



Review

A systematic literature review of barriers to the adoption of environmentally sustainable innovations in cattle farming: A European perspective

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ABSTRACT

Cattle farming poses a significant risk to environmental sustainability in Europe. It contributes to soil degradation, water pollution, loss of biodiversity, unsustainable resource consumption and more than two-thirds of agricultural methane emissions in the EU. Innovative technologies and practices provide potential solutions to counter this environmental damage. Despite extensive research on sustainable innovation adoption in agriculture, there is a noticeable lack of comprehensive research uncovering barriers to environmentally sustainable innovation adoption in the cattle farming context. This article reports on a systematic literature review identifying and analysing these barriers, based on a sample of 56 articles. The study uncovered barriers that were deeply rooted in the unique characteristics of both farmers and their farms. We build upon existing theories to explain how cattle farmers' identity influences their behavioural decisions regarding innovation adoption, analyse how they respond to various barriers and consequently, propose a new conceptual framework. This research contributes to existing literature by providing the most comprehensive and in-depth synthesis of the complex, interrelated barriers to environmentally sustainable innovations in cattle farming to date. It also contributes valuable new knowledge about the barriers that affect cattle farmers' environmentally sustainable innovation decisions, crucial for assisting decision-makers and policy developers to address and overcome these obstacles in the future.

1. Introduction

Agriculture is responsible for more than 50 percent of methane emissions in the EU, with cattle farming emitting more than two-thirds of these harmful gases (European Environmental Agency, 2025). Cattle farming produces not only greenhouse gas emissions, but also creates other environmental risks like, for example, soil degradation, water pollution, loss of biodiversity, and unsustainable natural resource consumption (Grout et al., 2020; McClelland et al., 2023; O'Callaghan et al., 2019; Rivera Huerta et al., 2021; Rotz et al., 2019). Innovative technologies and practices, such as feed additives and manure management, demonstrate significant potential to reduce cattle farming emissions by more than half (Bacéninaitė et al., 2022; Cárdenas et al., 2021; Colin et al., 2024; Hristov, 2024; Meo-Filho et al., 2024). The well-documented environmental threats posed by cattle farming raise the important question of why urgent measures to combat these

challenges are not adopted more rapidly and on a much greater scale.

The environmental damage resulting from cattle farming and particularly its methane emissions, poses a serious threat to meeting the SDGs, particularly SDG 13, which promotes mitigating the effects of climate change (United Nations, n.d.; Zhao et al., 2025). In practice, there exist numerous agricultural innovations aimed at helping meet the SDG targets. This includes *agroecology*-promoting biodiversity, soil health and natural resource conservation; *precision agriculture*-enabling efficient resource use and reduced environmental impact; *organic farming*-eliminating the use of synthetic pesticides and fertilisers to improve biodiversity and soil health; *regenerative agriculture*-restoring soil health, increasing carbon sequestration and resilience to climate change; and a *circular economy*-reducing waste, promoting resource efficiency and adding revenue streams for farmers (Hiywotu, 2025). Organic farming and other similar practices are also considered innovative, as they incorporate cutting-edge technology and research in their

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application (Rizzo et al., 2023). However, the ever-present barriers to environmentally sustainable innovations pose a significant challenge to the drive towards greater sustainability. These barriers could cause 'systemic failures' in organisations, including farms, exerting varying degrees of impact on distinct innovative products, processes and management practices (Coad et al., 2016; Madrid-Guijarro et al., 2009). Prior studies have analysed organisations' willingness and propensity to invest in innovation, as well as the obstacles impeding innovation (Galia and Legros, 2004; Pellegrino and Savona, 2017). Existing literature notes several barrier classification systems, with the most prominent being *internal* barriers, endogenous to an adopter, encompassing barriers related to resources, systems and human nature, versus *external* barriers, exogenous and referring to supply, demand and environment-related barriers (D'Este et al., 2012; Hadjimanolis, 1999; Hewitt-Dundas, 2006). A profound understanding of the nature and impact of the barriers is essential for managing the process of innovation effectively (Cinar et al., 2019; Torugsa et al., 2016; Van de Ven, 1986). A comprehensive examination of these barriers in cattle farming could become a catalyst for overcoming these obstacles.

There is a paucity of research that 1) *Comprehensively investigates barriers to the adoption of a wide gamut of environmentally sustainable innovations, instead of only examining barriers to the adoption of a single or a handful of innovations* and 2) *Specifically investigates the cattle farming context to uncover such barriers, as opposed to the agricultural sector more broadly* (Campuzano et al., 2023; Long et al., 2016; Rose et al., 2016; Rose and Chilvers, 2018). To the best of our knowledge, no existing study addresses both the above issues, leaving a significant gap in the literature. Our study consequently aims to contribute to the body of knowledge on sustainable innovation adoption in farming by addressing this gap as presented in our research question: What are the barriers hindering the adoption of innovations towards environmental sustainability in cattle farming? Additionally, we contribute by building upon existing theories explaining how cattle farmers' identity influences their behavioural decisions regarding innovation adoption. We propose a new conceptual framework that provides a basic depiction of this study's identified barriers and how farmer identity ultimately shapes a farmer's decision whether to adopt sustainable innovations in their farming.

2. Theoretical background

The most prominent theories and models used to make sense of the process underpinning the adoption of environmentally sustainable innovations in farming are the Diffusion of Innovation Theory (DOI), the Theory of Planned Behaviour (TPB) and the Technology Acceptance Model (TAM). DOI explains the process through which new ideas, technologies, practices and processes spread amongst members of a social system over time (Rogers, 2003). This theory describes the factors that impact the adoption of an innovation, such as its perceived relative advantage, compatibility, complexity, trialability and observability and interpersonal communication (Peres et al., 2010; Rogers, 2003). Previous studies used the DOI to examine the factors influencing the adoption of environmentally sustainable innovations in farming (See: Campuzano et al., 2023; Lavoie et al., 2021; Tey and Brindal, 2012). TPB states that intentions and behaviours are influenced by attitudes, social norms and perceived behavioural control (Ajzen, 1991; Armitage and Conner, 2001). It has been applied to understand farmers' intentions to adopt sustainable practices (See: Borges and Oude Lansink, 2016; Läßle and Kelley, 2013; Sok et al., 2021). Lastly, TAM is most often used to study users' acceptance of new technologies, as mediated by the perceived ease of use and usefulness of the technology (Davis, 1989; Marangunic and Granić, 2015; Venkatesh and Davis, 2000). TAM has been applied extensively in agricultural research to examine farmers' adoption of new technological innovations, including those aimed at achieving environmental sustainability (Burton, 2004; Dai and Cheng, 2022; McCormack et al., 2021; Michels et al., 2020).

Whilst the above theories go some way towards explaining farmers'

decisions to adopt or reject innovations, farmer identity theory provides for a more comprehensive consideration of how a farmer's evolving self-identity in performing their roles as farmers within their farming communities, shapes their attitudes, norms, decision-making and behaviour (Dixon et al., 2022; McGuire et al., 2015; Spörri et al., 2024). There is a growing body of research on this relatively new farmer identity-informed perspective (e.g., Burton, 2004; Cullen et al., 2020; Jin et al., 2024; Leduc and Hansson, 2024; Li et al., 2024). Building on the works of social identity theory proponents like Mead; Goffman; Stryker, as well as Stets and Burke (e.g., Burke, 1991; Goffman, 1959; Mead, 1934; Stets and Burke, 2000; Stryker, 1968; Stryker and Burke, 2000), researchers explain that farmers' self-identity describes a complex and nuanced set of meanings (beliefs, self-perception, values, attributes) constructed and dynamically evolving through ongoing social interactions and subsequent feedback and verification within the social groups they affiliate with (Burton, 2004; Cullen et al., 2020; Jin et al., 2024; Letourneau and Davidson, 2022; McGuire et al., 2015; Spörri et al., 2024). In building social capital within these social networks, farmers share, amongst other things, reciprocal connections, norms, trust, knowledge, solidarity and cooperation that significantly influence farmers' identities and ultimately their attitudes, decisions and behaviour (Arnott et al., 2021; Lai et al., 2025). This links with DOI to explain the spread of new ideas and technologies among members of social networks (Rogers, 2003).

Farmers, through 'self-categorisation', adopt one or more farmer identities based on how they see themselves and perceive their farmer-related roles in society (Burton, 2004; Spörri et al., 2024; Vesala and Vesala, 2010). These different farmer identities that shape attitudes, decisions and behaviours include, for example, Productivist, Environmentalist (Conservationist), Diversifier, Innovator, Land caretaker, Lifestyle identity, Pragmatist and Traditionalist (Bartkowski et al., 2022; Jin et al., 2024). The functioning of farmer identity is complex, with each having a different abstract set of principle-level standards or ideas of the meaning of being a 'good farmer' (McGuire et al., 2013, 2015). A deep understanding of farmer identities will allow farmers' attitudes and behaviour to be shaped through tailored initiatives to facilitate the transition to environmentally-aligned self and social identities (Dixon et al., 2022; Li et al., 2024; Spörri et al., 2024).

Farming is more than merely a profession to many farmers; it is a way of life. A farm is regarded as more than a business, and a farmer, therefore, connects more deeply with their identity and the subsequent roles they must perform in society (Groth and Curtis, 2017; Letourneau and Davidson, 2022; Vayro et al., 2020). Farmer self-identity is multifaceted as farmers are required to fulfil various different roles. While farmers' primary role is to produce agricultural goods and services in a financially sustainable way, they are, for example, also expected to conserve nature and maintain the rural landscape, leading to farmers having to develop different identities, driving a complex set of nuanced and sometimes contradictory behaviours (Groth and Curtis, 2017; Spörri et al., 2024; Vesala and Vesala, 2010). We contend that this calls for a deeper understanding of the role of a farmer's identity in ultimately shaping their intention to adopt environmentally sustainable innovations.

