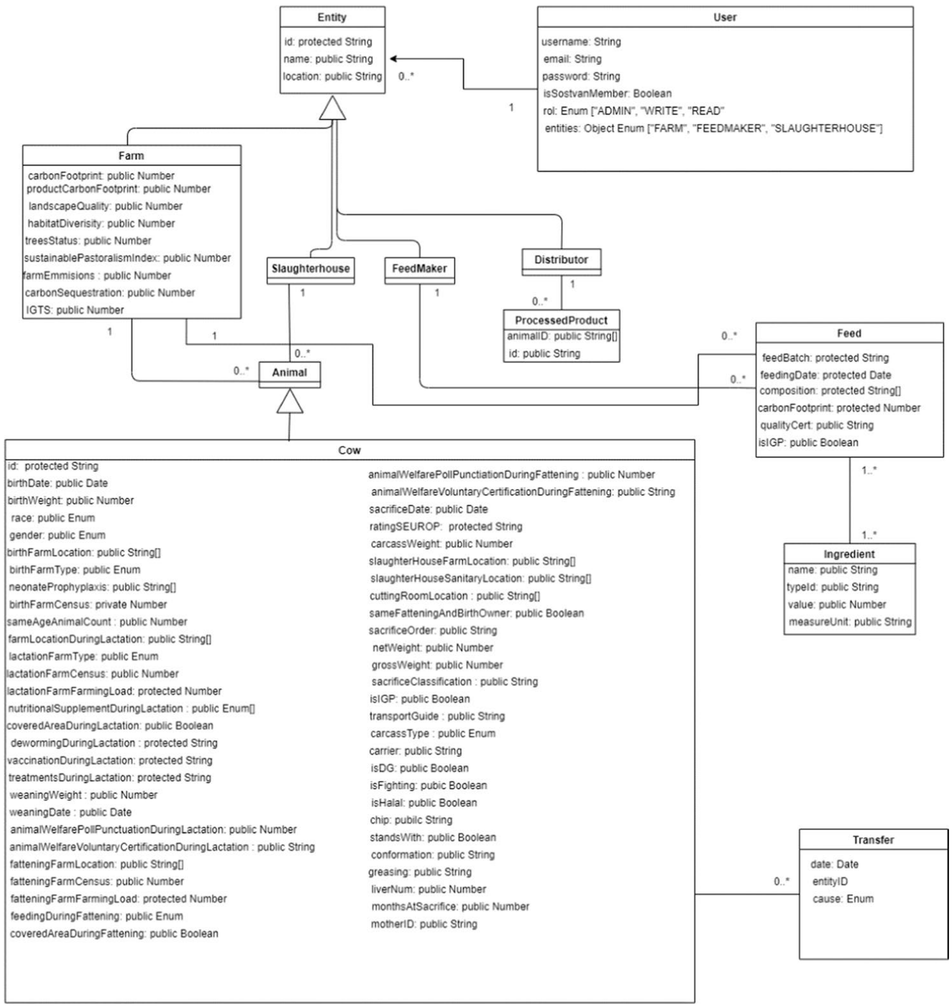

Fig. 2 Data stored in the blockchain. Source: own elaboration

by PI ($\beta = 0.734$; $p < 0.000$). PU was also explained by PEOU (H2; $R^2 = 45\%$; $p < 0.000$). H3, which tried to explain ATT through PU, was also supported ($R^2 = 54.2\%$; $p < 0.000$). Likewise, PEOU was an explanatory factor for ATT, which supported H4 ($R^2 = 59.4\%$; $p < 0.000$). ATT was an antecedent of BI, and it explained its variability by 64.9% ($p < 0.000$); thus, H5 was also supported. BI explained WTP, but at a lower percentage (10.1%). Finally, regarding H7, which pertained to the moderating effect of CEXP, it was found that this variable influenced the relationship between ATT and BI. This means that the greater the consumer's experience with traceable products, the greater their intention to use QR codes to obtain traceability information. Therefore, H7 was also supported.

