Journal of Industrial Ecology
https://doi.org/10.1007/s44498-026-00076-2

REVIEW

Industrial symbiosis in the wine value chain: a systematic review of research trends, barriers, and drivers

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Received: 29 September 2025 / Accepted: 6 April 2026
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Abstract
The wine industry generates large volumes of by-products with high valorization potential, making Industrial Symbiosis (IS) a key strategy for its circular transition. However, the supporting academic literature remains fragmented, hindering a clear understanding of its dominant trends and knowledge gaps. This systematic review maps the research landscape of IS in the wine value chain to identify its trends, thematic focuses, and research clusters. Following the PRISMA methodology, a search was conducted in Scopus and Web of Science, yielding a final sample of 122 articles. The synthesis combined descriptive statistics with a thematic analysis of key dimensions (methodologies, geographical areas, by-products, recipient industries stakeholders, drivers and barriers), followed by a cluster analysis on the 99 original research articles to identify distinct thematic patterns and research approaches. Results reveal a research field in an early stage of maturity, with a predominance of experimental laboratory studies (60%) focused on grape pomace. Technological issues emerge as the primary barrier (91.9%), while environmental sustainability is the main driver (94.9%). Cluster analysis identifies three distinct research trends: a dominant technocentric stream focused on high-value applications, a second centered on bulk bioeconomy solutions, and a critically underdeveloped cluster focused on systemic implementation. This paper reveals a significant gap between the explored technical potential and the under-researched socio-organizational dimensions required for real-world implementation. In conclusion, this study establishes a roadmap for future research, highlighting the need to shift focus towards business models, collaborative governance, social acceptance, and scaling-up strategies to realize the full potential of IS.

Keywords Wine value chain · Industrial symbiosis · Circular economy · Systematic review · Cluster analysis · Industrial ecology

1 Introduction

In 2023, a total of 7,141,570 hectares of vineyards were cultivated to produce 237.3 million hectoliters of wine from 74,684,758 tonnes of fresh grapes (OIV, 2024). Considering established generation rates —such as 1.70 to 3.05 tonnes of pruning waste per hectare, grape pomace accounting for approximately 20% of the grape weight, grape stems for 4%, and wine lees for 1.5% (BioVino, 2021)— this volume of production is estimated to generate over 35 million tonnes of by-products annually. This figure does not include other significant streams such as vine leaves, discarded grapes, or winery wastewater.

Given the substantial volume of by-products generated by the wine industry, the transition from a linear economic model to a Circular Economy (CE) represents a key strategy for waste reduction and resource efficiency (Geissdoerfer et al., 2017). Within this paradigm shift, Industrial Symbiosis (IS) emerges as a fundamental operational mechanism, defined as a collaborative inter-firm strategy for mutual benefit through the cyclical exchange of materials, energy, and water (Chertow, 2000; Lombardi & Laybourn, 2012), and has been identified as a relevant business model strategy for closing resource loops (Bocken et al., 2016). As a major global agri-food industry, the wine value chain is an ideal case study for applying these principles due to its large-scale generation of by-products rich in high-value biocompounds (Beres et al., 2017).

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Moreover, the spatial dimension of innovation plays a decisive role in the emergence of IS. According to the theory of regional innovation systems (Asheim & Gertler, 2006; Asheim et al., 2019; Fernandes et al., 2021) and industrial clusters (Porter, 1998), knowledge creation tends to concentrate geographically around specific industrial agglomerations to minimize transaction costs and facilitate tacit knowledge exchange. In the context of the circular bioeconomy, geographical proximity becomes a critical economic driver due to the high logistical costs of transporting low-density biomass (Chertow, 2000; Arfaoui et al., 2024). Consequently, mapping the geographical distribution of research is not merely a descriptive exercise but a necessary step to verify if scientific production aligns with actual wine-producing regions, thereby supporting regional smart specialization strategies (Foray, 2014).

Recent scholarship highlights that Circular Economy research is often fragmented and requires robust theoretical scaffolding to transcend descriptive analysis (Aryee, 2025; Blomsma et al., 2023). Furthermore, the transition from linear to circular models in agri-food systems faces specific challenges that differ from general industrial contexts (Hamam et al., 2023). Accordingly, to structure this review, we integrate three complementary theoretical perspectives into a cohesive Analytical Framework (operationalized in Sect. 2.4):

First, from a resource efficiency perspective and serving as the normative baseline, true circularity requires adhering to the waste hierarchy, prioritizing high-value upcycling and cascading use over simple energy recovery or disposal (Ellen MacArthur Foundation, 2013; European Parliament Council, 2008; Kirchherr et al., 2023). This implies that effective IS should not merely treat by-products as waste to be managed, but as inputs for new value chains, necessitating a shift towards "closing the loop" business models (Blomsma et al., 2023; Bocken et al., 2016; Stahel, 2010). Therefore, analyzing recipient industries is crucial to determine if the sector is moving towards high-value applications or remaining in lower-tier recovery.

Second, the translation of scientific potential into industrial reality is often hindered by the "Valley of Death" of innovation (Markham et al., 2010). Assessing the maturity of a field requires distinguishing between theoretical exploration in controlled environments and validated industrial solutions. The Technology Readiness Level (TRL) framework (Mankins, 1995) serves as a critical lens to diagnose this gap. A predominance of low-TRL studies (laboratory scale) without a corresponding rise in real-scale implementation suggests a field struggling to transition from "Science-Push" to "Demand-Pull" dynamics (Hekkert et al., 2007).

Third, from a socio-technical ecosystem perspective (Geels, 2019), IS is inherently a social process, reliant on "institutional capacity" and the "social scaffolding" required to coordinate diverse actors (Boons & Spekkink, 2012). The resilience of symbiotic networks depends heavily on "social embeddedness" (the trust, reciprocity, and governance structures established among stakeholders) rather than merely on the technical feasibility of material flows (Lombardi & Laybourn, 2012). The stakeholders, understood as any group or individual that can affect or be affected by a focal issue (Freeman, 2004), involves actors ranging from businesses, policymakers, academics, non-governmental organizations, and citizen groups at the forefront (Kirchherr et al., 2018). Consequently, ignoring the stakeholder structure and non-technical barriers leads to a fragmented understanding of why IS initiatives succeed or fail. This systemic view is crucial to understand the complex symbiotic networks (Sellitto et al., 2025) required for success.

Lastly, from a socio-technical transition perspective, the shift from linear to circular systems is often impeded by substantial "lock-in" mechanisms that favor existing regimes (Geels, 2011). Consequently, characterizing the enabling environment requires distinguishing between "hard" factors (technical, economic/financial/market) and "soft" factors (institutional/regulatory and social/cultural) (de Jesus & Mendonça, 2018). As empirically demonstrated by Kirchherr et al. (2018), cultural and market barriers are frequently more prohibitive than technological limitations in the circular economy transition. Therefore, a systematic mapping of barriers and drivers is not merely descriptive but essential to identify the specific leverage points needed to unblock the adoption of IS.

However, a critical disconnection persists between the theoretical potential of these by-products and the effective implementation of symbiotic networks. While the primary literature on winery by-products is extensive, the existing body of knowledge remains highly fragmented compared to the broader Circular Economy scholarship, which is increasingly focused on theoretical systematization (Aryee, 2025) and business model innovation (Rentería Núñez & Perez-Castillo, 2023).

As summarized in Table 1, which strictly presents the landscape of review articles identified through our systematic search protocol, the current wine-specific literature predominantly adopts a technocentric focus. A significant portion of reviews characterizing single by-products like grape pomace for bioactive recovery (Bordiga et al., 2019; Kokkinomagoulos & Kandylis, 2023), or concentrates on validating specific valorization technologies (Mateo & Maicas, 2015; Zacharof, 2017). Although recent works have begun to map the domain (Abbate et al., 2025) and explore circular ecosystems (Agnusdei et al., 2025), the mainstream literature still largely focusing on *what* can be technically achieved, often neglecting the systemic governance and network challenges (Sellitto et al., 2025) required to implement these exchanges in the real-world.