3. Methodology

This study employs a systematic literature review methodology informed by the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) statement (Dunne et al., 2021; Liberati et al., 2009; Moher et al., 2009; Page et al., 2021). Systematic literature review approaches conceptualise reviews as staged methodological processes involving planning, conducting and synthesising findings in a reproducible manner to obtain reliability unavailable from any individual study (Snyder, 2019; Tranfield et al., 2003). PRISMA is a widely adopted reporting guideline developed to improve the transparent, complete and accurate reporting of systematic reviews and includes the

documentation of study identification, screening, eligibility and inclusion procedures (Moher et al., 2009; Page et al., 2021). This section provides an overview of the systematic steps taken to obtain a sample of relevant, peer-reviewed literature and the coding thereof.

3.1. Literature search

The stages of the literature search process applied in this study are presented in Table 1. Only studies investigating farms in Europe were retained for this review. European countries, particularly those in Western and Northern Europe, generally rank highly in environmental sustainability amongst industrialised nations (Kırda and Aytekin, 2024). Additionally, many European nations have comparatively high-income levels, whereas developing countries often prioritise other development needs above environmental sustainability objectives (World Bank, n.d.; Zhao et al., 2022). Therefore, given the relatively greater importance placed on meeting environmental sustainability targets in European countries, it is a fertile ground from which to draw on current research in this area. The search was conducted on 21 November 2024 and limited to English language peer-reviewed research articles published between 1 January 2015 and 21 November 2024 (the search

Table 1
Literature search and screening steps.

Stage 1: Literature search	Stage 2: Screening of articles	Stage 3: Search for additional articles
<p>Literature for this review were obtained through the following process:</p> <p>Databases: Web of Science and SCOPUS were respectively searched for relevant literature</p> <p>Date: 21/11/2024</p> <p>Keywords: (<i>dairy farm* OR beef farm* OR cattle farm*</i>) AND (<i>sustain* OR green* OR climat* OR environment* OR transition* OR transform* OR mitigat* OR ecolog*</i>) AND (<i>innov* OR technolog* OR adopt* OR implement* OR develop*</i>) AND (<i>risk* OR obstacle* OR barrier* OR challeng* OR hinder* OR deter* OR difficult* OR bottleneck* OR problem* OR setback* OR hurdle* OR hamper* OR impede* OR obstruct*</i>).</p> <p>Filters: Only English-language peer-reviewed research articles accepted. No reviews included.</p> <p>Time period: 01/01/2015 - 31/12/2025.</p>	<p>Literature from the databases were collated and duplicates removed. Following this, articles were screened and removed according to the following criteria:</p> <p>Eligibility criteria:</p> <ul style="list-style-type: none"> • Only empirical studies in a European context. Articles investigating multiple regions were accepted if at least one of these regions fell within Europe. Studies located in transcontinental countries with significant regions within Europe were accepted, such as Russia or Turkey. • Must investigate some form of cattle farming (beef and/or dairy). Studies centred on multiple farm types were included as long as cattle farms were investigated. • Must include research on innovations towards environmental sustainability in cattle farming. • Must discuss barriers to the adoption of such innovations. • Multiple study perspectives accepted, including those of farmers, experts and the public. • Study area must fall within the scope of this review. Purely technical papers on new technologies were discarded. 	<p>After the conclusion of the screening process, additional articles for inclusion were searched for through the following steps:</p> <p>Reference lists of articles published in high quality journals in retained articles were scanned and relevant articles identified.</p> <p>These articles were then screened according to the same criteria as the above.</p> <p>The same process was repeated for the forward citations of the abovementioned articles in the remaining sample. These three stages yielded the final sample of research articles used in this review: 56 papers.</p>

date). This timeframe was selected to correspond to the adoption year of the Sustainable Development Goals (SDGs) by all United Nations countries at the 2015 New York summit.

Initial searches were conducted in Web of Science and repeated in SCOPUS (See: Foguesatto et al., 2021; Khan et al., 2021; Kyriakopoulos, 2024; Malanski et al., 2021; O'Donnell et al., 2025; Prancutè, 2021). Different keywords were iteratively tested to derive the most effective combination of search terms. The keywords comprised of different terms for cattle farms, sustainability, innovation and barriers, respectively. The keywords used for innovation were derived from and expanded upon Stornelli et al. (2021), whereas the terms for barriers were from Cinar et al. (2019), with the addition of the 'risk' keyword. The database search results were downloaded and collated, after which duplicate entries were removed.

3.2. Eligibility criteria and record screening

Records were screened according to carefully selected eligibility criteria, summarised in Table 1. A subset of 20 papers (out of 192) was independently reviewed by all three authors at the full-text screening stage to ensure inter-reviewer reliability. Each reviewer applied the same predefined exclusion and inclusion criteria to the subset. Discrepancies were resolved through discussion until consensus was reached, ensuring consistency and minimising subjective bias. Non-empirical studies, such as reviews, were removed from the sample, in line with other recent systematic reviews (See: O'Donnell et al., 2025; Ojeda-Matos and Jones-Crank, 2025; Thøgersen, 2023). Studies only considering innovations aimed at achieving non-environmental forms of sustainability, such as animal welfare or economic sustainability, were discarded, as such studies do not serve to answer this review's research question. A PRISMA diagram summarising the results of each step in the search and screening process follows in Fig. 1.

3.3. Data analysis and coding

This study employs thematic analysis to qualitatively analyse the final sample of papers retained through the systematic literature search process and provides bibliometric figures and statistics on the sample to reveal pertinent characteristics of the data. Through a methodical process of data familiarisation, coding, topic formulation and theme revision, thematic analysis is used to identify and derive patterns of meaning, or themes, from a dataset (Pham et al., 2024). Codes are the smallest units of analysis and are used to construct larger patterns of meaning in themes (Clarke and Braun, 2017). Coding was conducted through the NVivo analysis software. Different categories of codes were created from the articles in the final sample to capture barriers to innovations towards sustainability, types of innovations, study methodologies and study countries. Codes for the categorisation of barriers were abductively constructed based on analysis of the studies in the final sample, paired with prior reading on the topic in preparation for this review.

Themes may be conceptualised as shared patterns of meaning that are underpinned by a core concept (Braun and Clarke, 2019; Clarke and Braun, 2017). The different barriers hindering the adoption of innovations to environmental sustainability in European cattle farms found in the final literature sample were conceptualised as the main themes captured in this review. Pairwise co-reporting of barrier categories was assessed through a co-occurrence matrix and Jaccard similarity. This index expresses how similar two categories are by comparing how often they occur together, to how often they occur overall (Koleff et al., 2003; Real and Vargas, 1996). The top three strongest barrier associations by Jaccard are reported along with numerical co-occurrence counts. The use of co-occurrence together with network-based analysis approaches are common, accepted methods used in examining associations between constructs (Callon et al., 1983; Leydesdorff and Vaughan, 2006; Van Eck and Waltman, 2009).

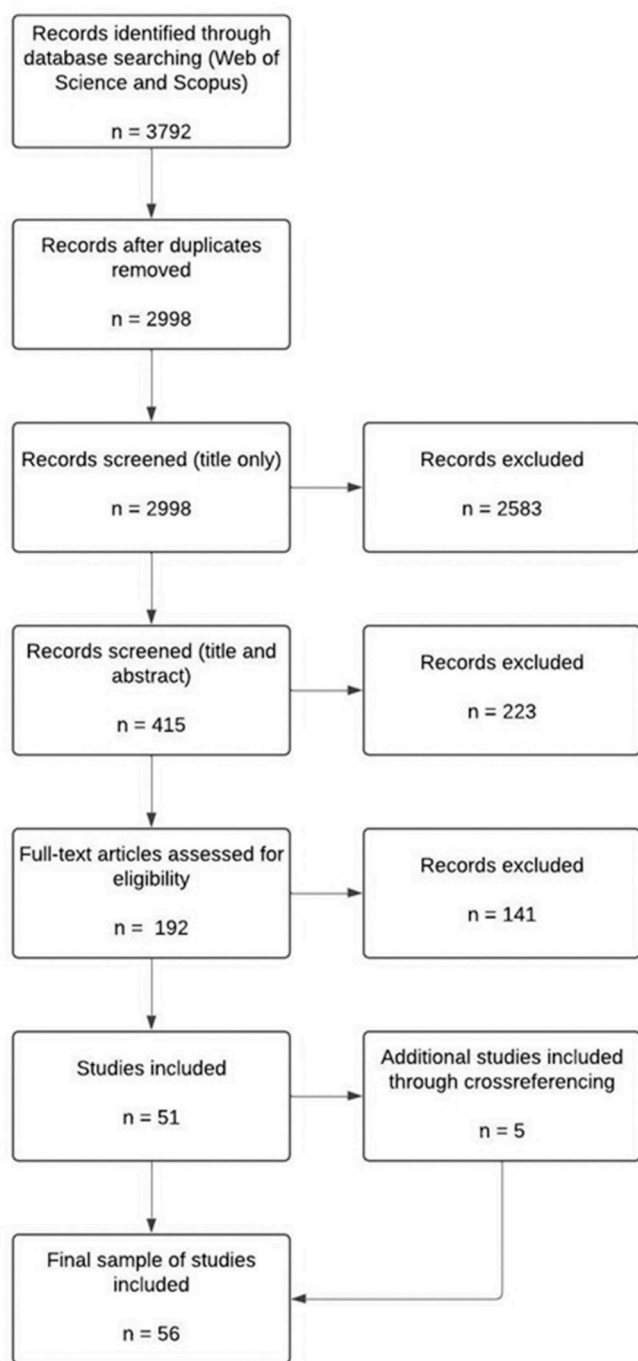


Fig. 1. Prisma diagram.

