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Review

From Vineyard to Value: A Circular Economy Approach to Viticulture Waste

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Abstract: Due to its significant environmental impact, the wine industry is one of the most analyzed agri-food sectors in terms of sustainability. These include waste emission, intensive land use, and high transport-related carbon footprint. The circular economy represents an opportunity to mitigate these impacts by promoting the valorization of wine waste. Through a systematic literature review, this research provides an overview of studies from 2018 to 2024 that deal with the transformation of wine waste, in particular vinification residues, into resources. The research covers the commodity sectors in which wine waste is reused, such as Food, Agriculture, and Energy. The analysis of the sample reveals that the countries in which the issue of valorization of wine waste is most studied are Italy, Spain, and Portugal. The study encourages a better integration of waste in the wine sector into business practices by assessing the environmental and economic impact. From a management point of view, the aim is to inform companies about effective waste management practices in order to promote the development of a more sustainable wine industry. Future research will focus on evaluating the effectiveness of these valorization pathways, also through case studies of good practice in implementing a circular business model.

Keywords: wine waste; wine industry; circular economy; food waste valorization; sustainability; systematic literature review

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1. Introduction

Waste management is not only an environmental issue but also a problem of resource use [1]. The agri-food sector has long been identified as one of the main sources of waste generation, especially with regard to industrial processing and transformation of raw materials [2,3]. In this scenario, intensification of agricultural activities, inefficient use of limited resources, and increased mechanization further contribute to greenhouse gas emissions, exacerbating global climate change [4]. Consequently, it is also important to improve resource management through recovery from waste streams [1]. Indeed, given the diversity of production chains and their specific characteristics, the agri-food sector stands out for its potential to valorize waste by treating it as a valuable resource [5]. For example, food waste can be used in industrial composting processes [2], or processed into functional ingredients to improve the nutritional properties of processed foods [6,7]. In addition, converting waste into biofuels and, more generally, recovering bioproducts from waste streams has great potential to achieve energy and resource sustainability goals [8].

This shift in perspective, turning waste into a resource, provides a better understanding of how technological innovations in the environmental sector can be integrated and linked to waste treatment [1]. The circular economy represents a crucial alternative to the linear economy, defined by overproduction and waste. A key factor distinguishing between the two economic models is the ability of circular systems to ensure that products retain their added value by transforming every waste product into a resource [9]. Thus, waste treatment is not limited to a mere disposal activity but becomes an opportunity for recovery and valorization, reducing pressure on natural resources [10].

The circular economy aims to reduce waste by turning it into new valuable resources, promoting reuse and up-cycling within biological and economic systems [8].

The wine industry is one of the most studied agri-food chains in terms of environmental sustainability due to its significant role in economic production and international trade [11,12]. The 2023 report of the International Organisation of Vine and Wine [13] estimates world wine production at 237 million hectolitres. In 2023, France, the world's leading wine producer, is estimated to have produced approximately 48 million hectolitres of wine. Notably, this value is 4.4% higher than that recorded in 2022 and 8.3% higher than the country's average over the previous five years. Italy, the second largest wine-producing nation globally, estimates a total production of 38.3 million hectolitres, while Spain reaches an estimated production of 28.3 million hectolitres. In particular, France, Italy, and Spain are responsible for approximately 50% of global wine production in 2023 [13].

The wine production process generates approximately 9 million tonnes of waste, which has a negative impact on the environment due to the disposal of this waste. Several studies, e.g., Refs. [9,14,15] have demonstrated the significant environmental impact of the wine supply chain due to the disposal and composting of waste outside of vineyards. These effects are particularly evident in soil quality, with erosion, soil salinity, and vegetation removal occurring as a result. Additionally, the use of chemical sprays, pesticides, and greenhouse gas emissions, in addition to the high carbon footprints of transport, contribute to environmental degradation in the atmosphere.

In wine production, the most common residues include grape seeds and pomace (which collectively constitute approximately 20–25% of the total weight of the harvest). Additionally, wine stalks and lees, i.e., the sediments formed during the fermentation and aging process, are also common wine waste [16].

Grape pomace is one of the main residues generated by the vinification process and is rich in bioactive compounds, including antioxidants, polyphenols, and other micronutrients [17]. These potentially valuable components can be recovered and valorized for alternative uses. For instance, polyphenols extracted from grape pomace are widely used in the cosmetic and nutraceutical sector due to their antioxidant properties [9,18,19]. At the same time, grape pomace, due to its yeast and nutrient content, is considered a potential source of biomass for energy production [20].

Stalks, i.e., the woody parts of the grapes and wine lees—consisting of solid sediments deposited during the winemaking process—are also typical by-products of the wine chain, rich in nutrients and with high potential for reuse in other sectors. Stalks, for example, can be converted into compost or used in biogas production. At the same time, lees, due to their yeast and nutrient content, are often destined for the agricultural sector as fertilizers or as a source of biomass for energy production [21].

In addition, the wine supply chain faces the problem of disposing of large quantities of residual water containing organic and mineral compounds derived from plant cleaning and maintenance operations [22]. According to [23], this water can be treated to reduce environmental impact and, in some cases, recycled for agricultural or industrial uses.

Therefore, the high volume of waste produced represents a significant environmental challenge for the wine sector and a potential resource for developing sustainable strategies [24].

Managing these by-products from a circular economy perspective could reduce disposal costs and offer new economic development opportunities [25]. These include providing low-cost materials for new businesses through recycling [24,25], creating income and employment opportunities [26,27], and protecting our environment by reducing the negative effects of waste [28,29].

This model finds application in the wine supply chain context, enhancing waste from the production process [15,16]. This transition towards by-product recovery and valorization practices has generated both environmental and economic benefits [20,30]. Indeed, wineries can reduce waste disposal costs and develop new lines of by-products, gaining access to emerging markets, such as (i) the food supplement market, where pomace, rich in polyphenols and antioxidants, can be used to create flours and extracts to improve the nutritional value of food products [31,32]; (ii) the cosmetics market, thanks to polyphenol and fatty acid extracts that can be used in creams and serums for their antioxidant properties [31]; (iii) the energy market, since wastewater residues can be treated by hybrid gasification supported by thermal plasma to produce hydrogen-rich biogas [33].

Such applications highlight the opportunity to develop a more sustainable and profitable production system where waste becomes a key resource [20,34].