Table 1 Thematic overview of previous literature reviews on winery by-products identified through the systematic search process

CE focus	Reference	Waste stream	Key contribution to CE and IS
LCA and sustainability management	(Abbate et al., 2025)	General / System-wide	Identifies the gap between CE theory and practical implementation; highlights the need for industrial symbiosis managerial strategies
	(Abinandan et al., 2024)	Farming / Wastewater	Uses Life Cycle Assessment (LCA) to demonstrate how eco-innovations (e.g., constructed wetlands) reduce the carbon footprint of wine production
	(Marques et al., 2025)	Agri-food System	Reviews LCA integration with CE principles, identifying environmental hotspots to optimize resource use across the cradle-to-grave cycle
	(Soceanu et al., 2021)	Grape Pomace	Analyzes the economic efficiency of waste recovery, linking physicochemical characteristics to economic viability in waste management
Biorefinery (cascading use)	(Jin et al., 2018)	Plant-derived waste	Proposes integrated processing (biorefinery) to produce multiple value-added products, minimizing waste generation compared to single-component extraction
	(Zacharof, 2017)	Solid & Liquid Waste	Framework for a winery biorefinery: using waste as feedstock for bioconversions to produce platform chemicals, biofuels, and energy simultaneously
	(Muhlack et al., 2018)	Grape Marc	moves beyond composting to advanced biorefinery strategies, including integrated ethanol production followed by bioenergy generation from spent marc
Material recovery: high-value bioactives (upcycling)	(Constantin et al., 2024)	Pomace, Skins, Lees	Reviews the transition from linear disposal to a circular bioeconomy by recovering antioxidants and functional compounds for health industries
	(Lopes et al., 2025)	Grape Pomace	Focuses on sustainable extraction methodologies for phenolic compounds, targeting pharmaceutical and cosmetic sectors
	(Chedea et al., 2021)	Pomace, Seeds, Cane	Proposes utilizing by-products for complementary therapies (ischemic heart disease), turning waste into high-value nutraceuticals
	(Tapia-Quirós et al., 2022)	Winery & Olive Waste	Discusses purification techniques for polyphenols to solve environmental problems through cross-industry valorization (olive and wine sectors)
	(Bordiga et al., 2019)	Grape Pomace	Assessing the "maturity" of valorization technologies, confirming that pomace recovery is now a consolidated industrial residue management strategy

Table 1 (continued)

CE focus	Reference	Waste stream	Key contribution to CE and IS
Material recovery: food and agricultural applications (re-use)	(Mainente et al., 2019)	Pomace Powder	Food fortification: Re-introducing stabilized pomace into the food chain (meat/fish derivatives) to enhance sensory and preservation properties
	(Plakantonaki et al., 2023)	Plant-based Waste	Valorization of dietary fibers to support zero-waste economies by creating secondary raw materials for food and textile industries
	(Kokkinomagoulos & Kandylis, 2023)	Grape Pomace	Reviews pomace applications (feed, fertilizer, packaging) within a CE vision, emphasizing the need for a legislative framework to support re-use
	(Toma et al., 2025)	Vineyard Residues	Agricultural Loop: Using natural polymers and recovered compounds to create protective coatings for vines, effectively using waste to protect the crop source
Wastewater valorization and energy recovery	(Kaur et al., 2024)	Wastewater	Recovery of Xanthan (biopolymer) from aerobic granular sludge, converting water treatment from a cost center to a resource recovery process
	(Li & Yu, 2020)	Wastewater	Microbial Electrochemical Technologies: Simultaneous treatment of wastewater and generation of electricity or hydrogen (Waste-to-Energy)
	(De Iseppi et al., 2021)	Wine Lees	Strategies for valorizing lees (sludge) to recover polysaccharides, preventing soil pollution associated with traditional disposal
	(Mateo & Maicas, 2015)	Winery & Oil Waste	Microbiological processes to convert residues into biofuels, enzymes, and edible mushrooms, offering a cost-effective alternative to physical/chemical treatments
	(Dell'Omo et al., 2014)	Biomass	Application of Hypercritical Separation Technology (HYST) for physical disaggregation of biomass to produce food ingredients and second-generation biomethane
Sector-wide circular economy reviews	(Provenzano et al., 2024)	Vinification Residues	Systematic review of waste-to-resource pathways across Food, Agriculture, and Energy sectors, highlighting the integration of waste into business models
	(Cozma et al., 2020)	Grape Pomace	General overview of environmental issues caused by disposal versus the potential of valorization strategies

However, despite their valuable contributions, these existing reviews present two main limitations that hinder a comprehensive understanding of IS implementation. First, the majority employ a narrative approach focused on specific technical niches (e.g., extraction technologies), often neglecting the systemic dimension required for IS. Second, and more critically, none have performed a structural and quantitative analysis of the overall research landscape to identify the disconnect between technical potential and actual implementation. This leaves a significant gap in understanding both the dominant research focus and the systemic barriers (technological vs. socio-organizational) limiting the transition. The present study is specifically designed to fill this theoretical and practical gap by applying not only a rigorous systematic review methodology but also an innovative thematic cluster analysis to characterize the different research typologies existing in the literature.

Accordingly, the main objective of this paper is to systematically analyze and synthesize the academic literature on Industrial Symbiosis in the wine value chain. To achieve this, and to diagnose the factors hindering the scaling-up of IS, the following specific objectives, framed as Research Questions (RQs), were defined:

– RQ1: What is the evolutionary trajectory, geographical distribution, and current state of the scientific production on IS in the wine industry? (To assess the field's consolidation, area focused, and growth patterns).
– RQ2: Which methodological approaches, by-product streams, and recipient industries dominate the research agenda? (To evaluate the alignment of research with the waste hierarchy and determine the Technology Readiness Level (TRL) of the field, distinguishing between theoretical exploration and industrial reality).
– RQ3: According to the literature, what are the main stakeholders, barriers, and drivers shaping the development of IS in this sector? (To map the socio-organizational scaffolding and identify the bottlenecks hindering real-world adoption).
– RQ4: Beyond descriptive trends, what underlying structural patterns, or research types, can be identified, and what do they reveal about the field's maturity? (To identify distinct research typologies and diagnose the systemic maturity of the CE transition in this sector).

By answering these questions, this article provides a robust and structured synthesis that serves as a roadmap for future researchers, practitioners, and policymakers interested in unlocking the potential of IS for the circular transition of the wine value chain. Beyond the sectoral analysis, this study contributes to the broader Industrial Ecology scholarship by providing an empirical methodology based on structural clustering and implementation maturity diagnosis to visualize the "gap" between technocentric research and systemic adoption. This approach offers a reproducible blueprint for diagnosing the circular transition maturity in other agri-food industries facing similar socio-technical bottlenecks.

The remainder of this paper is structured as follows. Section 2 presents the methodology, including the eligibility criteria, the study selection and data extraction process, and the methods used for aggregate analysis and synthesis. Section 3 presents the results of the selection process and the characteristics of the included studies, as well as the thematic and cluster analyses that answer the research questions. Section 4 discusses the findings, proposes a future research agenda, and outlines the study's own limitations. Finally, Sect. 5 summarizes the main conclusions and their implications.

2 Methods

This study was conducted and reported following the PRISMA 2020 (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) statement (Page et al., 2021). The protocol for this review was not previously registered. Following the principles of evidence-based practice in management research (Tranfield et al., 2003), this study is designed as a systematic mapping review framed within a pragmatic management review. This approach allows for a rigorous structural analysis of the field while aiming to provide insights relevant not only to the academic community but also to industry practitioners and policymakers.

2.1 Eligibility criteria

The criteria for study selection were established a priori to comprehensively address the research questions. Eligibility was determined based on five key dimensions: the economic sector, the activity of interest, expected outcomes, study type, and publication characteristics. These criteria are detailed in Supplementary Information SI1. The fundamental inclusion criterion required that a study described a real or potential symbiotic interaction, defined as the valorization of a by-product from the wine industry by a legally separate entity, either from another industry or from the same.

2.2 Information sources and search strategy

A systematic search was conducted in the Scopus and Web of Science Core Collection databases, selected for their extensive coverage of peer-reviewed academic literature (Zhu & Liu, 2020). The search was finalized in May 2025, with no publication date restrictions applied.

To ensure the retrieved corpus could effectively answer the proposed Research Questions (RQ1-RQ4), the search strategy followed a "Two-Pillar Logic" (detailed in Supplementary Information SI2):

- Pillar 1: The Wine Value Chain. A comprehensive set of keywords was defined to cover the entire sector, from primary production (e.g., "Viticulture", "Vineyard") to processing and waste generation (e.g., "Grape pomace", "Winery wastewater"). This exhaustive scope ensures that the analysis of by-products (RQ2) is not biased toward a single residue.
- Pillar 2: Industrial Symbiosis and Circularity. Since the term "Industrial Symbiosis" is not always explicitly used in older literature, this pillar included related concepts such as "Eco-industrial park", "By-product exchange", and "Waste valorization". This broad inclusion criteria allows for capturing implicit symbiotic networks required to identify barriers and stakeholders (RQ3).

The final search query consisted of the intersection of these two pillars (Pillar 1 AND Pillar 2), applied to the Title, Abstract, and Keyword fields. The full Boolean strings and specific keywords for each database are provided in Supplementary Information SI2.

2.3 Study selection

The search results were imported into the Zotero bibliographic management software for deduplication. Subsequently, the selection process was conducted by two reviewers in two distinct phases:

- Phase 1 (Title and abstract screening): The reviewers independently screened the titles and abstracts of all unique records against the eligibility criteria. Each article was classified as "include," "exclude," or "unclear."
- Phase 2 (Full-text assessment): The full texts of all articles classified as "include" or "unclear" were retrieved. Each full-text article was then thoroughly assessed to make a final inclusion decision. Any disagreements between the reviewers during either phase were resolved through discussion and consensus.