4. Results of the systematic review

This section reports on the general characteristics of the identified studies and outlines the key findings from this systematic review.

4.1. Study characteristics

Fig. 2 shows the frequency of the locations investigated in the 56 final articles. It is important to note that some studies investigated multiple regions. With 18 studies, Ireland featured significantly more than other countries. The Netherlands appeared 10 times, followed by Germany at 8 and the UK and Italy at 7 apiece, with other countries appearing considerably fewer times. Ireland is relatively specialised at dairy farming, with one of the largest stocks of cattle in Europe, even

with a comparatively small human population (Eurostat, 2025). Few studies in the final sample are located in Eastern Europe. Most studies from this region focused exclusively on economic sustainability aspects without adequate consideration of environmental sustainability and were therefore excluded during screening.

Table 2 shows the methodologies used in the identified studies, with purely quantitative methodologies being most common, where structural equation modelling, cluster analysis and principal component analysis methods appear frequently. Qualitative papers often used in-depth interviews with farmers and experts, whereas approximately 21 percent of studies employed mixed methods methodologies.

The distribution of the identified studies per year is found in Fig. 3. With some exceptions, there appears to be an overall increasing trend of sample papers per year. This is likely caused by increased research interest in sustainability due to the introduction of the SDGs in 2015.

The distribution of articles per publication in the final sample is shown in Table 3, with the 56 articles being spread between 24 journals. The most frequently appearing journals were Agricultural Systems, Journal of Rural Studies, Journal of Environmental Management and Journal of Cleaner Production.

4.2. Bibliographic co-occurrence keyword network

Fig. 4 illustrates the co-occurrence keyword network of the included studies using VOSviewer. The size of each node reflects how frequently each keyword is included in sample papers, with the lines showing connections between keywords used in the same article (Hale et al., 2023; Kyriakopoulos, 2024). While the prominence of central terms such as ‘adoption’, ‘agriculture’ and ‘barriers’ reflect the literature search strategy, the network structure provides insight into how research within these constraints are conceptually organised. The most central and highly-connected node in the network is ‘adoption’, signifying that these barriers are examined mainly through an adoption-focused lens. This central cluster is predominantly associated with behavioural constructs, such as cultural theory, decision-making and perspectives.

The network reveals several more weakly connected thematic clusters beyond this core. Climate- and policy-oriented terms form a peripheral cluster with somewhat limited integration into the more central adoption-focused literature. Moreover, modelling-related keywords appear isolated from all but the central cluster. This suggests a lack of integration of these respective quantitative methods from the other thematic clusters, such as those related to sustainability or agriculture. Notably, ‘consumer acceptance’ appears as a small node with few connections to the central adoption and behaviour cluster. This suggests that the core adoption literature in this sample shows little incorporation of research related to consumer responses to innovation adoption. This aligns with findings in this review that public and consumer challenge barriers are largely under-researched in this context. Overall, while this network is constrained by the bounds of the applied search terms, the clustering and patterns of connectivity displayed highlight a fragmented research landscape.

4.3. Innovations typology

Environmentally sustainable innovative technologies and practices are grouped into nature-based, technological and management-oriented approaches in Table A.1 in the appendix. These categories provide a structural overview, but due to the complexity of sustainability transitions in agricultural systems, some innovations span multiple approaches. Therefore, innovations are interpreted through their dominant mechanism of change within the non-linear stages of sustainable intensification proposed by Pretty et al. (2018). These mechanisms constitute efficiency, substitution and redesign. This distinction provides a framework for understanding how different innovation approaches contribute to sustainability. Technology or engineering

Study Country Frequency

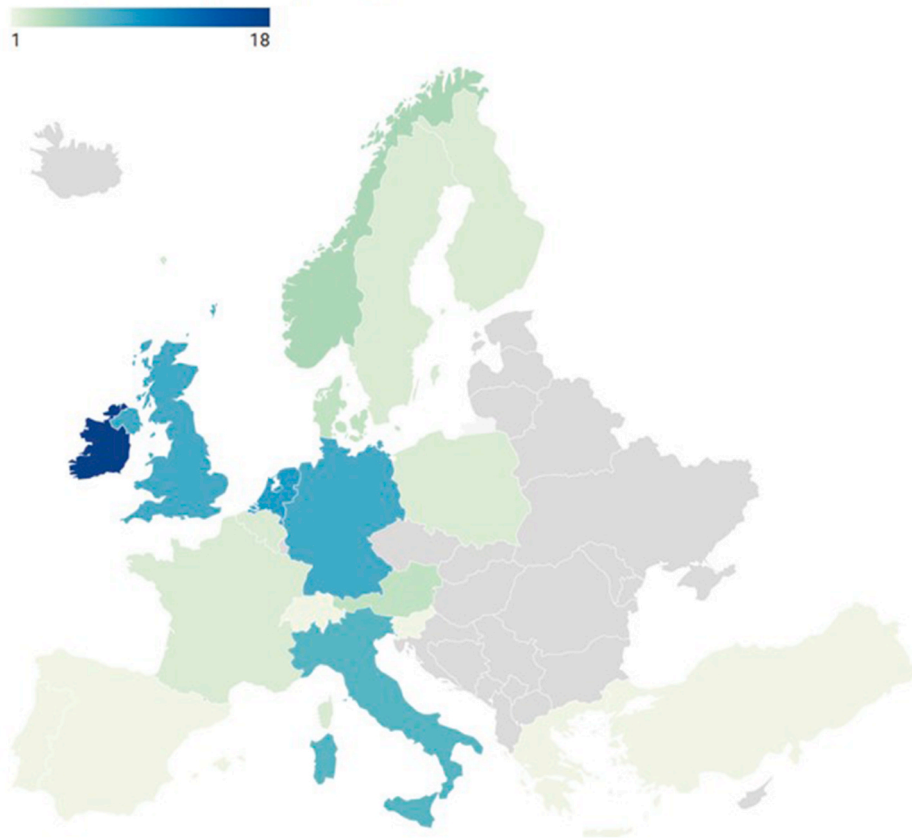


Fig. 2. Study countries (Made using Datawrapper).

Table 2
Study methodologies.

Methodology	Frequency	Percentage
Quantitative	26	46.43
Qualitative	18	32.14
Mixed methods	12	21.43

solutions may include both efficiency and substitution mechanisms, as they incorporate innovations that optimise input usage and production processes (e.g., automation and precision livestock farming), as well as those replacing conventional inputs with more sustainable alternatives (e.g., feed and crop or waste and slurry innovations). Conversely, nature-based solutions can be viewed as forms of redesign, as they rely on ecological processes and the integration of biodiversity into farming systems. Management-oriented innovations may comprise both

Study years

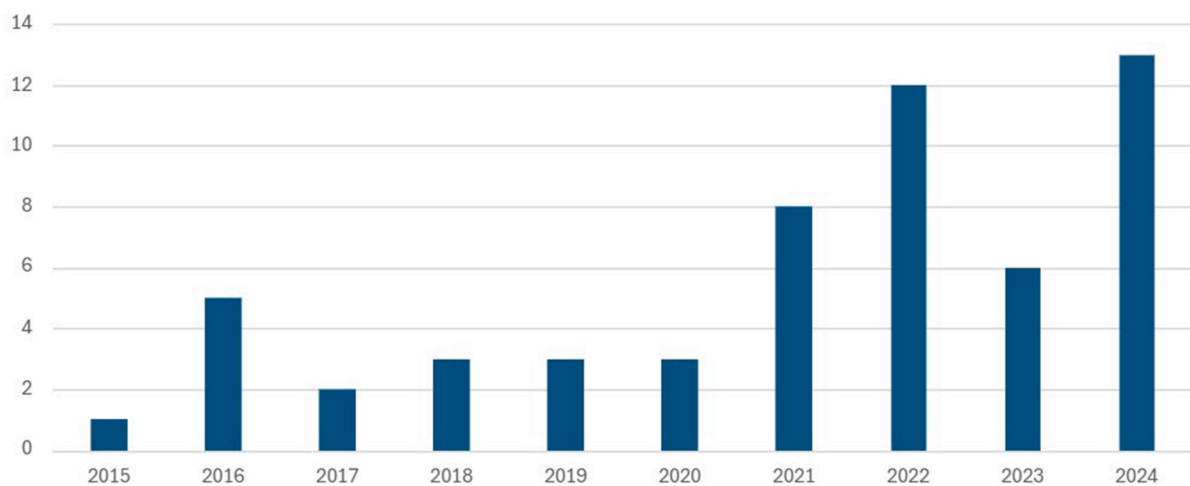


Fig. 3. Article year distribution.

Table 3
Articles per journal.

Journal Name	Frequency
Agricultural Systems	7
Journal of Rural Studies	6
Journal of Environmental Management	6
Journal of Cleaner Production	6
Sustainability	5
Animal	3
Journal of Dairy Science	3
Agriculture and Human Values	2
Land Use Policy	2
Sociologia Ruralis	2
Agribusiness	1
Agricultural and Resource Economics Review	1
Agroecology and Sustainable Food Systems	1
Agronomy	1
Environmental Science and Policy	1
Environments - MDPI	1
German Journal of Agricultural Economics	1
International Journal on Food System Dynamics	1
Italian Journal of Animal Science	1
Journal of Agricultural Economics	1
Norsk Geografisk Tidsskrift- Norwegian Journal of Geography	1
Polish Journal of Environmental Studies	1
Science of the Total Environment	1
Smart Agricultural Technology	1

efficiency and redesign mechanisms. Some practices include improving productivity and resource use efficiency, while others involve fundamental system changes, such as organic farming and grazing management.