Despite the relevance of the topic, scientific literature shows some significant gaps, in particular, the lack of a systematic analysis of the multiple applications of wine by-products in different economic sectors. Therefore, it is necessary to develop an in-depth study that not only collects and analyzes the existing literature in an organic way but also identifies the most studied by-products and their possibilities of reuse in different economic sectors. Such an analysis would help promote more sustainable solutions from a circular economy perspective and create an integrated framework that summarizes the main connections between waste from the wine chain and the sectors in which it can be valorized.

In this perspective, the study has several objectives: (i) to identify the main by-products of wine production, such as pomace, stalks and lees; (ii) to map the production sectors where these by-products find more opportunities for reuse, e.g., in the food, cosmetics, energy, or pharmaceutical sectors; (iii) to provide a comprehensive overview of existing studies, with particular attention to the contribution of the circular economy in helping wine producing companies to transform waste into valuable resources. The analysis will focus on the Mediterranean context, a leading wine-producing region, where the implementation of by-product management strategies can provide a replicable sustainability model on a global scale.

From a managerial point of view, this approach will provide agricultural companies with a practical tool to identify opportunities for the reuse of agricultural waste, carefully balancing both environmental and economic benefits [35]. Implementing effective waste management practices [36,37], combining innovation and sustainability, will also promote strategic collaborations between stakeholders such as producers, researchers, and policymakers. These efforts will contribute to the development of a more sustainable and resilient wine industry, aligned with the principles of the circular economy, capable of addressing global sustainability challenges and making a concrete contribution to the transition towards more responsible production and consumption patterns [38].

The article is structured as follows: the main literature reviews are analyzed in the next section, and the gap is identified with corresponding research questions. Section 3 describes the research methodology, while Sections 4 and 5 present the main findings and discussion. Finally, Section 6 describes the main conclusions.

2. Previous Studies

The topic of waste management in the wine sector plays an important role [39]. To date (17 September 2024), four literature reviews on the topic have been identified (Table 1).

The first paper on the topic is that of [40], which aims to summarise the state of knowledge on "wetlands" for the treatment of winery wastewater, focusing on large-scale on-site systems and highlighting the technical, environmental, and socio-economic advantages and disadvantages. This paper provides a comprehensive overview of wetlands for cellar wastewater treatment in terms of environmental, economic, and social aspects, resulting in a more holistic view of this sector.

Two articles, however, focus on the enhancement of grape pomace. Ref. [26] summarizes current knowledge on the bioactivity and health benefits of polyphenol-rich extracts from grape pomace samples. Furthermore, the potential for incorporating grape pomace into food formulations (enhanced physiochemical, sensory, and nutritional quality) and the intellectual property information supporting the potential application of grape marc in the food industry are also discussed.

Table 1. Literature review. Source: authors' elaboration.

Authors	Database	Keywords	Source	Aim
[40]	Scopus	"wine" AND "wastewater" AND "constructed wetland"	Science of The Total Environment	Evaluation of the technical, environmental, and social effects of wine wastewater treatment in constructed wetlands
[26]	PubMed, Scopus, Science Direct, Web of Science, and Google Scholar	"grape pomace wine industry", "grape pomace composition", "grape pomace functional properties", "grape pomace food enriched", "grape pomace industrial application", "grape pomace health benefits"	Foods	Evaluation of the properties of the grape pomace
[27]	Pubmed, Scopus, SciFinder, Scholar, and ISI Web of Knowledge	"grape pomace", "grape marc", "grape by-product", "winemaking waste", "phenolic compounds", "polyphenols", "valorization", "health benefits", "antioxidant activity", "anti-inflammatory properties", and "metabolism"	Antioxidants	Valorization of phenolic compounds in grape pomace
[9]	Scopus	TITLE-ABS-KEY (("WINE WASTE" OR "WINE INDUSTRY" OR "WINE SECTOR" OR "WINE BUSINESS OR "WINE PRODUCTION") AND ("CIRCULAR ECONOMY" OR "INDUSTRIAL SYMBIOSIS" OR "SUSTAINABILITY"))	Review of Managerial Science	Valorization of different winery waste and by-products through different channels and value chains

On the other hand, Ref. [27] provided an in-depth review of the valorization of grape marc phenolic compounds, focusing on recent advances in their extraction, chemical analysis, and characterization. While many studies have examined the phenolic content of grape marc, this review highlights the latest innovations in green extraction technologies that improve yield and efficiency, along with precise chemical analysis methods for profiling these bioactive compounds.

Finally, Ref. [9], through a systematic literature review, analyzed 67 scientific articles, further including grey literature to obtain a more comprehensive overview of the phenomenon under investigation by providing a complete picture of the different wastes and by-products of wineries and how they can be treated through different valorization channels and value chains, in the light of the industrial symbiosis paradigm. The authors divided waste into "resource" and "added value". Waste as a "resource" is intended for the renewable energy sector, while waste as "added value" is intended to be processed into by-products such as packaging, bioactive compounds, fertilizers, and functional additives. The results highlighted the urgent need for industry and the scientific community to investigate sustainable and profitable alternatives for valorizing wine waste.

Of the four reviews, the research developed by [9] appears to explore the scientific and managerial implications with greater depth and more comprehensive coverage, encompassing the entire production chain. In contrast, the other reviews adopt a more technical and scientific approach, focusing on a particular aspect of the topic. Based on the results obtained, in particular from the study conducted by [9], this research, therefore, aims to investigate further the issue of waste utilization in the wine sector, which includes the entire production chain and, through a systematic analysis of the literature, focus attention on the main wastes and how these are employed in the different production sectors, which may not necessarily include the wine sector. The intention is to consider a broader concept of circularity.

A gap in the existing literature is the absence of a study that analyzes the field of waste. Such a study would describe which wastes have been the subject of the most extensive research and how these have been applied in the various economic sectors as more sustainable solutions with a view to achieving a circular economy. To conclude, this research aims to provide a comprehensive overview of the studies analyzing how the circular economy can support companies in the wine sector in addressing the global sustainability challenge by transforming waste into a resource and identifying the product sectors most involved. Furthermore, this research aims to expand the literature on the topic. It is set in the context of valorizing wine by-products to foster the implementation of the circular economy, especially in Mediterranean countries, which are considered leaders in wine production.

Accordingly, the research aims to answer the following research questions:

- RQ1 What are the main wine wastes reused from a circular economy perspective?
- RQ2 What are the main sectors in literature in which wastes are reused?