The study search and selection process is summarized in the PRISMA flow diagram (Fig. 1).

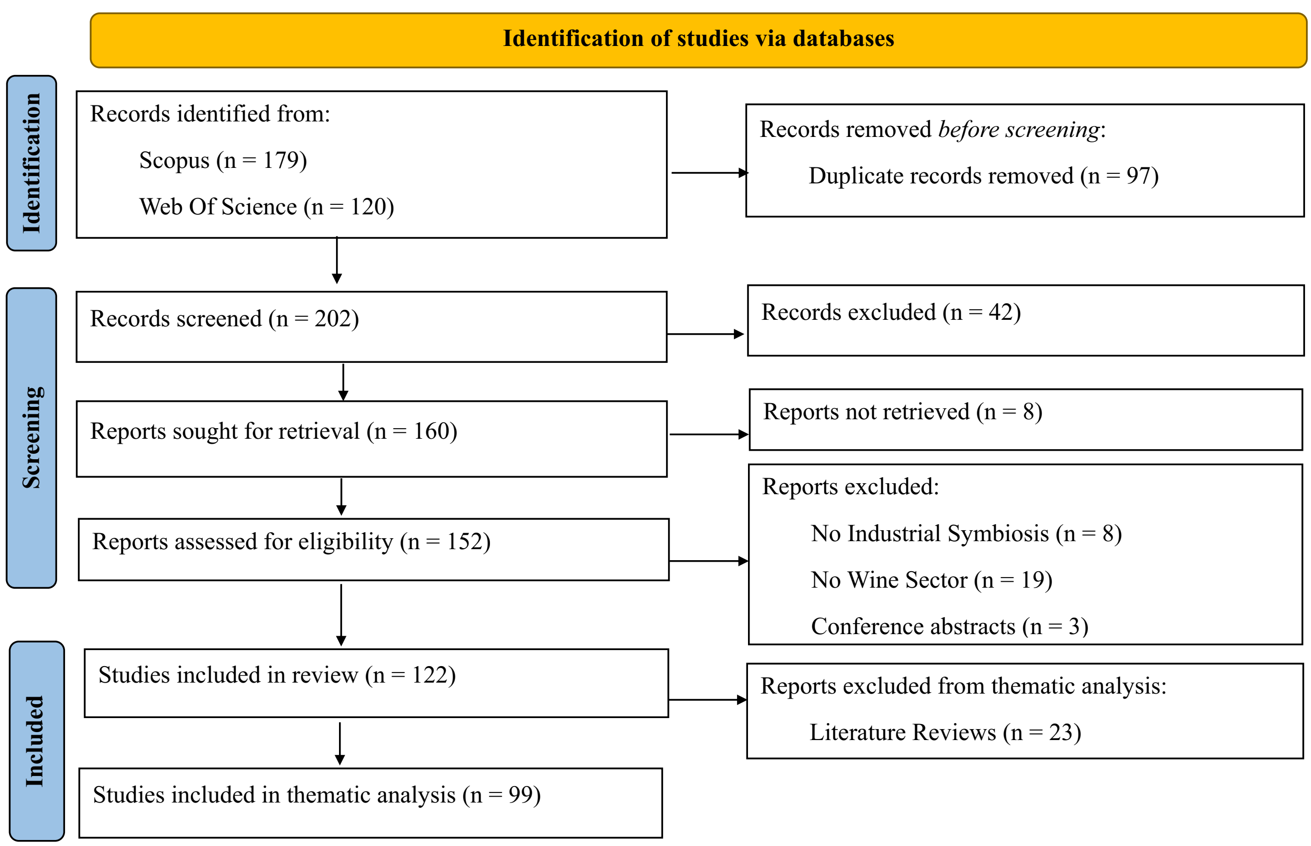

Fig. 1 PRISMA 2020 flow diagram of the study selection process

2.4 Data extraction process and analytical framework

A standardized data extraction form was developed in a spreadsheet to collect relevant information from each included study. The following data items were extracted: (a) bibliographic information (authors, year, journal); (b) geographical area of the study; (c) methodological approach; (d) type of winery by-product; (e) recipient industry; (f) stakeholders involved; and (g) mentioned barriers and drivers. The detailed operational definitions for each category are provided in Supplementary Information SI3.

Crucially, this process relied on a manual full-text assessment to generate a granular dataset, capturing specific nuances of IS implementation that are typically absent in bibliographic metadata. To ensure the analysis transcended a descriptive summary and aligned with the standards for framework-based reviews (Lim et al., 2022; Paul & Menzies, 2023), these variables were integrated into the analytical framework established in the Introduction:

- Evolution and context (a, b): To map the trajectory of the field and identify geographical clusters of research (RQ1).
- Maturity dimension (c): The methodological approach was used as a proxy for the TRL, distinguishing between theoretical exploration (lab-scale) and industrial reality (RQ2).
- Circular dimension (Items d, e): Mapping the nexus between by-products and recipient industries allows for assessing the alignment with the waste hierarchy (e.g., high-value upcycling vs. energy recovery) (RQ2).
- Systemic dimension (Items f, g): Stakeholders were coded to analyze the social embeddedness of the networks, determining if IS is driven by academic research ("science-push") or market demand ("demand-pull") (RQ3), while barriers and drivers were analyzed to diagnose specific bottlenecks hindering the transition to a circular wine industry (RQ3).

2.5 Data synthesis and analysis

The synthesis of the results combined a descriptive approach with advanced quantitative analysis. First, frequencies and percentages were calculated for the extracted categorical variables, and the temporal evolution of publications was analyzed.

To delve deeper into the literature's structure, a thematic cluster analysis was performed on the original research articles (N = 99). Distinct from bibliometric approaches that rely on metadata (e.g., co-citation or keyword co-occurrence), this study employs a content-based multivariate analysis applied to the manually coded dataset described in Sect. 2.4. This method allows for the grouping of studies based on the similarity of their thematic profiles. The process, facilitated by R software packages such as *factoextra* and *pheatmap*, was as follows:

- A binary data matrix (article × characteristic) was constructed. The full dataset, including the 23 literature reviews (marked as not applicable for thematic analysis), is available in Supplementary Information SI4 (1 = characteristic present; 0 = characteristic absent; NA = Not Applicable).
- The dissimilarity between articles was calculated using the Jaccard distance (Jaccard, 1901).
- An agglomerative hierarchical clustering algorithm was applied using the Ward.D2 linkage method (Ward, 1963).
- The optimal number of clusters was determined by triangulating the results from the average silhouette method (Rousseeuw, 1987), the elbow method (Thorndike, 1953), and a visual inspection of the dendrogram. The validation plots are shown in Supplementary Information SI5.
- Finally, the clusters were characterized by calculating the proportion of each thematic characteristic within each group and visualized using a heatmap.

A formal risk of bias assessment of individual studies was not performed, a decision consistent with the nature of this study as a systematic mapping review rather than an effectiveness synthesis. Given the high heterogeneity of study types included, applying a uniform bias scoring tool would be methodologically artificial and yield limited analytical value. Instead, analytical robustness was ensured through the rigorous PRISMA protocol, dual-reviewer screening, and a consensus-based coding process to minimize interpretive bias in the thematic analysis.

3 Results

3.1 Search results and screening outcomes

The initial database search identified a total of 299 records. After removing 97 duplicates, 202 unique articles were screened based on their title and abstract. In this phase, 42 articles were excluded for not being relevant to the research topic. The remaining 160 articles (105 classified as "include" and 55 as "unclear") were advanced to the full-text assessment stage.

Of these, 8 reports could not be retrieved (5 book chapters and 3 unavailable articles). After applying the eligibility criteria to the remaining 152 documents, a further 30 were excluded: 27 for not meeting the predefined criteria and 3 conference abstracts, as defined in the protocol. This resulted in a final sample of 122 articles for inclusion in the review.

The methodological approach of each of the 122 articles was identified. The 23 literature reviews were included in the descriptive analysis but excluded from the subsequent thematic and cluster analyses, for which a final sample of 99 original research publications was used.

3.2 Characteristics of the included studies

The chronology of publications (Fig. 2) confirms that the study IS in the wine industry is a recent and rapidly growing research domain. With a single pioneering study identified in 2005, 99.2% of the corpus was published in the period between 2013 and 2025. The publication trajectory follows an exponential growth pattern, with a Compound Annual Growth Rate of 12.7%. It should be noted that the apparent decline in 2025 is a direct result of the search being conducted in May 2025; thus, the final count for the year is expected to follow the upward trend.

The dissemination of this knowledge occurs across a diverse set of scientific journals, although a notable thematic concentration is observed. The journals *Foods* and *Antioxidants* (7 articles each) stand out as the primary publication outlets. They are closely followed by journals specializing in waste and biomass management, such as *Waste and Biomass Valorization* (4 articles), and in bioprocess engineering, such as *Food and Bioproducts Processing* (4 articles). The significant presence of cross-cutting multidisciplinary journals like *Sustainability* and *Applied Sciences* (4 articles each) is also noteworthy.