Analysis of the innovations studied in the sample reveals a number of key patterns. The most frequently examined innovation category is general management and circular economy innovations, while the most

studied technological category is precision livestock farming. Conversely, greenhouse gas capture technologies and renewable energy innovations have received the least research attention in this sample. Additionally, the organic farming category has the broadest geographic spread of studies, while nature-based innovation approaches (agroforestry and biodiversity; grassland conservation) have a narrow spread and are primarily investigated in the UK and Ireland.

4.4. Barrier categories

This section discusses the result of the barriers found in the literature, summarised in Table 4.

4.4.1. Farm and farmer attributes

Farm and farmer attributes barriers are classified into three sub-categories: farm attributes, farm environmental challenges and farmer attributes. The most frequent farm attributes hindrance is the incompatibility of some environmentally sustainable innovations with farm types or sizes, including unsuitability with existing infrastructure, location or production objectives, limiting effectiveness (Cantillon et al., 2024; Gallegos Rivero and Daim, 2017; Klefodimos et al., 2022). Additionally, farmers' ability to invest in new environmentally sustainable technology or infrastructure is limited when they do not own the land they farm, due to lacking incentives to invest time or money into adoption or lacking decision-making authority (Jordon et al., 2023; Van den Berg et al., 2023). Lastly, farm advisor-related challenges are found in advisors providing wasteful, unsustainable advice, or farmers waiting on advisor guidance to apply environmentally sustainable methods (e.g., Harrison et al., 2021; Van den Berg et al., 2023).

The farm environmental challenges subcategory comprises regional environmental challenges and weather conditions hampering the adoption of environmentally sustainable innovations. This includes

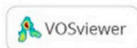
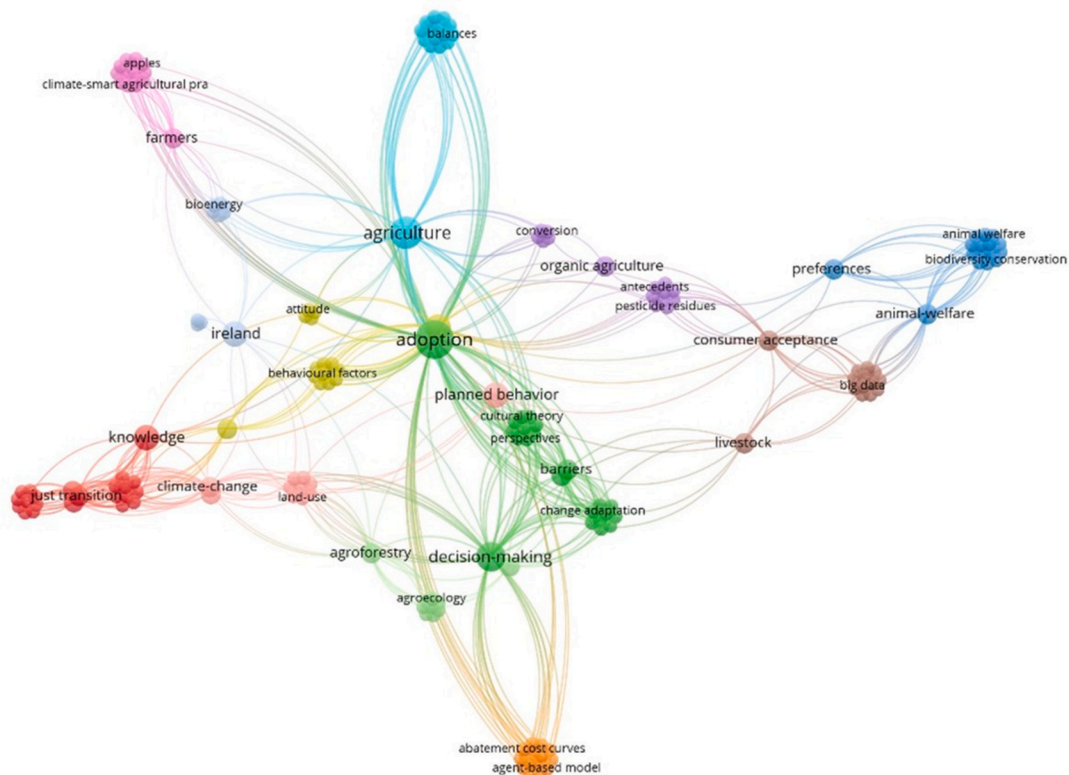


Fig. 4. Co-occurrence network of keywords (Made using VOSviewer).

Table 4

Barrier categories.

Main Barrier category	Barrier subcategory	Code	References
Farm and farmer attributes	Farm attributes	<i>Farm not owned; Advisor challenges; Farm type and size incompatibility</i>	(Cantillon et al., 2024; Daxini et al., 2018; Gallegos Rivero and Daim, 2017; Harrison et al., 2021; Jordon et al., 2023; Kleftodimos et al., 2022; Laple et al., 2024; Moerkerken et al., 2021; Van den Berg et al., 2023; Westerink et al., 2024)
	Farm environmental challenges	<i>Regional environmental challenges; Undesirable weather conditions</i>	(Buckley et al., 2016; Holohan et al., 2021; Jordon et al., 2023; Palma-Molina et al., 2023; Ronningen et al., 2021; Van den Berg et al., 2023)
	Farmer attributes	<i>Farmer age and health; Farmer in bad financial position; Unknowledgeable farmer; Farmer network issues</i>	(Benedicc et al., 2022; Bianchi et al., 2022; Cukur, 2015; Daxini et al., 2018; De Lauwere et al., 2022; Galliano and Siqueira, 2021; Harrahill et al., 2023; Harrison et al., 2021; Horrillo et al., 2016; Irwin et al., 2023; Jordon et al., 2023; Kreft et al., 2024; Naspetti et al., 2017; O'Connor et al., 2021; Palma-Molina et al., 2023; Van den Berg et al., 2023; Vermunt et al., 2022)
Farmer attitudes	Climate change perspectives	<i>Deny climate change contribution; Dislike of environmental measures; Perception of being blamed for environmental issues; Limited understanding of climate change risks and sustainability</i>	(Benedicc et al., 2022; Gebaska et al., 2020; Happel et al., 2022; Hyland et al., 2016; Nguyen et al., 2019; Puupponen et al., 2022; Van den Berg et al., 2023; Westerink et al., 2024)
	Farmer autonomy	<i>Feeling of overdependence on others; Perceptions of uninvolvement in decision-making</i>	(De Lauwere et al., 2022; Harrahill et al., 2021; Horrillo et al., 2016; Van den Berg et al., 2023)
	Farmer priorities	<i>Clashes with farmer lifestyle preference; Lack of Motivation; Perception of environmental sustainability as less important; Preference for profit over sustainability; Preference for traditional methods; Production level</i>	(Benedicc et al., 2022; Burton and Farstad, 2020; de Lauwere et al., 2022; Doidge et al., 2024; Galliano and Siqueira, 2021; Gebaska et al., 2020; Harrahill et al., 2023; Horrillo et al., 2016; Hyland et al., 2016; Irwin et al., 2023; Jordon et al.,

Table 4 (continued)

Main Barrier category	Barrier subcategory	Code	References
Finance	Farmer negative perceptions	<i>preference over sustainability</i>	2023; Luhmann et al., 2016; Lynch et al., 2018; Murphy et al., 2022; Ronningen et al., 2021; Shortall, 2019; van den Berg et al., 2023; Vermunt et al., 2022; Westerink et al., 2024)
		<i>Negative perception towards an innovation; Past negative experience</i>	(Bechini et al., 2020; Harrison et al., 2021; Irwin et al., 2023; Naspetti et al., 2017; Van den Berg et al., 2023)
	Cost	<i>High initial investment cost; Increased costs</i>	(Bechini et al., 2020; Bianchi et al., 2022; Cullen et al., 2024; Daxini et al., 2018; De Lauwere et al., 2022; Doidge et al., 2024; Engelberts et al., 2021; Harrahill et al., 2023, 2022; Harrison et al., 2021; Holohan et al., 2021; Hoogstra et al., 2024; Horrillo et al., 2016; Jordon et al., 2023; Lybæk and Kjær, 2019; O'Connor et al., 2021; Palma-Molina et al., 2023; Selvaggi et al., 2024; Van den Berg et al., 2023; Verburg et al., 2022)
Information and Uncertainty	Unsatisfactory financial returns	<i>Inability to reap financial benefit; Insufficient financial incentives; Low profitability; Slow financial return</i>	(Bechini et al., 2020; Hoogstra et al., 2024; Horrillo et al., 2016; Irwin et al., 2023; Jordon et al., 2023; Pedersen et al., 2024; Puupponen et al., 2022; Van den Berg et al., 2023; Vermunt et al., 2022)
	Financial risk	<i>Financial return uncertainty</i>	(Hoogstra et al., 2024; O'Connor et al., 2021)
	Information	<i>Farmer avoidance of information; Farmer distrust of information; Farmer lack of access to information</i>	(De Lauwere et al., 2022; Gallegos Rivero and Daim, 2017; Happel et al., 2022; Holohan et al., 2021; Irwin et al., 2023; O'Connor et al., 2021; Oyibo and Hansson, 2024; Van den Berg et al., 2023)
	Uncertainty	<i>Farmer legal uncertainties; Uncertainty over environmental impact; Uncertainty over impact on</i>	(Battini et al., 2016; Burton and Farstad, 2020; Doidge et al., 2024; Harrison et al., 2021; Herzog et al., 2021;

(continued on next page)

Table 4 (continued)