3. Materials and Methods

A systematic literature review was used to answer the research questions. The systematic literature review methodology was first adopted in medicine [28] and subsequently in other fields, such as social sciences, engineering [29,41], economics, and business [42–45].

The literature defines this approach as a means "to identify, evaluate and interpret the entire body of research relevant to a specific issue, subject area or phenomenon of interest" [46]. A systematic literature review integrates qualitative and quantitative assessments of a topic, enabling research questions to be answered and meeting study objectives [47].

The systematic literature review enables the understanding of a large body of literature [48], comprehensively analyzing and mapping primary studies using transparent and replicable approaches [49] and identifying research gaps and possible future advances [9]. The systematic literature review is a rigorous procedure. According to [47], systematic literature review is a specific methodology based on four steps: (1) identification of existing studies, (2) selection and evaluation of contributions, (3) analysis and synthesis of data, and (4) description of the results in such a way that provides clear conclusions. Also, the process model proposed by [50] comprised four steps: (1) material collection, (2) descriptive analysis, (3) category selection, and (4) material evaluation.

Following the guidelines proposed by [47,50], this review process has been structured in four steps, as shown in Figure 1:

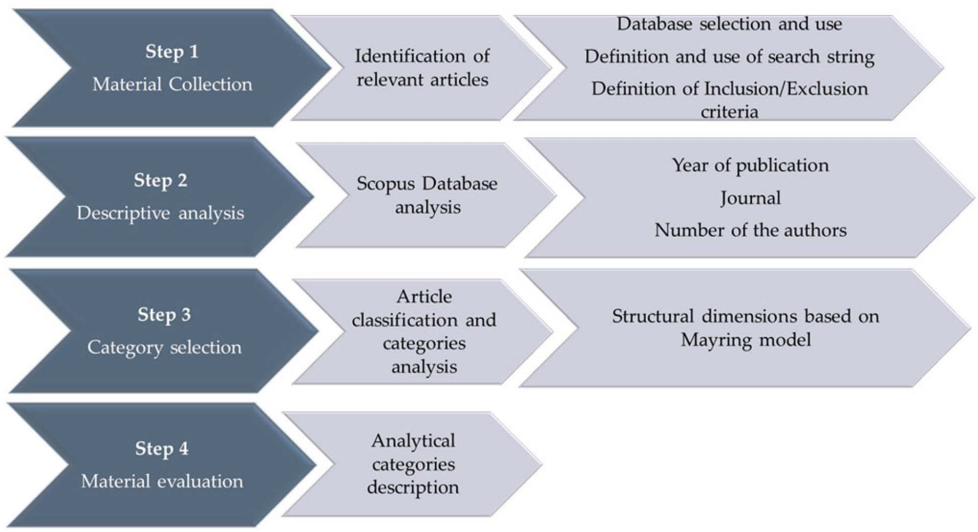

Figure 1. Revision process in developing the systematic literature review. Source: authors' elaboration.

3.1. Material Collection

The study refers to the Elsevier Scopus database, chosen for its comprehensive coverage as "a primary reference database with over 50 million records from about 5000 publishers" [41,44,51]. The search for relevant articles was conducted on 17 September 2024, and the string used on Scopus was "Wine" AND "Waste" AND "Circular Economy" OR "Sustainability". In the Scopus search, the research criteria were "Title, Keywords, Abstract".

The initial number of articles identified was 261. Subsequently, we applied the C-I-M-O framework to establish the inclusion/exclusion criteria [45] as follows:

Inclusion criteria: all papers that analyzed the topic of waste valorization in the wine sector and according to a circular economy approach.

Exclusion criteria: all papers that do not focus on the topic of waste valorization in the wine sector, although according to a circular economy approach.

Furthermore, limiting the search to scientific articles written in English, the number of articles was 169. By analyzing the abstracts, there were 91 articles, while by reading the entire article, the final sample consisted of 73 articles.

Figure 2 shows the process followed for the selection and analysis of articles.

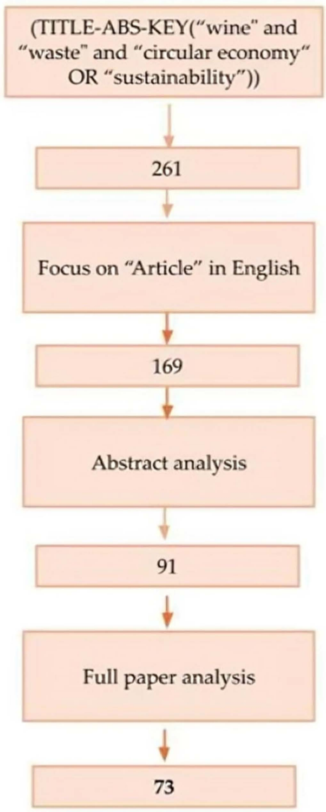

Figure 2. Item selection process. Source: authors' elaboration.

3.2. Category Selection

Based on [50] and considering the research questions, several structural dimensions were identified, for which, subsequently, analytical categories were identified to evaluate the material. Categorization uses inductive and deductive approaches [44,50,52]. The deductive approach defines dimensions and categories based on a specific theory or an existing model [53]. Therefore, they defined these aspects before proceeding with the analysis of the material [52]. In the inductive approach, dimensions and categories are defined by analyzing the material, thus shifting the focus from the specific to the general [45].

The inductive approach identified dimensions and related categories based on content analysis [54]. Therefore, an iterative process was applied, which involves first familiarising oneself with the selected sample of articles [55] and allowing themes to develop and emerge organically rather than selecting predetermined themes. Accordingly, the data were categorized [56]. This approach was used for the dimensions of waste, by-products, and keyword analysis.

Specifically, the waste dimension is divided into four analytical categories as follows:

- vine cultivation (waste from the first stage of the wine production chain, such as vine pruning and shoots);
- vinification residues (waste from harvesting, destemming, aging, and bottling, such as grape pomace, grape stems, and grape seeds);
- fermentation and maturation residues (focus on valorizing fermentation phase waste, such as wine lees and wastewater);
- leaf residues (vine leaves).

The same process was followed for clustering by-products generated by the valorization of wine waste:

- livestock and agricultural applications (such as animal feed and compost);
- food industry applications (as additives and new products with high nutritional value);
- chemical and energy industry applications (as biofuels);
- packaging and materials industry applications;
- pharmaceutical and cosmetics industry applications.