3.3 Thematic analysis

3.3.1 Geographical focus of the studies

The research is geographically concentrated in countries with well-established wine industries (OIV, 2024). The majority of studies focus on Italy (25%), closely followed by Spain (19.6%). Other Mediterranean countries such as Portugal (7.1%), Greece (5.4%), and France (4.5%) also feature prominently. A smaller yet significant number of studies are centered in other regions, including Australia, Lebanon, and Brazil (3.6% each).

3.3.2 Methodological approaches

The analysis of the methodological approaches employed in the literature reveals a research landscape clearly dominated by technical validation in controlled environments. The predominant category, by far, is Laboratory and Pilot Scale Studies, accounting for 60% of the total sample. This large portion of the research effort is primarily focused on three main streams:

– Methodologies for Bioactive Compounds: In studies aiming to recover high-value molecules, the methodological focus is strictly on extraction optimization and chemical characterization. As the most prominent experimental stream, research here prioritizes the identification and quantification of compounds, primarily polyphenols, utilizing advanced techniques such as ultrasound-assisted extraction (Bohn et al., 2024; Cisneros et al., 2024) deep

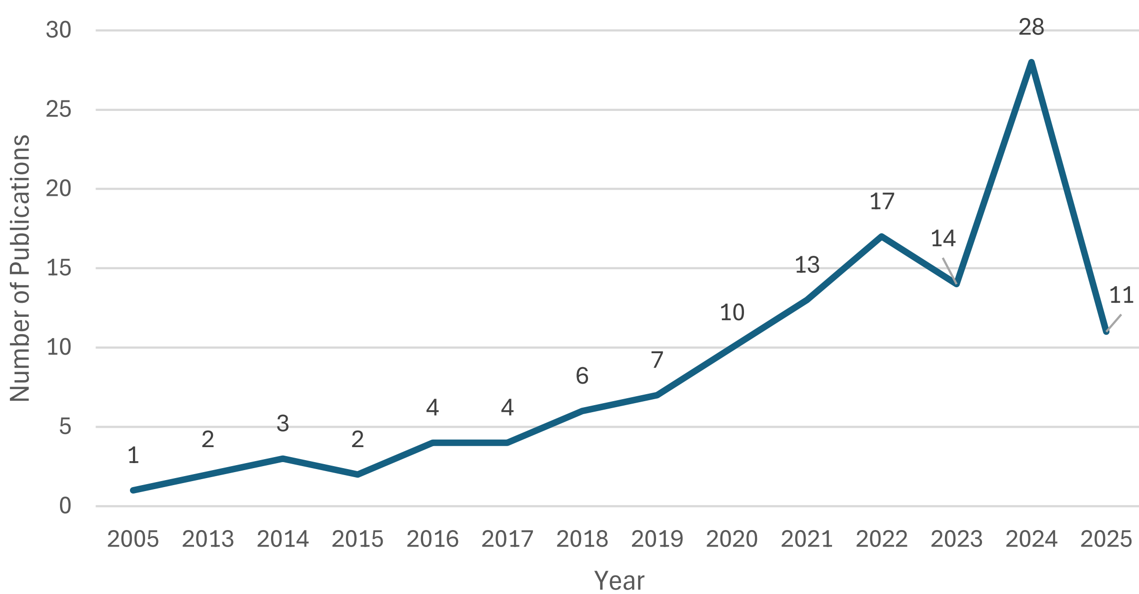

Fig. 2 Annual distribution of publications included in the systematic review (N = 122). The data for Fig. 2 can be found in Supplementary Information SI4 (Sheet “data_from_figure_2”)

eutectic solvents (Cioffi et al., 2023), or emerging techniques like ohmic heating (Coelho et al., 2023).

- Methodologies for Material Development: In contrast, research on new products employs formulation and physical testing methodologies. Here, experimental protocols focus on assessing the mechanical, structural, or sensory properties of the developed application. This encompasses the characterization of biomaterials, such as bio-adsorbents (Bustos et al., 2018; Duran et al., 2024) and sustainable construction materials (Font et al., 2018; Mendívil et al., 2017), as well as the formulation of new consumer products, such as functional foods (Balli et al., 2021; Jagadiswaran et al., 2021) or cosmetic formulations (Hubner et al., 2019).
- Methodologies for Bioconversion and Bioenergy: The third stream relies on bioprocess monitoring and kinetic analysis. Rather than product formulation, these studies utilize methodologies to evaluate biological or thermochemical conversion efficiency. Key examples include Biochemical Methane Potential (BMP) tests for anaerobic digestion (Díaz Domínguez et al., 2024; El Achkar et al., 2016), and fermentation monitoring for the production of biopolymers (Kovalcik et al., 2020; Martínez-Avila et al., 2021) or bio-based chemicals (Kucek et al., 2016).

In contrast to this strong experimental component, methodologies oriented toward systemic assessment and practical implementation have a notably smaller presence. Literature Reviews (14%) constitute the second-largest group, reflecting the need to synthesize knowledge in a rapidly expanding field. Meanwhile, Sustainability and Feasibility Assessments (6%), including LCA (Cortés et al., 2020; Ncube et al., 2021) and Techno-Economic Analysis (TEA) (de Souza Mesquita et al., 2024; Ioannidou et al., 2022), are still scarce despite their crucial importance in determining the real-world viability of the proposed solutions.

Similarly, Case Studies and Real-Scale Implementation (6%) and Social and Management Research (5%) are clearly underrepresented. The former offer valuable validation in operational environments (Belaud et al., 2017), while the latter explore the non-technological aspects essential for the success of IS, such as governance, collaboration, and business models (Czupryna et al., 2018; Mignani et al., 2024).

3.3.3 Valorization pathways: by-products, recipient industries, and their nexus

The thematic analysis reveals a clear hierarchy and specialization in the research focus, both in the by-products selected and in the target recipient industries. The interrelationship between these two axes, visualized through a flow analysis, allows for the creation of a detailed map of the main valorization pathways explored in the literature.

Grape pomace is established as the primary object of study, being the central focus in 55% of the analyzed articles, a figure consistent with its high generation volume and its recognized richness in bioactive compounds. The literature addresses its valorization both integrally, for applications such as enriching food products like pasta (Balli et al., 2021) or producing biogas (El Achkar et al., 2016), and fractionally, with a growing interest in its individual components. Specific studies focus on seeds for the extraction of oils and polyphenols (Chen et al., 2022; Salem et al., 2025) or on skins as a source of anthocyanins and fiber (Carullo et al., 2022).

The second tier of by-products follows at a considerable distance. Wine lees (12%), sediments rich in yeast and bitartrates, are primarily valued for their mannoprotein and β-glucan content (Chioru et al., 2024; De Iseppi et al., 2021). Grape stems (11%), rich in lignocellulose and tannins, are explored for both material applications (J. M. C. Fernandes et al., 2020) and for obtaining bioactive extracts (Serra et al., 2025). Pruning waste (10%), mainly vine shoots, is considered an abundant source of lignocellulosic biomass for bioenergy and biomaterials (Duran et al., 2024; Mendívil et al., 2017). Finally, liquid streams such as winery wastewater (6%) and vinasse (6%) are primarily addressed from a treatment and resource recovery perspective (Spennati et al., 2024; Vecino et al., 2020).

In parallel, the recipient industries also show a clear order of priority, with a strong orientation towards high value-added markets. The human food industry is the most explored receptor sector (identified in 56% of articles). Applications range from the development of functional ingredients with antioxidant or texturizing properties (De Iseppi et al., 2021) and natural preservatives (Pfukwa et al., 2019), to the creation of enriched foods such as bakery products or pasta (Balli et al., 2021; Jagadiswaran et al., 2021).

The pharmaceutical (42%) and cosmetic (35%) industries follow closely. Research in these fields leverages the bioactive properties of extracts for the development of dermatological drugs (Perra et al., 2021), wound healing formulations (Prelipcean et al., 2022), or anti-aging cosmetic products (Hubner et al., 2019).

Sectors associated with the bulk bioeconomy, although less frequent, are also important valorization routes. Energy and biofuel generation (29%), mainly through anaerobic digestion for biogas production (Failla & Restuccia, 2014), and agriculture (25%), through the production of compost or biochar to improve soil (Cortés et al., 2020), represent the main destinations for large volumes of biomass.