Main Barrier category	Barrier subcategory	Code	References
Technological and practice related		<i>animal welfare; Uncertainty over impact on output; Uncertainty over innovation outcome</i>	Holohan et al., 2021; Hyland et al., 2016; Jordon et al., 2023; Lybæk and Kjær, 2019; Palma-Molina et al., 2023; Pedersen et al., 2024; Puupponen et al., 2022; Rønningen et al., 2021; Shortall, 2019; Van den Berg et al., 2023)
	Burdensome adoption requirements	<i>Increased resource requirements; Labour intensive; Requires additional infrastructure; Requires additional skills, training and management; Time-consuming</i>	(Bechini et al., 2020; Bianchi et al., 2022; Daxini et al., 2018; de Lauwere et al., 2022; Díaz de Otálora et al., 2024; Doidge et al., 2024; Harrahill et al., 2022, 2023; Holohan et al., 2021; Horrillo et al., 2016; Irwin et al., 2023; Jordon et al., 2023; Lybæk and Kjær, 2019; Moerkerken et al., 2021; Pedersen et al., 2024; Van den Berg et al., 2023; Westerink et al., 2024)
	Negative effects	<i>Undesirable effect on farm output; Negative environmental impact; Negative impact on animal welfare; Reduces flexibility</i>	(Bechini et al., 2020; Cullen et al., 2024; Díaz de Otálora et al., 2024; Doidge et al., 2024; Herzog et al., 2021; Holohan et al., 2021; Horrillo et al., 2016; Jordon et al., 2023; Läßle et al., 2024; Lybæk and Kjær, 2019; Moerkerken et al., 2021; Westerink et al., 2024)
	Perceived ease of use	<i>Complexity; Impracticality; Poor technical support</i>	(Bianchi et al., 2022; Doidge et al., 2024; Harrahill et al., 2022; Harrison et al., 2021; Lybæk and Kjær, 2019; Van den Berg et al., 2023)
	Perceived usefulness	<i>Innovation output not useful; Insufficient environmental sustainability benefit; Quality or reliability issues</i>	(Battini et al., 2016; Bianchi et al., 2022; Cantillon et al., 2024; Doidge et al., 2024; Gallegos Rivero and Daim, 2017; Herzog et al., 2021; Läßle et al., 2024; Lybæk and Kjær, 2019; Moerkerken et al., 2021)
Policy and regulation	Farmer policy perceptions	<i>Environmental policy perceived as threatening; Farmers not represented in decision-making;</i>	(Happel et al., 2022; Harrahill et al., 2023; Hoes and Aramyan, 2022; Murphy et al., 2022)

Table 4 (continued)

Main Barrier category	Barrier subcategory	Code	References
Public and consumer challenges	Ineffectual policy	<i>Farmers perceive regulations as untrustworthy or unclear Adoption support lacking; Overly standardised policies; Policies allow greenwashing; Policies ineffective at increasing adoption; Policies lack clear strategy; Policies overlook trade agreements</i>	(Ayala et al., 2024; De Lauwere et al., 2022; Díaz de Otálora et al., 2024; Harrahill et al., 2023; Hoes and Aramyan, 2022; Hoogstra et al., 2024; Horrillo et al., 2016; Irwin et al., 2023; Läßle et al., 2024; Lynch et al., 2018; Murphy et al., 2022; Pedersen et al., 2024; Verburg et al., 2022; Vermunt et al., 2022; Westerink et al., 2024)
	Stringency	<i>Overly laissez faire regulations; Obstructive or stifling regulations</i>	(Benedičić et al., 2022; Hoogstra et al., 2024; Irwin et al., 2023; Nguyen et al., 2019; Van den Berg et al., 2023; Vermunt et al., 2022; Westerink et al., 2024)
	Knowledge	<i>Consumers unaware or lacking knowledge</i>	(Langer and Kühl, 2024; Stampa and Zander, 2022)
	Preferences and attitudes	<i>Heterogeneous consumer attitudes; Preference for animal welfare measures; Unwilling or unable to pay more</i>	(Langer and Kühl, 2024; Markova-Nenova and Wätzold, 2018; Pedersen et al., 2024; Stampa and Zander, 2022; Verburg et al., 2022; Wendt and Weinrich, 2024)
	Resistance	<i>Negative perception or scepticism; Resistance to farm technological advancement</i>	(Langer and Kühl, 2024; Pedersen et al., 2024)

undesirable climate, soil quality and other geographical features, like the loss of land to infrastructure development (e.g., Jordon et al., 2023; Palma-Molina et al., 2023; Rønningen et al., 2021), along with detrimental and irregular weather patterns (Buckley et al., 2016; Holohan et al., 2021; Van den Berg et al., 2023).

The most prominent farmer attribute barrier subcategory comprises farmers' knowledge deficits, ranging from farmers lacking the required expertise to employ new practices or technologies, lacking confidence about their knowledge to employ new methods, to being completely unaware of such innovations (e.g., Cukur, 2015; Horrillo et al., 2016; Jordon et al., 2023). Additionally, farmers' networks and those surrounding them not participating in or perceiving sustainable measures negatively hinders farmers' adoption (e.g., Cukur, 2015; De Lauwere et al., 2022; Naspetti et al., 2017). Lastly, farmer age and health (e.g., Daxini et al., 2018; Jordon et al., 2023) and financial position (e.g., Benedičić et al., 2022; Van den Berg et al., 2023) are also detrimental to adoption, as farmers over 65 or lacking physical health or finances to invest in sustainable innovations are less likely to adopt such technologies and practices. Paradoxically, age is occasionally positively

correlated with adoption, as younger farmers may lack necessary funds (Palma-Molina et al., 2023).

4.4.2. Farmer attitudes

Farmer attitudes barriers are classified under climate change perspectives, farmer autonomy, farmer priorities and farmer negative perceptions subcategories. The literature finds that farmers often prioritise other goals over environmental sustainability, largely fuelled by their farmer identity. Some farmers value keeping favoured production levels over environmental sustainability, whether 'productivist' identity farmers who prefer to maximise farm production or small-scale farmers intending to not exceed current farm production levels (e.g., Benedičić et al., 2022; Rønningen et al., 2021; Vermunt et al., 2022). As discussed in Section 2, farmer identities are linked to farmers' understood definition of what constitutes a 'good farmer' and what activities provide them with job satisfaction, which often manifests in a desire to maintain higher production levels and prioritisation of using land for farming, instead of environmental sustainability (Harrhill et al., 2023; Hyland et al., 2016; Rønningen et al., 2021). Similarly, farmers prioritising profits over the environment is another common barrier preventing adoption, as some farmers, particularly those with 'productivist' tendencies, only adopt sustainable innovations if they provide monetary benefits (e.g., De Lauwere et al., 2022; Luhmann et al., 2016; Lynch et al., 2018). Additionally, some farmers prioritise using traditional methods (e.g., Jordon et al., 2023; Murphy et al., 2022) or keeping their current lifestyle (Burton and Farstad, 2020) over environmental sustainability, whereas others view environmental sustainability as less important than other issues (Benedičić et al., 2022; Gebška et al., 2020; Hyland et al., 2016), or lack motivation to be sustainable (e.g., Doidge et al., 2024; Jordon et al., 2023).

The way farmers perceive climate change may also prevent adoption. Some farmers deny agriculture's contribution to climate change, repudiating its effect on emissions, biodiversity loss and water quality (e.g., Benedičić et al., 2022; Hyland et al., 2016; Nguyen et al., 2019). In other cases, the sense of blame for environmental issues experienced by some farmers may induce a passivity towards adopting environmentally sustainable innovations (e.g., Happel et al., 2022; Puupponen et al., 2022). Furthermore, some farmers have a poor understanding or awareness of climate change (Gebška et al., 2020; Hyland et al., 2016), whilst others hold productivist identities and dislike environmental measures altogether (Benedičić et al., 2022).

4.4.3. Finance

Financial barriers expectedly are a major hindrance to adoption and are characterised under cost, unsatisfactory financial returns and financial risks subcategories. *Increased costs* posed by environmentally sustainable innovations is the most frequently cited individual barrier in the literature, mentioned in fourteen studies (e.g., Bechini et al., 2020; Holohan et al., 2021; Horrillo et al., 2016; Van den Berg et al., 2023). Multiple studies confirm farmers regard increased costs as their main deterrent to adoption, as environmentally sustainable innovations frequently require more expensive resources, technologies, infrastructure or additional transportation, amongst other expenditures. Nine studies specifically mention high initial investment costs as significant obstacles for farmers to overcome (e.g., Cullen et al., 2024; Horrillo et al., 2016; O'Connor et al., 2021; Selvaggi et al., 2024). Environmentally sustainable innovations often require substantial upfront costs due to new technology, management structure or training requirements that farmers struggle to afford without instalment payment options, forming a significant barrier to adoption.

Additional financial barriers hampering adoption are found in unsatisfactory financial returns. The financial and/or resource costs of environmentally sustainable innovations, paired with a possible lack of satisfactory financial returns, contribute to the potential low profitability of such practices and technologies (e.g., Irwin et al., 2023; Jordon et al., 2023; Puupponen et al., 2022). Furthermore, farmers may lack

financial incentive to adopt environmentally sustainable innovations (Bechini et al., 2020; Van den Berg et al., 2023; Vermunt et al., 2022), be unable to capture financial benefits from adoption (e.g., Pedersen et al., 2024) or face slow return on investment (Jordon et al., 2023).

4.4.4. Information and uncertainty

Farmers regularly lack access to information about environmentally sustainable practices and technologies, relating to awareness of such measures, how to employ them, their costs, their trustworthiness and specific regulations (Happel et al., 2022; Holohan et al., 2021; O'Connor et al., 2021; Van den Berg et al., 2023). Another barrier is farmers' lack of trust in information about environmentally sustainable innovations, including a distrust of non-farmer advice, the media or advice that clashes with beliefs (e.g., Gallegos Rivero and Daim, 2017; Irwin et al., 2023; Van den Berg et al., 2023). Some non-adopting farmers intentionally avoid information to avoid clashes with prior beliefs related to their farms' environmental impact (De Lauwere et al., 2022; Oyibo and Hansson, 2024).