For keyword analysis, the iterative process was developed using VOSviewer1.6.19 software.

In the deductive approach, the identification of dimensions and related categories was based on analyzing models and frameworks in literature. For the classification of sectors, we referred to the 2014 Intergovernmental Panel on Climate Change Assessment Report [57], which discusses the different methodologies for classifying sectors and industries, focusing on the implications for economic analysis and climate change. For geographical focus, we relied on the science of geography.

Identifying the dimensions and their categories allows the analysis of the articles from different perspectives, contributing to a greater understanding of the topic and thus answering the research questions of this article in greater depth. The categorization process allows us to (1) classify the waste from the wine supply chain and study its valorization from a circular economy perspective and (2) analyze in which product sectors and geographical areas studies on the valorization of wine waste are most developed. Before analyzing the five structural dimensions, a general description of the sample was carried out.

This research defined three structural dimensions using the inductive approach, while two dimensions applied the deductive approach (Table 2).

Table 2. Approach, structural dimensions, and analytical categories. Source: authors' elaboration.

Approach	Structural Dimensions	Analytical Categories
Inductive	Waste	Vine cultivation Vinification residues Fermentation and maturation residues Leaf residues
Inductive	New products	Livestock and agricultural applications Food industry applications Chemical and energy industry applications Packaging and materials industry applications Pharmaceutical and cosmetics industry applications
Inductive	Keywords	Keywords families
Deductive	Sectors	Industrial sector
Deductive	Geographical focus	Geographical area analysis

4. Results

4.1. Descriptive Sample Analysis

The descriptive sample analysis classifies articles according to the following criteria: (1) date of publication, (2) journal, and (3) number of authors.

The first element analyzed is the year of publication of the selected articles. Most of the articles were published in 2023 (22 articles, 30% of the sample), and a considerable portion were published in 2021 (14 articles, 19% of the sample) (Figure 3).

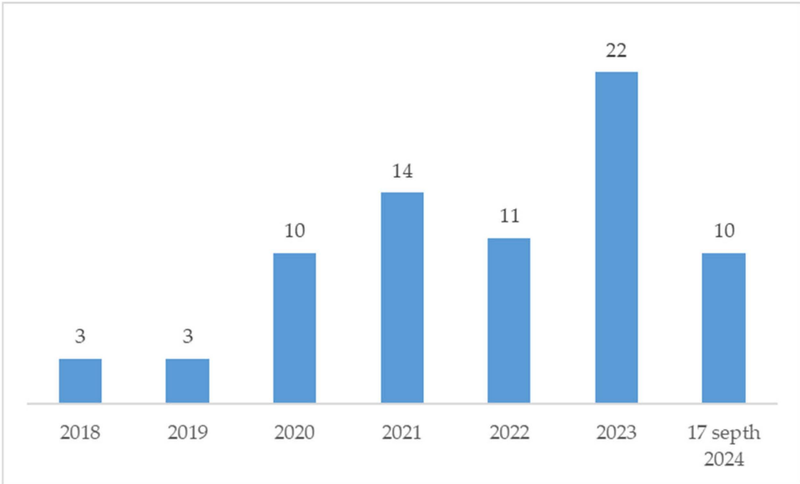

Figure 3. Documents distribution for years. Source: authors' elaboration.

Another analysis involved classifying the papers concerning journals. Table 3 shows the list of selected journals. "Applied Sciences", "Science of the Total Environment", and "Sustainability" are the journals with the highest number of papers (7 percent), followed by the journal "Foods" (5 percent).

Table 3. List of selected journals. Source: authors' elaboration.

Journals	f	%
Applied Sciences (Switzerland)	5	7%
Science Of The Total Environment	5	7%
Sustainability (Switzerland)	5	7%
Foods	4	5%
Antioxidants	3	4%
Molecules	3	4%
Waste Management	3	4%
ACS Sustainable Chemistry And Engineering	2	3%
European Biomass Conference And Exhibition Proceedings	2	3%
Fuel	2	3%
Agriculture (Switzerland)	1	1%
Analytical Letters	1	1%
BIO Web Of Conferences	1	1%
Biochar	1	1%
Biomass And Bioenergy	1	1%
Biomolecules	1	1%
Chemistry Africa	1	1%
Circular Economy And Sustainability	1	1%
Environmental Pollution	1	1%
Environmental Science And Engineering	1	1%
Environmental Technology (United Kingdom)	1	1%
European Food Research And Technology	1	1%

Table 3. *Cont.*

Journals	f	%
Fermentation	1	1%
Food Chemistry	1	1%
Food Technology And Biotechnology	1	1%
Frontiers In Chemistry	1	1%
Gels	1	1%
Green Chemistry	1	1%
International Journal Of Food Science And Technology	1	1%
Journal Of Environmental Chemical Engineering	1	1%
Journal Of Environmental Management	1	1%
Journal Of The Science Of Food And Agriculture	1	1%
Land Use Policy	1	1%
Life	1	1%
Mediterranean Fruits Bio-Wastes: Chemistry, Functionality And Technological Applications	1	1%
Microchemical Journal	1	1%
Nematology	1	1%
Nutraceutics From Agri-Food By-Products	1	1%
Plant Biosystems	1	1%
Polymers	1	1%
Proceedings Of The LACCEI International Multi-Conference For Engineering, Education And Technology	1	1%
Process Safety And Environmental Protection	1	1%
Recycling	1	1%
Reviews In Environmental Science And Biotechnology	1	1%
Revue Roumaine De Chimie	1	1%
Separation And Purification Technology	1	1%
Sustainable Chemistry And Pharmacy	1	1%
Waste And Biomass Valorization	1	1%
Water (Switzerland)	1	1%
Total	73	100%

Table 4 shows the results concerning the number of authors. Articles written by six or more authors account for 49%, followed by five authors (21%) and three (12%).

Table 4. The number of the authors. Source: authors' elaboration.

Number of Authors	f	%
>6 authors	36	49%
5	15	21%
3	9	12%
4	8	11%
2	4	5%
1	1	1%
Total	73	100%

4.2. Material Evaluation

This section reports the results, first showing the structural dimensions assessed by the inductive and deductive methods.