Table 3 Contrast of the hypotheses proposed in the model

	Independent variable	Dependent variable	Standardized beta (sig.)	Adjusted R^2 (sig.)
H1	Perceived information	Perceived usefulness	0.734***	53.9%***
H2	Perceived ease of use	Perceived usefulness	0.671***	45%***
H3	Perceived usefulness	Attitude toward use	0.736***	54.2%***
H4	Perceived ease of use	Attitude toward use	0.771***	59.4%***
H5	Attitude toward use	Intention to use	0.806***	64.9%***
H6	Intention to use	Willingness to pay (QR)	0.319***	10.1%***
H7	Attitude toward use	Intention to use	0.767***	66.1%***
	Consumer experience		0.114***	
	Attitude toward use × consumer experience		0.026+	

***=99.9; **=99.0; *=95; + =90

Discussion, conclusions, and future research avenues

The aim of this study was to assess consumer responses to QR code labels linked to a blockchain-based traceability system that provided information on beef characteristics and the ES associated with the animals' breeding processes. The study employed the TAM to analyze how consumers' perceptions of the usefulness and ease of use of the QR codes, as well as their attitudes toward blockchain-based traceability, influenced their willingness to pay for beef products with such information. By providing consumers with information about how their food is produced, the system analyzed here has the potential to influence purchasing behaviors, encourage sustainability, and contribute to changes in the market for extensive livestock products. This aligns with the broader vision of the EAT-Lancet Commission, which emphasized the need for dietary patterns that support both human and planetary health (Willett et al. 2019).

Our findings show that the extended TAM offers a good fit for understanding consumer behavior in the context of blockchain-enabled traceability in the beef sector. Specifically, PU was found to be significantly influenced by the ease of use of the QR code technology and the information it provided. Given that 99.5% of Spanish households have a cell phone with an internet connection (ONTSI 2022), it is reasonable to assume that many consumers are capable of accessing QR code information. However, it is important to note that while most consumers own mobile phones, further research is needed to determine the extent to which QR codes are used at the point of sale in supermarkets or food retailers. This is necessary to avoid the assumption that QR code usage is ubiquitous at all stages of the shopping process.

The results also align with previous research (Rese et al. 2014; Kim and Woo 2016) as they show that PU positively impacted the consumers' attitudes, which, in turn, influenced their intention to use the QR technology. This suggests that Spanish consumers are aware of the potential benefits of traceability and place value on using QR codes for verification, which enhances their purchasing intentions. More importantly, this study explored the link between BI and WTP, confirming that consumers are willing to pay a premium for beef products with traceability information, particularly when blockchain technology ensures the credibility and transparency of this information. This finding is consistent with research by Zheng et al. (2012) and Wang et al.

(2009), but it challenges earlier studies (Angulo et al. 2008; Calvo Dopico et al. 2016) that did not find such a strong relationship between traceability and consumers' WTP.

The implementation of blockchain traceability systems in beef labeling has the potential to enhance consumer trust by providing encrypted information on factors, such as biodiversity protection, carbon sequestration, and the maintenance of natural landscapes on farms. However, we must consider the broader implications of these systems for the beef supply chain. While traceability systems provide clear benefits for consumers, they may also pose challenges for producers in terms of costs, logistics, and compliance with regulations. For instance, producers may need to invest in the technology, certification, and maintenance of traceability systems, which could be a barrier for small-scale farms. However, the transparency offered by blockchain could lead to increased consumer trust and market access, thus potentially compensating for these costs in the long run.

Regarding environmental impacts, it is essential to emphasize that the potential of blockchain traceability to provide information on ES such as carbon sequestration and biodiversity preservation could play a significant role in promoting sustainability in the beef industry. The increased visibility of these services may satisfy consumer demand for sustainably produced products and encourage more environmentally conscious production practices. However, the extent to which blockchain-based traceability systems can be adopted on a large scale across the beef industry remains to be seen. It is crucial to further investigate how these systems could be scaled up and whether the environmental benefits they promise are significant enough to offset the associated costs and challenges, particularly in a global context where supply chains are often complex and fragmented.