The most significant uncertainty-related barrier is the uncertainty around the environmental impact of environmentally sustainable innovations, apropos of current research on its shortcomings and from farmers unsure about their impact on the environment and how such methods can reduce damage (Battini et al., 2016; Burton and Farstad, 2020; Herzog et al., 2021; Hyland et al., 2016; Pedersen et al., 2024; Shortall, 2019). Further uncertainty is found in whether environmentally sustainable innovations will reach their intended outcomes and be tenable with available resources (Drucker, 1985; Harrison et al., 2021; Meissner and Kotsemir, 2015). Additional uncertainty barriers constitute uncertain impacts on animal welfare through potential cow health issues (Holohan et al., 2021; Lybæk and Kjær, 2019), uncertainty over detrimental impact on farm output (Holohan et al., 2021; Van den Berg et al., 2023) and legal uncertainties facing farmers (Doidge et al., 2024; Puupponen et al., 2022).

4.4.5. Technological and practice related

Technological and practice related barriers may constitute burdensome adoption requirements, negative effects, perceived ease of use and perceived usefulness. Adoption of innovations towards environmental sustainability in cattle farming normally require increased inputs. This may include increased resource requirements, such as more straw, irrigation water or fertiliser (e.g., Bechini et al., 2020; Daxini et al., 2018), being overly time-consuming to implement (e.g., Holohan et al., 2021; Westerink et al., 2024), requiring additional skills, training and management structures (e.g., Holohan et al., 2021; Horrillo et al., 2016), new infrastructure (e.g., Doidge et al., 2024; Holohan et al., 2021; Pedersen et al., 2024) and being labour-intensive (e.g., Jordon et al., 2023; Lybæk and Kjær, 2019).

Environmentally sustainable innovations occasionally bear unintended consequences to cattle farms, harming its adoption, including harming farm production (e.g., Díaz de Otálora et al., 2024; Horrillo et al., 2016; Westerink et al., 2024). Adoption may also result in environmental side effects or costs (e.g., Díaz de Otálora et al., 2024; Herzog et al., 2021) or potential damage to cow health (e.g., Doidge et al., 2024; Holohan et al., 2021).

Farmers may not adopt due to concerns surrounding innovations being impractical or infeasible (Doidge et al., 2024; Harrhill et al., 2022; Van den Berg et al., 2023). Similarly, farmers may perceive some sustainable innovations as overly complex and difficult to use (Doidge et al., 2024; Harrison et al., 2021) or feeling that they lack access to sufficient technical support (Bianchi et al., 2022).

4.4.6. Policy and regulation

Policy and regulation barriers are classified under farmer policy perceptions, ineffectual policy and stringency. Some farmers have mentioned perceiving a power imbalance in how policy decisions are made without their involvement, citing a lack of opportunity to

participate in discussions that determine their own futures and not being listened to by those in power (Harrahill et al., 2023; Hoes and Aramyan, 2022; Murphy et al., 2022). Farmers have also perceived certain environmental sustainability-related regulations and policies as unclear or untrustworthy, leading to frustration and uncertainty (Harrahill et al., 2023; Hoes and Aramyan, 2022). Finally, some farmers consider environmental policies to be a threat (Harrahill et al., 2023).

The most prominent hindrance concerning policy and regulation is the ineffectuality of relevant policies. *Overly standardised* policies and legislation are largely insufficient at considering the heterogeneity of the sector, including different farm types or sizes, often lacking adequate support for smaller farms, farms producing both beef and dairy or farms employing circular initiatives (e.g., Ayala et al., 2024; De Lauwere et al., 2022; Hoogstra et al., 2024; Pedersen et al., 2024). Additionally, institutional support is lacking when it comes to delivering required assistance through grants, subsidies and other governmental schemes needed to minimise cost and other burdens farmers shoulder when adopting environmentally sustainable innovations (e.g., Hoogstra et al., 2024; Irwin et al., 2023; Murphy et al., 2022; Verburg et al., 2022).

4.4.7. Public and consumer challenges

Finally, public and consumer barriers are categorised under knowledge, resistance and preferences and attitudes. Similar to farmers lacking knowledge, the public lacking knowledge on environmentally sustainable innovations hinders adoption. This may manifest in the public not being aware of the benefits of environmentally sustainable innovations, or may result in societal acceptance thereof to depend on the levels of trust commanded by respective farmers (Langer and Kühl, 2024; Stampa and Zander, 2022).

Considering societal preferences and attitudes, a major roadblock is consumers being unwilling or unable to spend more money on agricultural goods from farms employing potentially costly environmentally sustainable practices, including pesticide-free and/or organically reared cattle (e.g., Markova-Nenova and Wätzold, 2018; Pedersen et al., 2024; Wendt and Weinrich, 2024). Some studies report on society prioritising animal welfare in agricultural goods over environmental sustainability, with consumers being willing to pay more for such products, possibly rejecting farming innovations that could harm animal welfare (Langer and Kühl, 2024; Markova-Nenova and Wätzold, 2018; Stampa and Zander, 2022).

4.4.8. Interrelationships and importance of barriers

The above barriers should not be treated exclusively like independent constructs, as they are sometimes interrelated and may co-occur. Recognising these interrelationships is important for developing holistic understanding of where adoption failures originate and which interventions are most likely to enable positive outcomes. Table 5 presents the prevalence, co-occurrences and Jaccard values of the respective main barrier categories with their top partner, as well as the countries in which a barrier appeared in more than half of the studies (with minimum 3 occurrences), enabling a critical analysis of the interrelationships between the barriers. Full co-occurrence and Jaccard value matrices are available in the appendix (Tables A.2, A.3). It is important to note that these interrelationships describe patterns of co-reporting in the literature, revealing associations rather than causal links.

Table 5 shows that whilst farmer attitudes (27 studies) and farm and farmer attributes (26 studies) were the most frequently reported barrier categories, public and consumer challenges appeared in only 6 studies. It is imperative to note that a low frequency in this sample does not necessarily imply that a barrier is less important, but rather, less researched. All but one of the studies identifying public and consumer challenges barriers were located in Germany, indicating a clear absence of research on this barrier in other European countries. Conversely, as mentioned in Section 4.4.3, while finance barriers do not appear the most, they were often noted in the sample as particularly important, with initial costs of introducing new technologies and practices and

Table 5
Main barrier data information.

Barrier	Prevalence	Main partner (Co-occurrence; Jaccard)	Country prevalence
Farm and farmer attributes	26 (46%)	Technological and practice related (15; 0.429)	Ireland (10 of 18 studies)
Farmer attitudes	27 (48%)	Information and uncertainty (13; 0.371)	UK (7 of 7 studies)
Finance	24 (43%)	Technological and practice related (16; 0.500)	Netherlands (6 of 10 studies), Ireland (10 of 18 studies)
Information and Uncertainty	21 (38%)	Farmer attitudes (13; 0.371)	Norway (3 of 4 studies), UK (5 of 7 studies)
Policy and regulation	19 (34%)	Farmer attitudes (12; 0.353)	Netherlands (7 of 10 studies)
Public and consumer challenges	6 (11%)	Policy and regulation (2; 0.087)	Germany (5 of 8 studies)
Technological and practice related	24 (43%)	Finance (16; 0.500)	Ireland (11 of 18 studies), Italy (4 of 7 studies)

maintenance over time being critical factors limiting farmer adoption (e.g., Bianchi et al., 2022; De Lauwere et al., 2022; Van den Berg et al., 2023).

From a temporal perspective (see Appendix, Fig. A.3, A.4, A.5, A.7), 2024 emerged as the year in which the largest number of studies identified finance, information and uncertainty, technological and practice related barriers and policy and regulation, spanning the most diverse range of countries. This trend likely reflects the recent proliferation and promotion of projects evaluating sustainable innovations in cattle farming across Europe, such as anaerobic digestion and precision livestock farming technologies (Bianchi et al., 2022; Harrahill et al., 2023). These initiatives have drawn increased empirical attention to the practical implementation challenges encountered within specific policy contexts in recent years.

The co-occurrence and Jaccard matrices reveal principal interactions between barriers and show that technological and practice related barriers is the most relationally connected barrier category, exhibiting three of the five strongest pairwise associations. The most prominent inter-relationship is the nexus between finance and technological and practice related barriers, with a Jaccard value of 0.500 and co-occurring in 16 studies. This reflects a strong association, as innovations with substantial environmental sustainability potential commonly require both significant investment costs and additional skills, training or management structures to operate effectively (Bianchi et al., 2022; Harrahill et al., 2023). The second strongest pairwise association is between farm and farmer attributes and technological and practice related barrier categories, with a co-occurrence of 15 studies and a Jaccard value of 0.429. This pattern may reflect a misalignment between farm characteristics and specific innovations, as well as resistance among certain subgroups of farmers (e.g. those who are older or lack the required knowledge and skills), thereby hindering the adoption of these innovations (Daxini et al., 2018; De Lauwere et al., 2022; Jordon et al., 2023). The third strongest association is between information and uncertainty and farmer attitudes (Jaccard = 0.371, intersection = 13), indicating that these barriers appear together frequently in the sample studies. This aligns with prior empirical research showing that farmers' perceptions of risks and uncertainty are associated with their attitudes towards climate change mitigation and adaptation strategies, indicating that informational constraints and attitudinal responses are closely intertwined (Arbuckle et al., 2015; Eitzinger et al., 2018). Lastly, the co-occurrence and Jaccard matrices reveal public and consumer challenges as the most isolated category with the weakest pairwise associations. This reflects the low prevalence of this category and highlights the gap in the

literature, underscoring the need for future research to explicitly link public and consumer challenges to farmer adoption behaviour.