4.2.1. Waste Analysis

The analysis of the papers shows that the largest waste from the supply chain used in a circular economy perspective is vinification residues (accounting for 77% of the total sample). These include pomace, seeds, stalks, and mixed cellar waste (Table 5) [58].

Table 5. The main waste from the wine supply chain. Source: authors' elaboration.

Waste	f	%
Vinification residues	56	77%
Vine cultivation	8	11%
Fermentation and maturation residues	8	11%
Leaf residues	1	1%
Total	73	1

Grape pomace is an important solid waste [59] and includes grape seeds, skin, and pulp obtained by pressing and crushing to extract juice or must. It is estimated that one kilogram of marc remains after 6 L of wine [15]. Grape pomace is rich in structural carbohydrates, lignin, and other components such as oil and polyphenols, products with potential value [60]. The pomace extraction process in red and white wine production is different, and the pomace concentration also varies. Red grape pomace can be obtained 2–3 weeks after fermentation, but in the case of white grapes, it can be obtained immediately after pressing with pumps [61].

A large portion of wine cellar waste comprises seeds, making up to 30% of the wet pomace generated during the winemaking process. Seeds contain 25–40% moisture, polysaccharide sugars, organic acids, oils and fatty acids, phenols, nitrogen substrate, and minerals. In addition, some studies show a potential extraction of gallic acid [62]. The number of bioactive compounds that can be extracted from seeds is directly related to antioxidant properties [61].

Although stalks are not part of the winemaking process, their production is directly related to the winemaking process, so they are considered an imported waste of wineries [63]. They are removed to reduce their effects on the organoleptic test and excessive astringency before the vinification stages. Grape stems have a moisture content of 55–80%, and the common disposal use of stems is for animal feed or, most often, dumped in landfills [61].

Waste from vine cultivation and the fermentation and ripening process also play an important role (8%). Vine pruning residue is an abundant lignocellulosic source of a significant percentage of cellulose. This residue is typically burnt in the agricultural field, causing environmental pollution [64].

Wastewater comes mainly from washing rooms, machinery, floors, and product containers. This also includes wastewater generated in the distillery [61]. As far as lees are concerned, these are obtained after the winemaking clarification process. Wine lees are generally collected from the bottom of the container, as they can be collected as residue after filtration or centrifugation. Lees are important because they can interact with the wine's polyphenols and greatly impact the wine's color and organoleptic properties. In most cases, wine lees are disposed of with wastewater [61].

A lower percentage, one percent, comprises vine leaves. In detail, vine leaves are a primary waste wine industries produce during grape harvesting procedures. The practice is for the leaves collected by the industries to be dumped in landfills or burnt [61].

4.2.2. Analysis of By-Products

All the items collected can be presented in five clusters, representing the by-products generated by the waste of the wine supply chain. Table 6 shows the division of the sample into the five clusters. The largest cluster is the Chemical and Energy Industry Applications (47%), followed by the Livestock and Agricultural Applications Cluster (22%), and finally, the Food Industry Applications Cluster (21%).

The Chemical and Energy Industry Applications cluster consists of 34 articles published between 2018 and 2024, and within it are articles on the extraction of phenols from wine industry waste and energy production. For example, the study by [65] focused on selecting the most efficient extraction step, considering recovery yields and capital and operational expenditure. Furthermore, this work aimed to explore the performance of the water-ethanol system in extracting polyphenols considering different grape varieties. How phenolics are extracted from a circular economy perspective is a recurring theme in the articles [18,66–68], just as the authors need to classify the knowledge and properties of phenolic compounds present in the main grape by-products [19,26]. In addition, the cluster consists of several articles that refer to biorefinery. For example, the article by [69] promotes the integrated valorization of oenological by-products for a 'smart' conversion of waste, optimizing biomass. Ref. [61] refers to the integrated biorefinery from the conventional biorefinery system as an alternative to processing winery by-products as raw materials. On the other hand, Ref. [70] assessed the potential of by-products as an energy source for hot water boilers.

Table 6. New products from winery wastes. Source: authors' elaboration.

New Products	f	%
Chemical and energy industry applications	34	47%
Livestock and agricultural applications	16	22%
Food industry applications	15	21%
Packaging and materials industry applications	4	5%
Pharmaceutical and cosmetics industry applications	4	5%
Total	73	100%

The cluster Livestock and Agricultural Applications includes articles from 2018 to 2023. The cluster refers to the conversion of waste into feed and compost. About the first new agricultural product, the articles that deal with the conversion of by-products of the wine industry into feed with important nutritional properties and a low environmental and economic impact [36,71,72] are referred to. The first study, Ref. [73], concerning bio compost, focused on the environmental implications of a pathway to recover wine waste by composting to obtain a high-quality fertilizer. Further study topics concern the conversion of wine waste into biochar to combat pest growth [31] and the suitability of vermicomposting for processing grape marc into an environmentally friendly organic fertilizer [74].

Food industry applications include articles from 2019 to 2024 on converting waste into nutraceuticals and natural food additives [75,76]. For nutraceuticals, the first articles dealt with converting oil from grape seeds into seed oil for culinary use, whose nutritional properties are appreciated [77,78]. Articles dealing with converting supply chain waste into bakery products are also interesting. For example, Ref. [79] investigated the conversion of grape marc into gluten-free flour; in Ref. [80], the conversion of grape marc into bakery yeast; Ref. [81] dealt with the conversion of defatted grape seed flour in addition to traditional flours to obtain low-calorie foods.

Five percent of this sample comprises clusters of applications in the packaging and materials and pharmaceutical and cosmetics industries. The first cluster consists of articles analyzing the processing of waste into packaging, such as the article by [82], in which the antimicrobial activity of chitosan film extracted for the first time from grape seed oil was analyzed to assess its potential in food packaging; and articles on Textile dyes. Ref. [83] highlighted the importance of valorizing grape pomace as a potential source of bio-colorants for the textile industry, emphasizing the need to improve dyeing processes to make the use of grape pomace-derived bio-colorants more effective and economically viable.

The Pharmaceutical and cosmetics industry applications cluster concerns authors who have detected functional compounds in wine waste for the pharmaceutical and cosmetics industry due to their antioxidant, anti-inflammatory, antifungal, or scavenging activities [58,84].