The Sankey diagram in Fig. 3 visualizes the interrelationships between these two axes. Grape pomace confirms its versatility, connecting with virtually all industries but

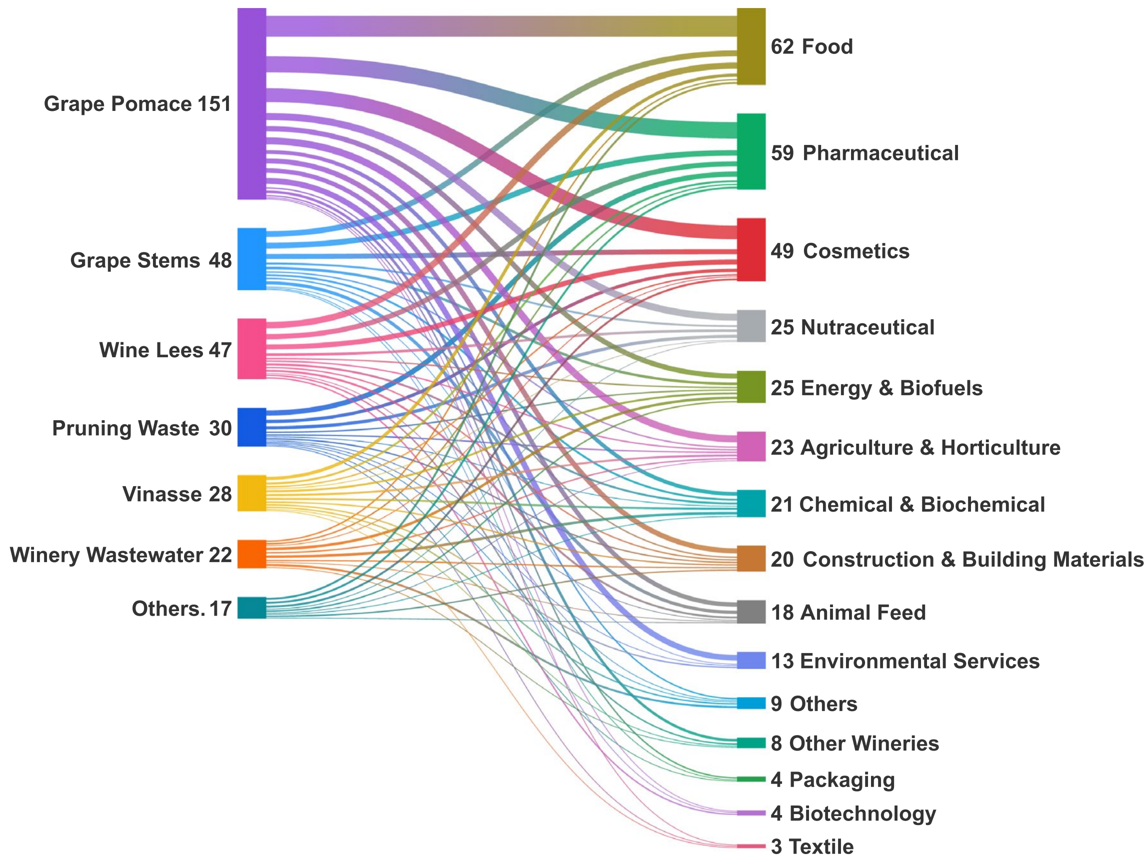

Fig. 3 Flow of connections between winery by-products and recipient industries in the literature. The data for Fig. 3 can be found in Supplementary Information SI4 (Sheet "data_from_figure_3"). Note: The width of each flow and the size of each node represent the number of connections identified across the 99 analyzed articles, not the number of unique articles. A single article can contribute to multiple flows

directing its thickest flows towards the top three: Food, Pharmaceutical, and Cosmetics, which reinforces its perception as the by-product with the highest value potential.

A functional specialization in other by-products is also observed. Lignocellulose-rich streams, such as grape stems and pruning waste, show significant connections with sectors like "Energy & Biofuels" and "Construction & Building Materials" (Mendívil et al., 2017), while still maintaining secondary flows towards high-value applications. Wine lees, in turn, stand out for their strong connection to the Food and Pharmaceutical industries (De Iseppi et al., 2021; Kucek et al., 2016). Finally, liquid streams (vinasse and wastewater) exhibit the highest specialization, being oriented predominantly towards Energy production and the provision of Environmental Services (Díaz Domínguez et al., 2024; Praveen et al., 2024).

3.3.4 Stakeholder analysis

The analysis of the stakeholder ecosystem reveals that Industrial Symbiosis in the wine sector is structurally perceived as a multilateral process rather than a simple bilateral exchange. As detailed in the network configuration data, a significant majority of the studies (84.8%) involve networks of three or more actors, with the most common configuration involving three to four distinct stakeholders. Indeed, only two articles identify the winery as the sole actor, one of which analyzes collaborative innovation projects among different wineries (Pezzillo Iacono et al., 2013).

The ecosystem is anchored by a "Production-Knowledge" axis. While Wineries are, predictably, the central node identified in 90 articles as the primary by-product generators, the second most dominant stakeholder is not an industrial partner but Research Centers and Universities, identified in 71 articles. This high prevalence suggests that the literature characterizes academia not merely as an observer, but as an active technology provider, essentially filling the R&D gap for wineries to validate the potential of their residues.

Downstream from this axis, the industrial valorization chain is composed of distinct processing and recipient actors. Final Recipient Industries (e.g., pharmaceutical, cosmetic, or food companies) appear in 67 articles, validating the market demand. However, the literature emphasizes the logistical complexity of the sector by frequently identifying

Intermediate Processing Industries (58 articles) and Distilleries (10 articles). These actors are characterized as critical physical aggregators, necessary to collect biomass from dispersed vineyards and reach the economies of scale required by the final users. Additionally, Providers of Other Inputs (24 articles) are often cited, reflecting the cross-sectoral nature of symbiosis where wine waste is co-digested or co-formulated with other streams.

However, the most striking finding is the structural imbalance regarding enabling and governance actors. Despite the theoretical importance of institutional support for Circular Economy transitions, Public Administration and Government bodies are identified as stakeholders in only 4 articles. Similarly, coordination actors such as Consultants/Facilitators (7 articles) and Sectorial Associations/Clusters (4 articles) are marginally represented. This reveals a research landscape that heavily prioritizes the technical and material connections (Winery-University-Industry) while largely overlooking the regulatory and social scaffolding required to govern these complex networks.

3.3.5 Barriers and drivers for industrial symbiosis

The literature analysis identified a broad spectrum of factors that inhibit (barriers) or promote (drivers) the implementation of Industrial Symbiosis in the wine value chain.

3.3.5.1 Barriers to implementation The distribution of identified barriers is notably asymmetric. Technological and Technical Knowledge barriers overwhelmingly dominate the discourse, being mentioned in 91.9% of the articles. This category encompasses a set of interrelated challenges. A cross-cutting theme is the variability and heterogeneity of the raw material, as the composition of by-products is affected by genetic, edaphoclimatic, and processing factors (Castangia et al., 2024; Di Nicolantonio et al., 2023), which complicates process standardization. This is compounded by inefficiencies in the transformation processes, such as low extraction yields (Olejar et al., 2019; Perra et al., 2021), the loss of bioactive compounds due to thermal treatments (Balli et al., 2021), the inhibition of biological processes by phenolic compounds (Martínez-Avila et al., 2021), and membrane fouling issues in purification technologies (Tapia-Quirós et al., 2022). Finally, the industrial scaling-up challenge is identified as a critical bottleneck that hinders the transition from laboratory proof-of-concept to viable industrial applications (Jesus et al., 2020; Varisco et al., 2017).

Economic Barriers (18.2%) constitute the second most significant obstacle. The literature highlights high initial capital expenditure (CAPEX) for valorization technologies (Ioannidou et al., 2022; Ncube et al., 2021), as well as operating expenditure (OPEX) associated with complex pre-treatments or reagent consumption (Díaz Domínguez et al., 2024; Farru et al., 2022). The volatility of market prices for the new products and the need to achieve economies of scale add a layer of financial risk and uncertainty (Ioannidou et al., 2022; Pezzillo Iacono et al., 2013).

Organizational and Logistics Barriers (13.1%) refer to difficulties in coordinating among actors (Chen et al., 2022), managing the seasonality of by-products (Ortiz et al., 2020), and establishing networks of trust (Czupryna et al., 2018). The remaining categories, such as Environmental (7.1%), Cultural and Social (6.1%), Corporate Culture (5.1%), and Policy and Regulatory barriers (3.0%), are mentioned less frequently.

3.3.5.2 Drivers for implementation In contrast to the barriers, the drivers present a more balanced distribution. The primary driving force is the Environmental dimension (94.9%). The need to adopt the principles of the Circular Economy, reduce environmental impact, and valorize waste in line with policies such as the European Green Deal functions as the main legitimizing framework for the research (Castangia et al., 2024; de Souza Mesquita et al., 2024). The Cultural and Social dimension emerges as a strong driver (53.5%), given the growing consumer demand for natural, sustainable, and functional products over synthetic alternatives (Balli et al., 2021; Wittenauer et al., 2016). In turn, this demand creates economic incentives, such as the generation of new revenue streams and the reduction of waste management costs (Di Nicolantonio et al., 2023; Meini et al., 2020).

Policy and Regulatory (15.2%) and Organizational and Logistical (8.1%) drivers are cited less often but are recognized for their enabling role through public funding and the creation of collaborative networks.