5. Discussion

Our systematic review contributes to the growing body of literature on the adoption of innovations aiming to achieve sustainable farming in four main ways.

5.1. Synthesis of barriers

First, we provide a comprehensive synthesis of barriers to the adoption of environmentally sustainable innovations in cattle farming, one of the most environmentally impactful agricultural sectors. Unlike most existing studies that focus on barriers to a single or a limited set of innovation types (e.g., Gallegos Rivero and Daim, 2017; Puupponen et al., 2022; Vermunt et al., 2022), or that examine a broader, heterogeneous agricultural context without concentrating on cattle farming (e.g., Campuzano et al., 2023; Long et al., 2016; Rose et al., 2016; Rose and Chilvers, 2018), our findings provide more targeted and in-depth information about future potential synergies among innovations applicable to cattle farming, as well as relevant barriers to their adoption. It is worth noting that certain barriers tend to be inherently more prominent for specific types of innovation, such as how organic farming adoption is frequently hindered by consumers not being willing or able to pay more for organic dairy and meat products, or how grazing management and cattle housing innovation adoption are often hampered by being labour intensive.

5.2. Public and consumer challenges

Second, the findings highlight a significant research gap: barriers stemming from public and consumer challenges are under-represented in the literature compared to technical or financial hurdles. This lack of attention is problematic, as these “social” barriers often represent the ultimate bottleneck to achieving a truly systemic transformation of the sustainable agri-food sector (Krampe et al., 2024). Public reaction to environmentally sustainable innovations has occasionally been a major roadblock. The adoption of Bovaer in select UK cattle farms—an innovative feed supplement potentially reducing cow methane emissions by 30–45%, for example, met severe public backlash following propagation of misinformation about its safety, inciting widespread boycotts of dairy products containing the additive and, in response, some farmers’ rejection of it (Eardley et al., 2024; Heiser, 2025; Mitloehner, 2025). This example illustrates how public perceptions may directly shape market dynamics and influence farmer decision-making beyond farm-level considerations.

Cases like the above highlight the importance of understanding the dynamic feedback loop between public perceptions and farmer adoption decisions. The feedback loop may operate through public misinformation or scepticism generating negative media coverage. This can influence consumer behaviour and potentially result in boycotts, which may in turn create market and reputational risk for farmers and potentially deter adoption or cause abandonment of previously adopted innovations. The influence of public reaction to farmer sustainable innovation adoption behaviour has received minimal empirical research in the context of European cattle farming, representing a critical gap in the adoption literature. This may stem from adoption-focused research historically centring on farm-level decision-making, where demand-side dynamics are often treated as external, rather than integral to the adoption process. We suggest that future studies investigate 1) what characteristics of sustainable agricultural innovations make them particularly vulnerable to public backlash; 2) what communication strategies may be used to prevent the spread of misinformation about sustainable innovations in farming; and 3) how farmer support networks and advisory services can buffer against the reputational risks associated

with innovation adoption.

Addressing these questions, however, requires careful consideration of both theoretical and methodological aspects to fully capture the complexities of the innovation adoption process. The theoretical approaches commonly used to explain innovation adoption in cattle farming, such as the Theory of Planned Behaviour (TPB) and the Technology Acceptance Model (TAM), cannot capture this feedback loop due to being largely linear and static in nature or application, representing a major limitation in existing studies.

Therefore, alternative frameworks such as the Social Cognitive Theory could be considered (Kamali et al., 2025). This would allow for the exploration of dynamic interactions, such as how farmers engage with peers, stakeholders and their environments, which can result in both the adoption and non-adoption of innovations. Furthermore, it would help examine how the use of innovations may reinforce or reshape perceptions over time, ultimately affecting whether farmers continue using or abandon these innovations. Methodologically, a triangulated approach can be employed. A dyadic longitudinal survey design, which collects data from the public and farmers within the same regional clusters over 3–5 years, can enable cross-lagged panel analysis to disentangle the reciprocal relationship between public backlash and adoption. Fuzzy-set Qualitative Comparative Analysis can subsequently be employed to identify the specific configurations of social, economic and institutional conditions that trigger innovation adoption or rejection. These empirical insights can then parameterise agent-based models to simulate feedback loops between media coverage, public attitudes and farmer decision-making. This allows for the prediction of system-level behavioural shifts under varying scenarios, such as fluctuating levels of misinformation and stakeholder engagement.

5.3. Theoretical implications and farmer identity

Third, this study advances the literature by proposing a conceptual framework (Fig. 5) that integrates the dynamic, identity-centred processes that shape adoption decisions. We argue that the role of farmer identities in innovation adoption should be further explored. Farming is more than just a business; it is closely tied to a farmer’s sense of self and the roles they are expected to perform in society (Groth and Curtis, 2017; Letourneau and Davidson, 2022; Vayro et al., 2020). Therefore, how farmer identities evolve and interact with other factors in shaping decision-making around innovation adoption warrants further investigation. This dynamic process may be more effectively examined through the lens of Social Cognitive Theory. Such an approach should ideally be applied specifically to cattle farming, given the distinct practices and stakeholder networks that differentiate it from other farming sectors. Most importantly, research should move beyond framing farmers solely as having businesspeople identities (Leduc and Hansson, 2024).

5.3.1. Conceptualising farmer identity and framework overview

The conceptual framework links farmer identity to the barriers identified in this study and innovation adoption outcomes. It illustrates how farmer identity shapes not only how barriers to adoption are perceived, but how farmers respond to them in their decision-making processes, as explained below.

As depicted in Fig. 5, A., farmer identity is conceptualised as comprising two interdependent dimensions, being farmer self-identity (encompassing farmers’ values, self-perception, beliefs and self-categorised farmer types) and farmer social identity (arising from interactions within farmers’ social groups, including role expectations and social capital within networks). These dimensions are continuously constructed and reconstructed through social interaction and meaning-making, showing that identity is not fixed but is an evolving construct. This framework therefore conceptualises farmer identity as dynamic rather than static, in contrast to TPB and TAM, which typically operationalise behaviour through pre-established mental constructs and offer limited scope for capturing the dynamic and socially embedded

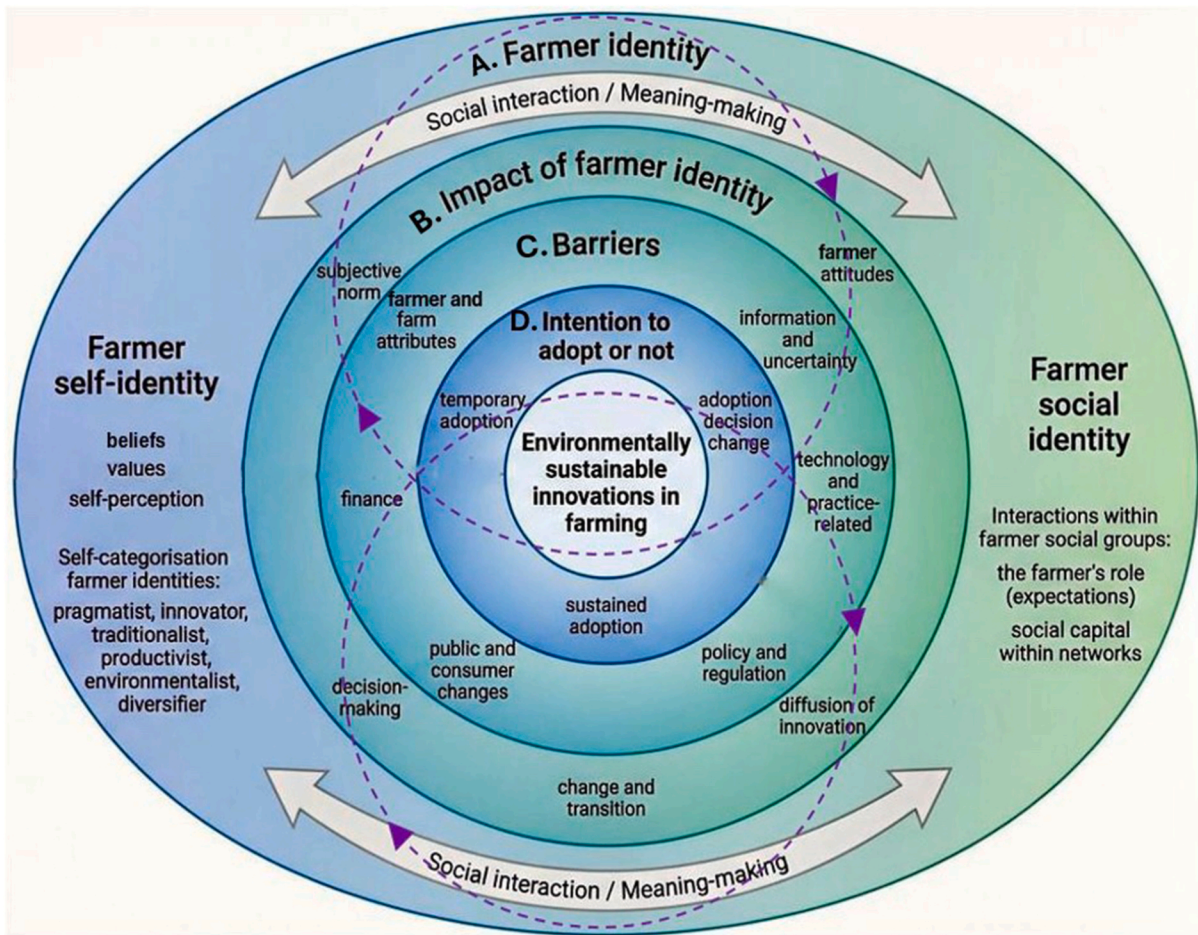


Fig. 5. Conceptual framework.

nature of identity.