4.2.3. Keyword Analysis

The VOSviewer software 1.6.19 (www.vosviewer.com; [85]) was used to analyze keywords. This software helps users visualize data maps of bibliometric networks based on similarity visualization [44,85] and is generally used to perform literature reviews in research studies [60,86]. Co-occurrence analysis facilitates counting articles that were published simultaneously [44]. The distance between nodes (keywords) "is approximately inversely proportional to the similarity (correlation in terms of co-occurrence) of the keywords" [87]. Furthermore, "a smaller distance generally indicates a stronger relationship" [88]. Through this logic, the software builds a network of keywords (adjectives and nouns) that recur in more than one document, displaying them in a 2D map. In addition, it also has a clustering tool that links keywords to clusters based on their recurrence [87,88]. In this study, the configuration considered consists of binary counting, using only keywords repeated at least five times [44]. Keywords that did not match this setup were excluded manually, and the interpretability criterion was used to determine the number of clusters [87,89].

The analysis returned 1198 keywords, 46 of which matched the inclusion criteria. Words included in the abstract of articles were removed (e.g., "design/methodology/approach", "article"). Figure 4 shows the network visualization in which a label represents a label and a circle with different sizes. The sizes were determined according to their weight. The most recurrent keyword was "Wine" (40 occurrences, 272 total link strength, 43 links), followed by "Circular Economy" (46 occurrences, 229 total link strength, and 43 links), "Nonhuman" (14 occurrences, 144 total link strength, and 43 links). In addition, the software identifies 4 clusters. The first cluster contains 12 elements and highlights the enhancement of phenolic compounds in wine waste, focusing on antioxidant characteristics. In particular, the cluster shows the relationship between "Winery waste", "Extraction", "Phenolic compounds", and "Antioxidants".

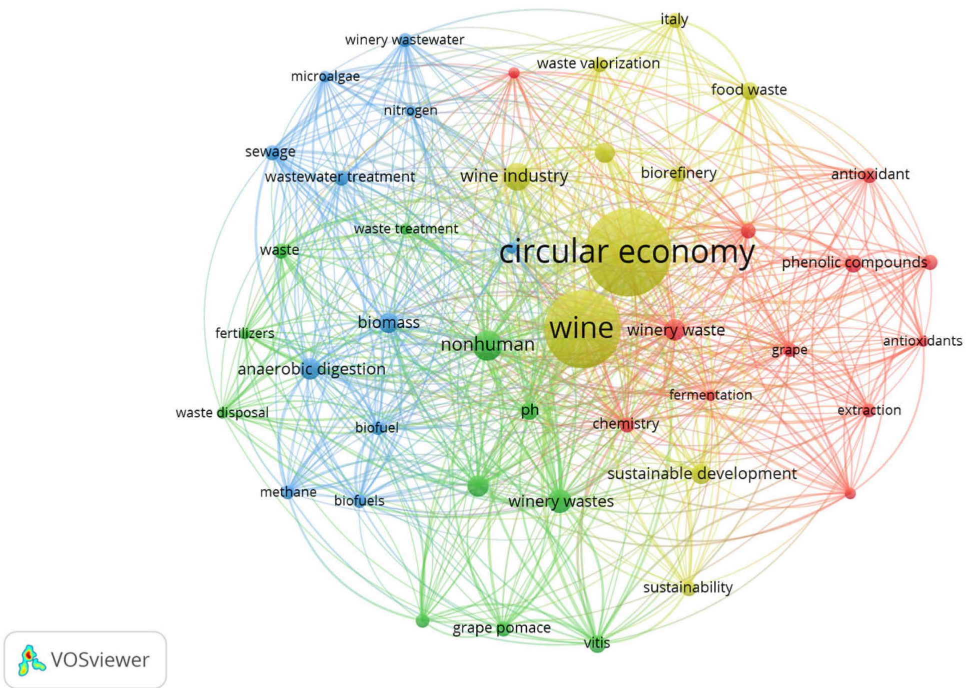

Figure 4. Network visualization. Source: Authors' elaboration.

Cluster 2 comprises 11 items and shows the relationship between "Winery wastes" and "Fertilisers". The cluster highlights the conversion of wine waste into compost, including through "waste disposal" and "waste treatment".

Cluster 3 comprises 11 elements and shows waste conversion from the wine industry into green Energy. The presence of the keywords "Biofuel", "Anaerobic digestion", and "Methane" highlight the valorization of winery wastewater into bioenergy.

Finally, cluster 4, consisting of 10 items, illustrates the relationship between "Circular Economy" and "Wine industry" in a more general way. In particular, the cluster highlights how reusing waste from the sector is a "sustainable development" and "valorization" strategy. Furthermore, the relationship between the valorization of wine waste and Italy is highlighted. The composition of cluster 4 confirms what was stated in the sub-section (Section 4.2.4. Geographical Focus). Italy has the highest number of articles published as it is directly interested in the topic. Italy is the second largest wine producer in the world, with 38.3 million hectolitres [13].

4.2.4. Geographical Focus

The geographical origin of the articles was obtained by considering the first author's country (Figure 5). The analysis shows that Italy and Spain have the highest number of articles (22 articles, corresponding to 30% of the total), followed by Portugal (10 articles). This is also confirmed by the analysis made according to the authors' continent of origin. Europe is the first continent, with 61 articles (84%), followed by South America, with six articles (8%).