3.3.5.3 Comparative analysis of barriers and drivers Figure 4 provides a comparative view that reveals the duality of certain dimensions. The Technological and Knowledge dimension stands out for being mentioned far more frequently as a barrier (91.9%) than as a driver (57.6%), underscoring that the challenges of scaling-up and efficiency currently outweigh the optimism generated by innovation. Conversely, the Environmental dimension acts almost exclusively as a driver (94.9%) and rarely as a barrier (7.1%), cementing its role as the main conceptual driving force of the field. The Economic dimension, meanwhile, is perceived more often as a business opportunity (47.5%) but is also considered a significant risk factor (18.2%).

3.4 Cluster analysis of research trends

To synthesize the identified thematic patterns and group studies with similar characteristics, a hierarchical cluster analysis was performed on the 99 original research articles.

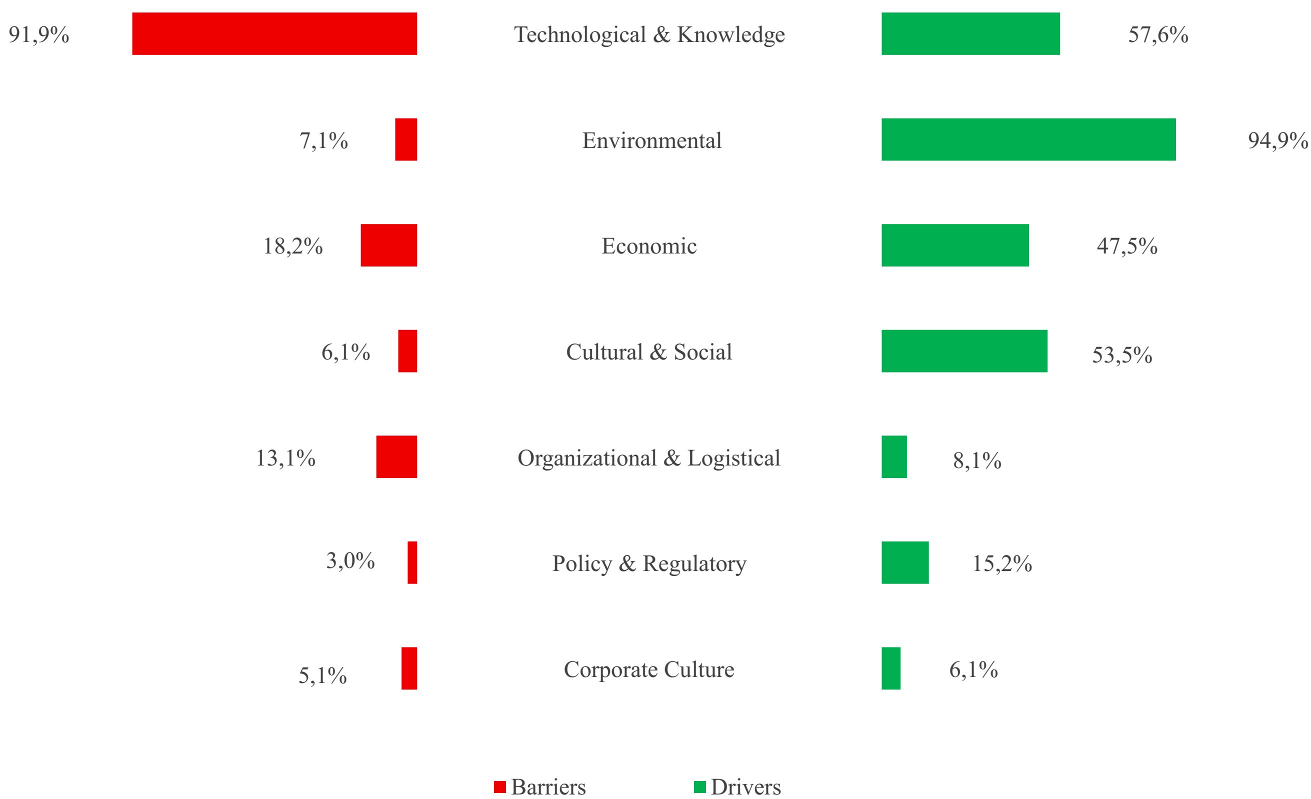

Fig. 4 Diverging bar chart showing the prevalence of barriers and drivers by dimension. The data for Fig. 4 can be found in Supplementary Information SI4 (Sheet "data_from_figure_4"). Note: Percentages indicate the proportion of articles that mention each thematic dimension, calculated separately for barriers and drivers

The selection of a three-cluster solution was robustly supported by the average silhouette method, which reached its maximum value at k = 3, as well as by the elbow method and a visual inspection of the dendrogram (see Supplementary Information SI5 for validation plots).

The heatmap in Fig. 5 visualizes the thematic profiles of these three clusters. The columns represent the 47 thematic characteristics, and the rows represent each of the three clusters. The color of each cell indicates the prevalence (mean proportion) of a characteristic within a cluster, where warm colors (red/orange) indicate high prevalence and cool colors (blue) indicate low or no prevalence.

A detailed characterization of each cluster is presented below. To support this characterization with quantitative evidence, Table 2 details the specific prevalence of barrier categories within each group, highlighting the structural differences in perceived bottlenecks.

3.5 Cluster 1: Bioeconomy and integral valorization (N = 32)

This cluster represents a pragmatic and diversified approach aligned with the circular bioeconomy. Methodologically, it is distinguished by incorporating a broader analytical toolkit, presenting the highest proportion of Sustainability and Feasibility Assessments (25.0%) and Modeling and Simulation (21.9%). While grape pomace remains a key feedstock (53.1%), this cluster analyzes a wider and more balanced range of by-products, including liquid streams. Its valorization pathways are primarily directed towards bulk bioeconomy sectors, such as Energy & Biofuels (46.9%) and Agriculture & Horticulture (40.6%). Consistent with its focus on industrial-scale solutions, this cluster not only identifies the Technological barrier (93.8%) as predominant but also highlights Economic (34.4%) and Organizational & Logistical (21.9%) barriers as significant obstacles.

3.6 Cluster 2: New high value applications (N = 62)

This cluster, the largest in the sample, embodies a highly specialized research stream focused on "value extraction" for high-margin markets. Its methodological profile is completely homogeneous, with 100% of its studies being of an experimental laboratory nature. The research is heavily concentrated on grape pomace (61.3%) to serve high value-added sectors, with the strongest connections to the Food (77.4%), Pharmaceutical (67.7%), and Cosmetics (51.6%) industries. In stark contrast to cluster 1, bulk bioeconomy

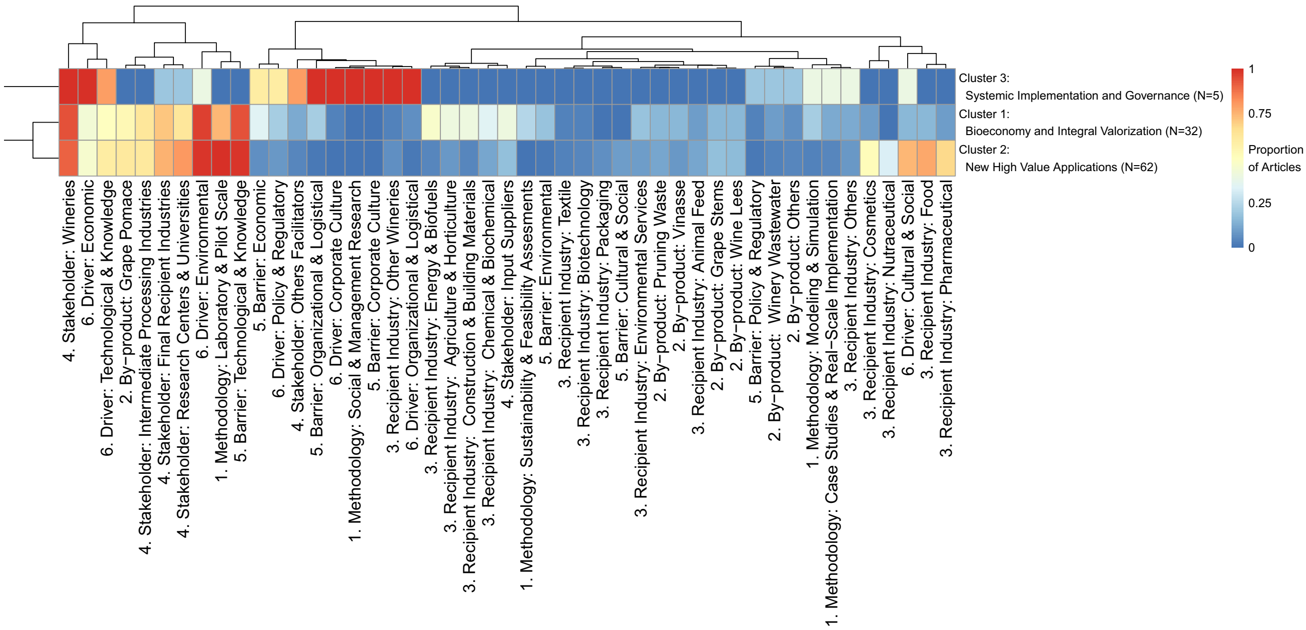

Fig. 5 Heatmap of the thematic profiles of the three research clusters. The data for Fig. 5 can be found in Supplementary Information SI4 (Sheet "data_from_figure_5")

Table 2 Prevalence of barrier categories across the three identified research clusters

Barrier Category	Cluster 1 (n=32)%	Cluster 2 (n=62)%	Cluster 3 (n=5)
Corporate Culture	0	0	100
Cultural & Social	0	9.7	0
Economic	34.4	6.5	60
Environmental	18.8	1.6	0
Organizational & Logistical	21.9	1.6	100
Policy & Regulatory	3.1	1.6	20
Technological & Knowledge	93.8	98.4	0

Note: Percentages indicate the proportion of articles within each cluster that identify the specific barrier category

sectors are practically absent. The main drivers are consumer demand (Cultural & Social, 74.2%) and technological advancements. Reflecting its academy-driven and proof-of-concept nature, the Technological barrier is virtually ubiquitous (98.4%), while non-technological barriers are almost entirely absent from its discourse.