In conclusion, this study demonstrates that traceability through blockchain and QR codes offers a valuable tool for influencing consumer behavior and promoting sustainability in the beef sector. The positive relationship between traceability information and WTP highlights the growing consumer demand for transparency, which is likely to be a key factor in the future of beef consumption. However, the challenges faced by producers, especially small-scale ones, need to be carefully addressed to ensure the widespread adoption of these technologies. For beef producers, retailers, and policymakers, the findings of this study underscore the importance of investing in traceability systems to meet consumer expectations for both transparency and sustainability. Additionally, as consumers become more familiar with these technologies, their intention to purchase traceable products will likely increase, creating opportunities for the broader food industry to adopt similar practices.

While this study contributes to the understanding of consumer behavior regarding traceability technologies, it is not without limitations. First, although it allowed for a broad analysis with a representative response rate, the sampling method pertained exclusively to the Spanish population. This could have biased the results due to economic, social, or cultural factors. Future researchers should replicate the model presented here in different countries with varying contexts to test the robustness of our findings.

Another important limitation relates to the measurement of WTP, which is inherently subjective, especially in hypothetical scenarios where no reference price is provided. This lack of a benchmark may lead to over- or underestimation of actual consumer behavior. Future scholars should consider alternative methods to capture more accurate estimations of WTP.

Furthermore, there may be other external factors influencing consumer behavior and WTP, such as governmental or European promotional campaigns, sudden price changes due to inflation, or demographic issues affecting beef consumption and the acceptance of QR technology. The impact of these variables should be explored in future studies.

Finally, while the TAM proved to be a useful framework for understanding consumer behavior, future researchers could consider comparing this model to alternative methodologies, such as structural equation modeling, to better verify the relationships between the constructs in the proposed model.

The above limitations offer valuable opportunities for further research and allow future scholars to build on the findings of this study.

Finally, this work can be used by different actors (producers, distributors, and/or policymakers) looking for the application of technological tools in the field of food traceability. The results of this research show the key potential of digital technologies, especially blockchain-based traceability systems, to strengthen transparency, sustainability, and consumer confidence in meat value chains. In the case of producers, the gradual adoption of digital traceability platforms that allow critical information to be recorded, guaranteeing its integrity and verifiability throughout the production cycle, is recommended. Institutional support is essential to minimize entry barriers and maximize the use of these tools.

For downstream actors and distributors, the integration of these systems represents an opportunity to strengthen traceability at the commercial level and communicate sustainability attributes to the final consumer—for example, through solutions such as QR codes linked to blockchain records. For their part, policymakers can incentivize the development of these technologies through subsidies or tax benefits and the establishment of clear regulatory frameworks in this line of work.

Appendix

See Tables 4 and 5, Fig. 3.

Table 4 Distribution by province of respondents' residence over total responses

	Valid percentage		Valid percentage
Albacete	.4	León	1.3
Álava	.9	Lérida	.8
Alicante	3.1	Lugo	.5
Almería	.9	Madrid	23.3
Asturias	4.9	Málaga	3.4
Ávila	.8	Murcia	1.8
Badajoz	1.5	Navarra	1.4
Barcelona	12.1	Orense	.3
Burgos	.8	Palencia	.5
Cáceres	.9	Pontevedra	2.8
Cádiz	2.7	Salamanca	.6
Cantabria	2.0	Segovia	.3
Castellón	.9	Tarragona	1.8
Ciudad Real	.7	Toledo	2.0
Córdoba	1.6	Valencia	5.6
Cuenca	.3	Valladolid	1.2
Gerona	.6	Vizcaya	1.6
Granada	1.4	Zamora	.5
Guadalajara	.3	Zaragoza	2.4
Guipúzcoa	1.0	Vizcaya	1.6
Huelva	.5	Zamora	.5
Huesca	.3	Zaragoza	2.4
Jaén	.9		
La Coruña	3.1		
La Rioja	.5		