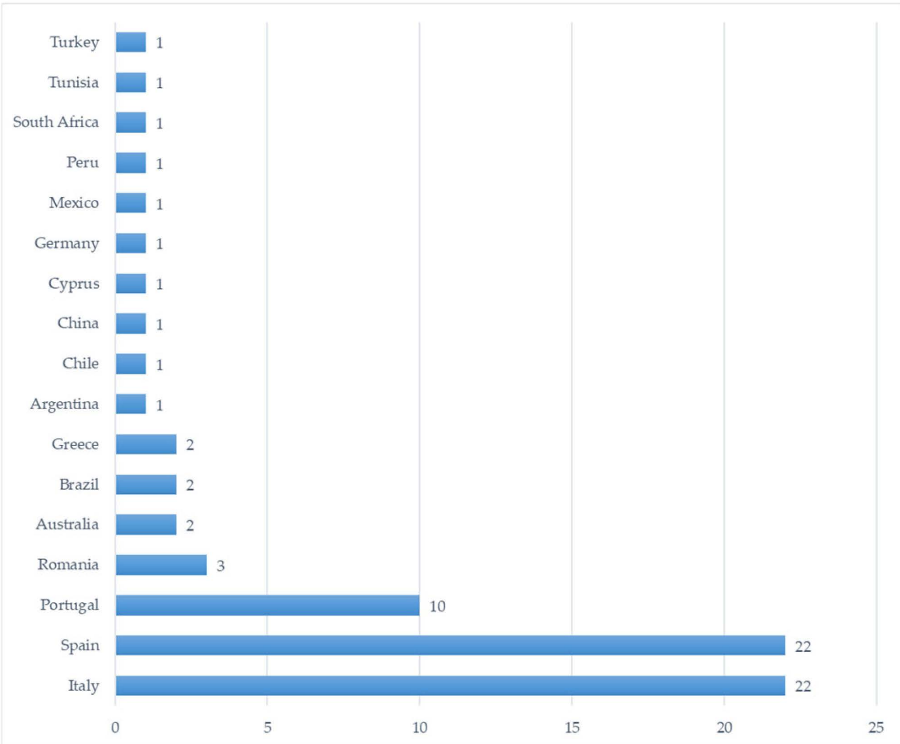

Figure 5. Number of papers by country. Source: authors' elaboration.

Figure 6 shows the temporal distribution of articles about the continent of the first author. As can be seen, as of 2018, Europe is the first continent to study these topics. An important peak is reached in 2023. Latin America started its research activity with a slight delay, with only one article published in 2021 and constant publications over the following years.

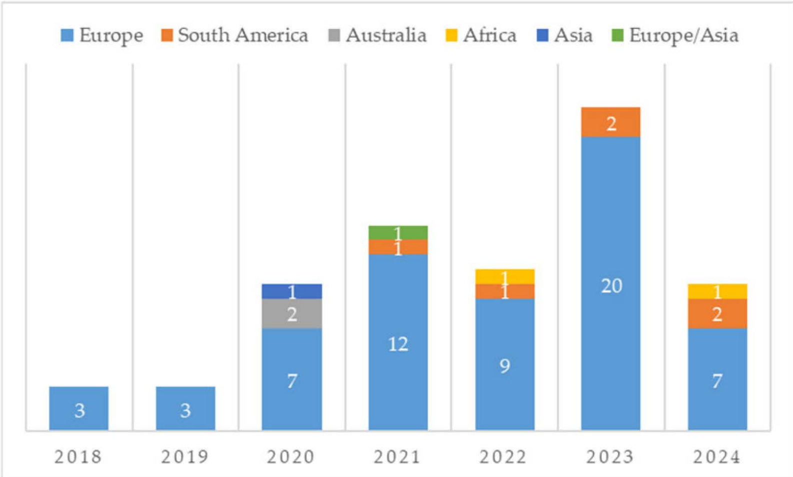

Figure 6. Temporal distribution of papers considering different continents. Source: authors' elaboration.

4.2.5. Sector Analysis

The findings reveal that three sectors have drawn researchers' interest. The first is the Food sector (30 percent), followed by the agricultural sector (22 percent) and the energy sector (21 percent) (Table 7).

Table 7. The main sectors. Source: authors' elaboration.

Sectors	f	%
Food	22	30%
Agricultural	16	22%
Energy	15	21%
Pharmaceutic	9	12%
Industrial	5	7%
Cosmetics	3	4%
Manufacturing	3	4%
Total	73	1

Table 8 shows wastes from the wine supply chain and the sectors where they are reintroduced.

Table 8. Integration between wine wastes and sectors. Source: authors' elaboration.

		Food	Agricultural	Energy	Pharmaceutic	Industrial	Cosmetics	Manufacturing
Vinification residues	Grape pomace	11	10	4	6	2	2	1
	General residues	1	1	4	1		1	2
	Grapeseeds	5		1		1		
	Grape stems	1	1		1			
Vine cultivation	Vine pruning		2	3	1			
	Vine-shoots	2						
Fermentation and maturation residues	Wine wastewater	1	2	1				
	Wine lees	1		2		1		
Leaf residues	Wine leaves					1		

Table 8 confirms what has already been demonstrated in previous results. Grape pomace, general residues, and grapeseeds are the most widely used wastes, particularly in the food, agricultural, energy, and pharmaceutical sectors. Following these, grape pomace is most utilized in all these sectors, while general residues are most utilized in energy, and grapeseeds have a significant application in the Food sector.

The results revealed that these economic sectors are the ones in which the by-products of the wine industry are used the most.

The results showed that in the food sector, for example, pomace is used to produce food packaging [82]. Grape pomace and seeds are also processed and converted into alternative flours for gluten-free products, as Ref. [79] demonstrated. Defatted grape seed flour can be a source of functional macro- and micronutrients that help maintain optimal health and well-being [81].

In addition, the processing of grape marc has resulted in levulinic acid, which is used as a flavoring and preservative agent in food and beverage applications [76].

Pomace, cellar waste, and seeds are also processed into supplements and functional products [90]. In addition, the three by-products are mentioned in several studies dealing with the extraction and recovery of polyphenols, with their strong antioxidant and anti-inflammatory capacities [18,65,78].

In a closed-loop circular economy, wine marc and seeds are reintroduced into wine production as marc has a high potential for bioactive compounds that can be stored in the well-known polyvinylpolypyrrolidone, a chemical extract used industrially in wine clarification and stabilization [91].

The wastes above are also reused in the agricultural sector. Grape marc is an additive that improves food quality and organoleptic characteristics in the fish sector [92]. Grape marc and cellar waste are also used as pesticides. Indeed, Ref. [93] shows that biochar from grape marc effectively controls gall nematodes, i.e., endoparasites that feed on host plants and pose a serious threat to agriculture. Ref. [94] also studied the antiparasitic potential of winery waste against nosema ceranae, an important pathogen in beekeeping. This study is important as no drugs are available to combat nosema. Pomace is also used as fertilizer. Studies by [31,95] determine the potential of grape marc as a soil bioavailability product. The results demonstrated a reduction in the presence of the pest in tomatoes and beet, which increased soil fertility and crop yields. In addition, Ref. [72] demonstrated the conversion of pomace), stalks, and wine lees into high-value-added feed and food of animal origin. The study demonstrates improved animal health and growth performance, improved egg, meat, and milk quality, and reduced methane and nitrogen emissions.

In the energy sector, pomace is converted into solid biofuels [80], while cellar waste is used to produce biomass [96], methane [61,97,98], and hydrogen [99]. In particular, the study estimated the potential for producing hydrogen and biogas from wine waste to replace existing fuels in the Brazilian local bus fleet.