3.7 Cluster 3: Systemic implementation and governance (N = 5)

Though the smallest, this cluster identifies a conceptually distinct niche group centered on the socio-organizational dimensions of IS implementation. Its methodology is characterized by the complete absence of experimental studies, being dominated by Social and Management Research (100%) and Case Studies (40%). The focus shifts from specific by-products towards the architecture of the symbiotic network, often involving intra-sectoral collaboration between wineries (100%). Crucially, the perceived barriers are not technological but rather Corporate Culture (100%), Organizational & Logistical (100%), and Economic (60%). This cluster is unique in its exploration of the non-technological factors—such as trust, governance, and business models—that enable or hinder the transition from theoretical potential to real-world industrial symbiosis.

Finally, to address the evolutionary trajectory of the field (RQ1) with greater granularity, Fig. 6 illustrates the distribution of clusters over time. The analysis of the retrieved corpus suggests that the observed "structural imbalance" is persisting rather than diminishing. While the field has experienced exponential growth in the 2021–2025 period, this surge appears to be driven primarily by techno-centric research and, especially, by research on new high-value applications. In contrast, Cluster 3 (Systemic Implementation) remains marginally represented in the sample even in the most recent years. This indicates that, within the scope of this review, the increase in scientific production has not yet translated into a proportional rise in studies focused on governance and systemic implementation.

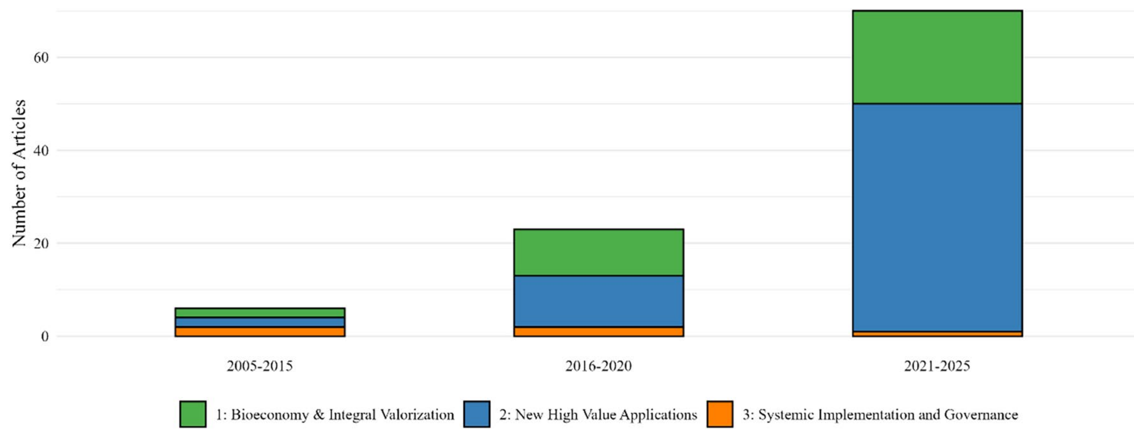

Fig. 6 Evolution of the thematic clusters over time (grouped by publication period). The data for Fig. 6 can be found in Supplementary Information SI4 (Sheet "data_from_figure_6")

4 Discussion

4.1 The current state of research: a field in the potential validation phase

The results of this systematic review outline the profile of an emerging and dynamic research field that is strongly linked to its geographical and industrial context. However, the findings conclusively show that the field is in an incipient stage of maturity, predominantly focused on validating the technical potential of winery by-products. The predominance of laboratory-based experimental studies (60%), the intense focus on grape pomace as a model raw material, and the prominence of research centers over recipient industries are clear indicators that the scientific agenda is largely oriented toward answering the fundamental question: "What can be done with these by-products?". This approach aligns with the initial Technology Readiness Levels (TRL 1–4), suggesting a field driven by "Science-Push" dynamics rather than market-driven "Demand-Pull" mechanisms (Hekkert et al., 2007).

The cluster analysis provides the empirical basis for a conceptual framework of the field. As detailed in Sect. 3.4, the two largest clusters reflect complementary technocentric strategies for closing resource loops (Bocken et al., 2016). However, a critical interpretation of these results reveals a fundamental disconnection between this technological potential and the structural reality of the wine sector. Unlike manufacturing industries where IS models are often based on continuous flows and co-located facilities (Chertow, 2000), the wine value chain is governed by extreme seasonality (Zacharof, 2017) and spatial dispersion (Asheim & Gertler, 2006; Porter, 1998). The concentration of waste generation into a few weeks creates a "temporal mismatch" that standard manufacturing models do not face, necessitating complex logistical buffers (e.g., intermediate distilleries) that are largely ignored by the dominant lab-scale literature (Clauser et al., 2016).

This oversight explains the critical gap evidenced by Cluster 3 ("Systemic Implementation and Governance"). Its extremely small size (only 5 articles) compared to the technocentric clusters demonstrates that knowledge about the non-technological aspects of IS is critically underdeveloped. While scholars emphasize that IS is inherently a process of "social embeddedness" requiring trust and institutional capacity (Boons & Spekkink, 2012; Lombardi & Laybourn, 2012), the current research landscape treats wine by-products merely as chemical reservoirs. This neglects the empirical evidence suggesting that cultural and market barriers are frequently more prohibitive than technological limitations in the circular transition (Kirchherr et al., 2018).

Consequently, the fact that 91.9% of the analyzed articles cite "technological issues" as the primary barrier requires a nuanced interpretation. As reflected in Table 2, this figure is heavily skewed by the weight of Clusters 1 and 2. In sharp contrast, Cluster 3 (Systemic Implementation) does not report technological barriers at all, but identifies organizational and corporate culture challenges. Rather than proving that the main bottleneck is engineering-based, this figure likely reflects a methodological artifact of the predominant technocentric research. More critically, recent scholarship warns that what manifests as a technical failure to scale up is frequently a "coordination failure masquerading as a technical limit" (Hamam et al., 2023). As emphasized by Sellitto et al. (2025), the difficulty in moving from laboratory proof-of-concept to industrial viability is deeply entangled with governance and market design. For instance, a technology may be deemed "inefficient" simply because the fragmented supply of raw materials prevents necessary economies of scale. Therefore, the pervasive "technological barrier" is often a symptom of the "socio-organizational void" that prevents the aggregation of consistent flows.

Consequently, this scarcity of studies on real-world implementation (TEA, LCA, case studies) suggests that the field is at a dangerous inflection point. Without addressing the specific "hard" and "soft" sectoral barriers (de Jesus & Mendonça, 2018) —such as the logistical cost of transporting low-density biomass or the need for intermediate aggregators— the risk that many promising innovations described in Clusters 1 and 2 will fail to cross the "valley of death" of innovation (Markham et al., 2010) is considerable. The lack of a robust body of knowledge on implementation factors constitutes the main barrier to translating the theoretical potential into large-scale industrial impact.

Synthesizing these findings, an inductive conceptual pattern emerges: the sector is currently characterized by a "Technological lock-in" —understood as a diagnostic metaphor borrowed from socio-technical transitions theory (Geels, 2011) to describe the observed structural imbalance, rather than as a formal demonstration of the economic mechanisms of path dependence. Consequently, the structural imbalance between the hyper-accumulated technical knowledge (Clusters 1 and 2) and the scarce implementation research (Cluster 3) indicates that the field has reached a saturation point where further investment in purely technical optimization yields diminishing returns. Therefore, the critical sector-specific leverage points to unblock the circular transition are no longer technological, but institutional. Specifically, future progress depends on developing collaborative business models and regional governance structures capable of managing the unique "temporal mismatch" caused by the seasonality of wine production.

4.2 Implications for future research, practice and policy

The structural analysis of the literature and the identification of existing knowledge gaps have direct implications for the future research agenda as well as for industrial practice and public policy.