5.3.2. Identity and barrier perception

In Fig. 5, level B., farmer identity shapes the attitudinal, normative and decision-making processes through which farmers evaluate barriers (with farmer attitudes themselves forming a barrier). Specifically, self-identity influences farmer attitudes towards sustainable innovations (e.g., whether a practice is perceived as consistent with being a 'good farmer'), while social identity shapes subjective norms (e.g., perceived approval or disapproval from others in the farming community). Additionally, the social capital within farmers' social networks could facilitate or hamper the change of attitudes and transition to new approaches and, ultimately, the diffusion of innovations (see the link with Diffusion of Innovation Theory). Together, these processes feed into adoption decision-making, encompassing perceptions of risk, ease of use and compatibility with farmer objectives. These processes also align with and extend constructs central to TAM and TPB.

This flows into C., the barrier categories identified in this study. The framework links farmer identity to these barriers by illustrating how the barriers are not experienced the same, but are interpreted and mediated through identity, resulting in differences in how barriers influence adoption decisions.

For example, a farmer identifying as a productivist may interpret financial barriers as more critical constraints compared to an environmentalist farmer, who may place greater emphasis on environmental benefits, despite potential financial hindrances. Similarly, a farmer holding a traditionalist identity may assign greater importance to technology and practice-related barriers (such as perceived ease of use) than a more adaptive, pragmatist farmer. Information and uncertainty

barriers are shaped by identity through distrust of non-peer knowledge sources and deliberate information avoidance. Here, farmers disengage from evidence that could create dissonance with their self-image. Farm and farmer attributes barriers are similarly identity-mediated, as productivist or traditionalist farmers are more likely to treat structural constraints as reasons for non-adoption. Farmer attitudes are most directly constituted by identity, as factors such as climate change denial and resistance to environmental measures are direct expressions of farmers' self-concept and may not be addressed by information provision alone. Policy and regulation barriers may be amplified when perceived regulations threaten farmers' identity as food producers. *Overly standardised* regulations, in turn, may exacerbate resistance by failing to account for differences in how farmer identity types view environmental obligations. Finally, public and consumer challenges feed into adoption decisions through farmers' social identity, where hostile consumer reactions may threaten farmers who have adopted sustainable innovations, as illustrated by the Bovaer case.

These variations demonstrate that farmer identity shapes the relative importance of barrier categories, thereby structuring how farmers prioritise constraints and make adoption decisions.

5.3.3. Dynamic adoption processes

Finally, in Fig. 5, Level D., innovation adoption outcomes vary from non-adoption to temporary or sustained adoption and incorporates the possibility of a farmer changing their initial adoption decision. This captures the longitudinal, non-linear nature of adoption processes, addressing the limitation of static adoption models. The farmer's attitudes, subjective norms and decision-making, together with the social capital within the farmer's social network, will ultimately determine

whether the barriers can be overcome to confirm their willingness to embrace environmentally sustainable innovations. This conceptual framework illustrates that, while identifying the barriers to sustainable innovation adoption in farming is essential, understanding how farmer identity shapes responses to these barriers is critical.

5.3.4. Conceptual framework research agenda

While our conceptual framework establishes a link between farmer identity and the adoption of sustainable innovations in European cattle farming, there is a need to move beyond general correlations. Future research should empirically validate these relationships by quantitatively testing how specific identity profiles intensify or mitigate particular barriers. The following hypotheses are proposed for future testing:

H1. The adoption of sustainable innovations is significantly more constrained by financial barriers among farmers with a productivist identity than among those with an environmentalist identity.

H2. The adoption of sustainable innovations is significantly more constrained by technology-related barriers among farmers with a traditionalist identity than among those with a pragmatist identity.

H3. Perceived social identity congruence (the degree to which an innovation is seen as fitting the farming community to which a farmer belongs) moderates the relationship between information-related barriers and adoption intention, such that higher congruence mitigates the negative impact of these barriers.

5.4. Policy implications

Fourth, our findings provide both shared and country-specific implications for policymaking. Initiatives aimed at promoting sustainable innovations in cattle farming at a European level should address the barriers of greater importance as priority, such as technological and practice-related barriers, finance, and farm and farmer attributes. However, addressing technological and practice-related barriers may be more effective in increasing adoption if finance and farm and farmer attributes are considered in tandem. Some barriers are more prominent in certain countries, such as technological and practice-related barriers for Ireland and Italy, public and consumer challenges barriers for Germany and information and uncertainty for Norway and the UK and should be addressed effectively through country-specific initiatives.

Policymakers should explicitly consider farmer identities in policymaking to facilitate cattle farmers' transition towards embracing sustainable innovations. Prior to intervention design, extension services should use a diagnostic tool, e.g. developed by leveraging and adapting validated identity scales, to segment the farming population, while also capturing individual attributes (such as trusted stakeholders and information sources) and farm-specific characteristics during routine farm advisory visits. Such a baseline allows agricultural advisors to deliver tailored messaging that resonates with the core values of each segment, for instance, emphasising economic resilience for productivists versus ecological outcomes for environmentalists, using each group's preferred communication channels. Policy should also actively foster cross-segment peer learning. For example, facilitating structured dialogue between innovators and pragmatists can provide the social validation needed for broader adoption, lowering perceived transition risks and encouraging greater acceptance of sustainable innovations.

Moreover, the heterogeneous effects of self-identities on farmers' innovation adoption should also be accounted for to inform more targeted policymaking. For example, the experiences of small-scale farmers—those operating on fewer than 5 ha and accounting for 63.8% of farms in the European Union—are especially shaped by a sense of belonging, social connectedness, and safety, rather than a sole focus on agricultural productivity (Eurostat, 2022; Iles et al., 2020; Trauger et al., 2010). Additionally, there are significant differences in the farmer identities held across European countries, shown by Jin et al. (2024) in

their study of Spanish, Swiss, Swedish, UK and Czech farmers. This underscores the need for policymakers to understand the prevalent farmer identities inside their countries to enable tailored policies and communications to local contexts.

5.5. Limitations and future directions

Limitations of this study include that the nature of the papers included in our systematic review did not allow us to account for the distinction between farmer adoption of innovations and their actual continued use, where innovations become 'locked-in' and their use becomes entrenched in a farm's operations (Arthur, 1989; Meynard et al., 2018; Zhao et al., 2020). There might be additional barriers preventing the use of environmentally sustainable innovations from becoming dominant and continuing indefinitely. We recommend that future research be conducted longitudinally, to study whether farmers have maintained their use of such innovations over time and to explore the causal mechanisms underpinning their maintained use. Additionally, this review does not include formal quality appraisal of included studies, due to the high heterogeneity in study designs of the literature sample analysed. This made the application of a single quality appraisal tool impractical. This may limit the assessment of methodological rigour across studies and should be considered in light of potential variation in study quality. Whilst the coding process was conducted systematically, it necessarily involved interpretation to categorise barriers. Future studies could formally assess inter-rater reliability to further strengthen methodological transparency. The exclusion of grey literature and non English-language sources may have introduced some publication bias, potentially underrepresenting barriers salient in countries with limited English research outputs. Furthermore, this review focused on European countries only; therefore, the identified barriers and their relative importance cannot be directly generalised to other regions, particularly those with substantially different socioeconomic and cultural contexts. For example, information- and uncertainty-related barriers to innovation adoption may be more prominent or pronounced in societies characterised by relatively low levels of trust in government institutions and agricultural companies (Carolan, 2006; Jayashankar et al., 2018; Köster et al., 2025). These results may also not be generalisable to Eastern European countries, as a very limited number of studies relevant to this review were conducted in that region. Thus, future research examining other regions is recommended to uncover how contextual conditions, along with farmer-, farm- and innovation-related barriers, co-evolve and jointly influence the trajectory of innovation adoption. Lastly, as public and consumer-related barriers are less explored than other obstacles, we suggest that future studies should further investigate such barriers to understand what factors precipitate public outcry and negative perceptions towards sustainable innovations and explore mechanisms for meaningfully integrating public opinions into innovation management processes, in order to prevent widespread public rejection.

6. Conclusion

In conclusion, this systematic review synthesises barriers to the adoption of environmentally sustainable innovations in European cattle farms across 56 peer-reviewed research articles. The review identifies and examines the interrelationships between seven main barrier categories: farm and farmer attributes, farmer attitudes, information and uncertainty, technological and practice-related, policy and regulation, finance and public and consumer challenges.

A key contribution of this review is the identification of public and consumer challenges as a critically under-researched barrier category despite its potential importance. This barrier appears in only six studies, of which five were located in Germany. The Bovaer case illustrates how public misinformation can generate a feedback loop from consumer behaviour to farmer adoption decisions, a dynamic that existing linear

adoption models are unable to capture.

To address this theoretical gap, this review proposes an original conceptual framework centred on farmer identity that integrates constructs from the Theory of Planned Behaviour, Diffusion of Innovations and Technology Acceptance Model. This framework generates potential future research directions and offers a practical tool for policymakers to design identity-sensitive interventions. Ultimately, fostering the adoption of environmentally sustainable innovations in cattle farming is not merely a financial or technical challenge, but is a social and identity-related challenge that requires approaches that match its complexity.

CRedit authorship contribution statement

Roland Reinhold Bezuidenhout: Writing – original draft, Visualization, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Paul Trott:** Writing – review & editing, Supervision, Conceptualization. **Shan Jin:** Writing – review & editing, Supervision, Conceptualization.

Declaration of competing interest

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

Appendix A. Supplementary data

Supplementary data to this article can be found online at <https://doi.org/10.1016/j.jenvman.2026.129767>.

Data availability

Data will be made available on request.

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