Table 5 Summary of the descriptives of the samples

Gender	Men: 574
	Women: 584
Age	Under 30: 21.3%
	Between 30 and 64 years: 75.5%
	Over 65 years old: 3.2%
Education	Primary education: 6.04%
	Compulsory secondary education: 31.26%
	Higher education (Bachelor's degree or equivalent): 52.41%
	Master's degree and PhD: 10.29%
Income	Under 2000 euro: 18.8%
	Between 2000 euro and 3000 euro: 69.2%
	Over 3000 euro: 12%
Household members employed	All household members employed: 61.1%
	Other situation: 38.9%

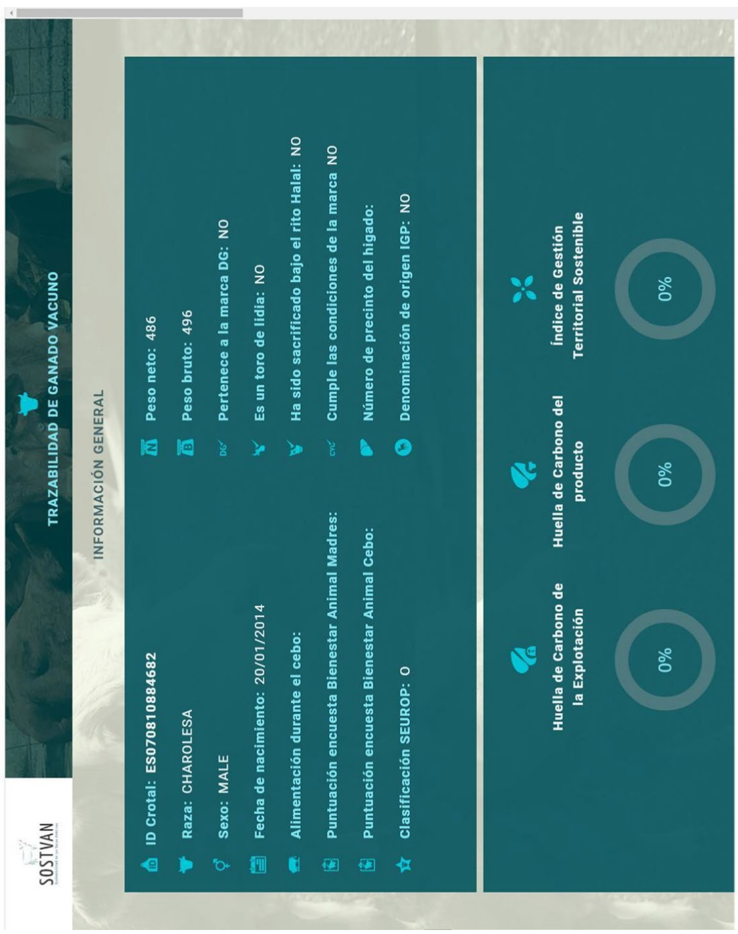

Fig. 3 Information contained in QR code simulating blockchain traceability information

Abbreviations

ATT	Attitude toward use
BI	Intention to use (behavioral intention)
CEXP	Consumer experience
ES	Ecosystem services
KMO	Kaiser–Meyer–Olkin test
PEOU	Perceived ease of use
PI	Perceived information
PU	Perceived usefulness
QR	Quick response
SOSTVAN	Proyecto Sostenibilidad de Vacas Nodrizas
TAM	Technology acceptance model
WP_QR	Willingness to pay
WTP	Willingness to pay

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Author contributions
RC-G worked on conceptualization, methodology, validation, formal empirical analysis, and writing the manuscript. AZ-G worked on conceptualization, methodology, validation and writing of the manuscript. EL-O worked on conceptualization, data curation, validation, writing of the manuscript, review and editing and supervision of the final version of the manuscript.

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Availability of data and materials
The data supporting the findings of this study are available from the corresponding author, Eva Lahuerta-Otero, upon reasonable request.

Declarations

Competing interests
I declare the authors have no competing interests as defined by the journal policies, or other interests that might be perceived to influence the interpretation of the article.
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