The results of this review suggest the need to promote a rebalancing of the research agenda on IS in the wine value chain. It is essential to shift from a predominantly technocentric approach towards a more systemic and interdisciplinary analysis that considers the economic, commercial, social, and environmental dimensions in an integrated manner.

Based on the identified gaps, particularly the scarcity of studies corresponding to Cluster 3 and the structural constraints of the sector, we propose a priority agenda tailored to the specificities of the wine value chain:

– Technological scaling-up: While proof-of-concept research is necessary, it is crucial to increase the number of studies focused on higher TRLs. However, in the wine sector, scaling up requires addressing the specific "temporal mismatch" between the concentrated generation of by-products during the short harvest season and the continuous demand from the industry. Future research should move beyond static extraction methods to investigate decentralized stabilization technologies (e.g., mobile pre-treatment units for drying or ensiling). A key proposition to be tested is whether decentralized stabilization significantly reduces the carbon footprint and logistical costs compared to centralized raw material collection systems, thereby overcoming the barrier of low-density biomass transport in fragmented territories.
– Economic viability and business models: It is imperative that research integrates the economic dimension more systematically through Techno-Economic Analyses. More TEA are required to assess the profitability of valorization pathways. Furthermore, given the atomization of producers, standard linear business models are often unviable. Research must develop and test collaborative business models adapted to the reality of Small and Medium Enterprises (SMEs). Specifically, scholars should investigate cooperative biorefinery models where wineries act not merely as waste suppliers, but as shareholders in the value created. We posit that collaborative models involving equity sharing are likely to demonstrate higher long-term network resilience than simple spot-market trading models, as they better align incentives to mitigate the risk of price volatility for derived products (e.g., grape seed oil, polyphenols)
– Market analysis and social acceptance: The commercial viability of innovations depends on their market acceptance. Studies are needed to analyze the perception and willingness to pay of consumers for products containing ingredients derived from winery by-products. This involves navigating complex regulatory landscapes, such as Novel Food regulations, and understanding the "clean label" trend. Future empirical inquiries should analyze the "neophobia" effect, testing the hypothesis that explicit labeling of "upcycled wine ingredients" may enhance brand value in cosmetic applications (due to storytelling potential) while potentially facing consumer resistance in traditional food products.
– Governance and social dynamics: The most critical gap lies in understanding the socio-organizational factors. Future research must address the collaborative governance mechanisms that facilitate the creation and maintenance of IS networks. Unlike generic industrial parks, the wine sector possesses unique institutional assets, such as Designations of Origin (DOs) and wine clusters. Consequently, a priority research avenue is to study how these existing territorial bodies can act as "trust anchors" to coordinate heterogeneous actors. It is hypothesized that symbiotic networks governed by these pre-existing institutions will exhibit lower transaction costs and higher

stability than ad-hoc networks, leveraging established social capital to facilitate conflict resolution and data sharing.

The key takeaway for wineries, recipient industries, and public administrations is that the transition to effective IS is a systemic, economic, and collaborative challenge, not just a technological one. While continued investment in technological improvements to enable scalability is crucial, the future establishment of symbiotic networks essentially depends on investing in the creation of "symbiotic innovation ecosystems" that foster collaboration.

In this regard, geographic proximity and inter-organizational relationships have a major impact on the viability and success of symbiotic exchanges (Chrysikopoulos et al., 2024), thereby consolidating IS as a key factor in regional and local development. Such collaborative approaches provide benefits and advantages that would not be achievable in isolation, such as knowledge exchange and cost reduction (Simioni et al., 2024). This implies a need for foundational support, such as the development of digital platforms for exchanging information on by-product flows, the creation of tax incentives for companies participating in symbiotic networks, and the adaptation of regulatory frameworks that facilitate the consideration of by-products as resources rather than waste.

However, to move beyond these generic prescriptions, policy frameworks must adapt to the specific structural reality of the wine sector. Rather than focusing solely on generic digitalization or operational tax cuts, public support should target the specific logistical and reputational barriers of the industry:

- Infrastructure for seasonality: Policies should fund CAPEX for collective infrastructure, such as inter-winery storage hubs or intermediate aggregators. This is essential to enable small producers to manage the "temporal mismatch" of waste generation (seasonality) and stabilize biomass before transport.
- Territorial certification schemes: We propose the creation of quality labels for upcycled products analogous to wine Designations of Origin (DOs). By extending the territorial brand to derived products (e.g., "Grapeseed Oil from Rioja/Bordeaux"), the symbiotic network can leverage the pre-existing reputation of the region. This creates a market incentive for wineries to collaborate, as the by-product inherits the "symbolic capital" of the wine, transforming a waste management problem into a premium branding opportunity.
- Institutional integration: Consequently, policies should foster the integration of digital material flow monitors directly into DO regulatory bodies. Since these bodies already audit grape production, expanding their scope to certify by-product flows would minimize bureaucratic friction and guarantee the traceability required for high-value markets.

4.3 Limitations of the study

It is important to acknowledge the inherent limitations of this systematic review to properly contextualize its findings and conclusions.

First, there are limitations related to the search and selection process. Although two of the most important academic databases (Scopus and Web of Science) were used, the exclusion of other sources, such as Google Scholar, or of grey literature (e.g., technical reports from European projects, unpublished doctoral theses) may have led to the omission of relevant documents not indexed on these platforms. Likewise, the decision to restrict the search to articles published in English, while a common practice to ensure the feasibility of the review, may introduce a linguistic bias, potentially excluding important contributions published in other languages from key wine-producing regions.

Second, there are limitations in the depth of the analysis of the included evidence. The primary objective of this review was to map and structure a heterogeneous research field. For this reason, and in line with thematic mapping reviews (or scoping reviews), a formal assessment of the methodological quality or risk of bias of each of the included primary studies was not performed. Therefore, the findings of this review reflect what the literature has published, without weighting the quality or robustness of the evidence from each individual article.

Additionally, it should be noted that the review protocol was not pre-registered in repositories such as PROSPERO or OSF. While the full search strategy and coding protocols are provided in the Supplementary Information SI2 and Supplementary Information SI3 respectively to ensure reproducibility, the lack of pre-registration constitutes a limitation regarding current transparency standards.

Finally, the thematic coding and analysis process, although based on a predefined and rigorous protocol to minimize subjectivity, is not entirely exempt from a degree of researcher interpretation, especially in the assignment of articles to complex thematic categories. However, the implementation of cross-checks and consensus discussions sought to mitigate this risk as much as possible.

These limitations do not invalidate the presented results, but they do delimit the scope of the conclusions. The findings should be understood as a structural snapshot of the state of published research, offering a solid foundation upon which future research can build with greater depth and specificity.

5 Conclusion

In response to the initial research questions, this systematic review concludes that the literature on Industrial Symbiosis in the wine value chain is in an early stage of maturity. It possesses a solid and growing knowledge base in the realm of laboratory validation but exhibits a significant gap regarding real-world implementation. The structure of the field, as revealed through our cluster analysis, confirms this dichotomy between a strong technocentric focus and a still incipient exploration of economic, social, and governance factors.

The current research trajectory is structurally misaligned with industrial needs. While our analysis shows that 91.9% of studies focus on technological barriers, structural factors such as logistics (13.1%) and regulation (3.0%) are marginally addressed. This finding highlights a clear disconnect between academic research and industrial reality, where logistical costs and legal frameworks are often the true deal-breakers.

Therefore, future progress will depend on the ability of the research community and industrial stakeholders to transcend disciplinary silos and adopt a more systemic and interdisciplinary approach. Building a true circular economy in the wine industry will not be achieved solely through new technologies, but through the simultaneous construction of the business models, networks of trust, and governance frameworks that can transform scientific potential into real and lasting socioeconomic and environmental impact.

Supplementary Information The online version contains supplementary material available at https://doi.org/10.1007/s44498-026-00076-2.

Acknowledgements The authors would like to thank the anonymous reviewers and the editorial team for their constructive comments and valuable feedback, which have significantly improved the quality of this manuscript. Furthermore, special thanks go to Adegas Moure SA for their continuous support, collaboration, and for fostering the environment that made this research possible.

Author contributions Ó.P.-T. and X.V. contributed to the study conception and design. Ó.P.-T. performed the literature search, data extraction, and formal analysis. The first draft of the manuscript was written by Ó.P.-T. X.V. supervised the research and critically reviewed and edited the manuscript. All authors read and approved the final manuscript.

Funding Open Access funding provided thanks to the CRUE-CSIC agreement with Springer Nature. This research has been supported by Adegas Moure SA through the Industrial Doctorates Program of Xunta de Galicia (Consellería de Educación, Ciencia, Universidades e Formación Profesional) and by the ICEDE research group, to which the authors belong, Galician Competitive Research Group ED431C 2022/15 financed by Xunta de Galicia and project "REVALEC" REFERENCE PID2022-141162NB-I00 financed by MCIN/AEI/https://doi.org/10.13039/501100011033/EFRD,EU.

Data availability The data that supports the findings of this study are available in the supporting information of this article.

Declarations

Conflict of interest The authors declare no competing interests.

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