5. Discussion

This study highlighted the potential of valorizing wine waste to contribute to circular economy principles by closing the loop on resource use and reducing environmental impact [10].

Analyzing the results made it possible to answer the research questions formulated in the initial phase:

- RQ1 What are the main wine wastes reused from a circular economy perspective?
- RQ2 What are the main sectors in literature in which wastes are reused?

5.1. RQ1 What Are the Main Wine Wastes Reused from a Circular Economy Perspective?

The circular economy presents a transformative approach to waste management in the wine industry, which is known for its significant waste generation. Indeed, the winemaking process produces a variety of by-products that collectively account for approximately 20–30% of the total mass of wine production [100]. The large volume of waste represents both an environmental challenge and an unexplored economic potential if properly exploited. The adoption of circular practices, such as the valorization of by-products generated during fermentation and maturation phases, e.g., residual sludge, through thermo-chemical treatment processes to produce green energy, represents a significant contribution to improving the overall efficiency of the supply chain [6,33]. Effective management and valorization of winery waste are crucial to minimize the environmental impact of the wine industry. Innovative approaches are emerging that explore the potential of this waste to create value-added products [37,101].

The marc, for example, which is the main by-product of the winemaking process, both in terms of quantity and composition, represents a resource rich in bioactive compounds such as dietary fibers, lipids, minerals, polyphenols, and proteins. Grape marc is used as animal feed or in pharmaceuticals due to the high presence of phenolic compounds [38], known for their antioxidant and anti-inflammatory properties. It has been shown that it can also be used to clarify wine, reducing the presence of harmful substances, with potential benefits in reducing allergens [58].

The seeds, conversely, constitute the part of the berry with the highest antioxidant activity [35]. Therefore, they can be used for the extraction of bioactive compounds, which can be conveniently utilized for cosmetic, nutraceutical, and pharmaceutical purposes [102].

Wine by-products are also used in the food sector, where they become functional ingredients and natural additives. For instance, marc and seeds are processed and converted into alternative flours for gluten-free products [79] by their two main components, dietary fiber and polyphenols, which are used to improve nutraceuticals in food [15]. Besides food, wine-making residues are exploited in agriculture, where they are used as natural fertilizers and pesticides. By-products of wine processing are transformed into solid biofuels, which reduce dependence on fossil fuels and contribute to more sustainable energy production [80]. Through anaerobic fermentation, these residues can be converted into biogas, biomass, and methane [61,96–98].

Another important waste category that has been less studied is wine lees, which account for about 5% of wine by-products. Lees are complex wastes to manage, both due to the high presence of polyphenols, which makes their treatment and valorization on an industrial scale difficult [58], and due to the presence of pesticides accumulated during grape cultivation, which poses further challenges for their treatment, leading to research into more effective and sustainable methods for cleaning and processing these residues [15].

In this context, new technologies play a crucial role in making lees, and lees in general, suitable for wider commercial use [58]. Advanced wine waste treatment technologies are an important tool for improving the sustainability of the sector, creating economic value, and reducing environmental impact [103]. Recently, several innovative technologies, such as ultrasounds, have been developed to improve the recovery of bioactive compounds like polyphenols and reduce the environmental impact through more sustainable processes [104].

Not only wine lees but also other wastes such as grape pomace are used, with anaerobic digestion transforming them into digestate, which improves soil properties [105]. Stalks can also be converted into biochar and syngas through pyrolysis, contributing to clean energy [105].

These developments testify to the potential of the circular economy in the wine sector. In this economy, any residue can be converted into a helpful resource for different applications, with environmental benefits and new income opportunities for wineries.

5.2. RQ2 What Are the Main Sectors in Literature in Which Wastes Are Reused?

Wine waste poses challenges and opportunities for companies operating inside and outside the wine supply chain, calling for new strategies for sustainable and innovative residue management [10]. Such residues do not simply represent a burden in terms of disposal. However, they are also a potential resource for broader and more diversified production processes, ranging from food and cosmetics to agro-industrial and energy sectors [80,102]. By adopting circular strategies, companies can make the most of these by-products, gaining competitive advantages, reducing disposal costs and promoting sustainability while at the same time responding to the growing market demand for environmentally friendly solutions.

With growing environmental awareness, the demand for sustainable products such as biofuels, bioethanol, and renewable energy has also intensified. These products are particularly sought after in geographical areas where energy costs are high and where the recovery of agricultural waste is an advantageous solution to mitigate the impact of production costs. Due to rising energy prices globally, wineries that turn waste into energy resources can achieve significant savings while reducing the use of fossil fuels and contributing to cleaner production [61,106]. Grape marc and other by-products lend themselves to producing bioenergy that can be reintegrated into production processes, ensuring a virtuous cycle that minimizes the environmental impact of the wine sector.

The food industry has been equally interested in integrating wine production residues into new products, as evidenced by the focus on pectin extracted from grape pomace [106]. Pectin is a natural thickener widely used in the food and pharmaceutical industries, and its recovery from wine by-products is a solid justification for more in-depth research, with potential environmental and economic benefits for the industry [15]. This interest has led to numerous experiments and applications, ranging from producing natural food additives to formulating nutraceuticals, opening new markets, and diversifying supply.

The analysis of by-products also highlighted how the circular economy can concretely valorize these residues. Among the main applications identified, the use of these wastes to produce alternative fuels emerges, with 21% of by-products used for the generation of biofuels such as biodiesel and bioethanol, followed by compost (16%), which can be used as a natural fertilizer for agriculture, and new food products (15%) that meet a growing demand for environmentally friendly and gluten-free ingredients. Through these applications, the wine industry reduces its ecological footprint and satisfies a market that is increasingly aware of product sustainability [107].

The analysis of the keywords used in the research further confirms the potential of these circular practices. In cluster 2, which refers to waste management, key terms such as "waste disposal" and "waste treatment" emerge, highlighting the focus on optimizing waste management. Cluster 3, dedicated to green energy, reflects the interest in the conversion of waste into renewable energy sources, highlighting how the valorization of waste can contribute to the production of biogas and syngas, which can be used to feed the wine supply chain itself [79]. An innovative approach to green energy production is the conversion of sewage sludge into syngas, combining plasma thermal technology with carbon capture, utilization, and storage [33].

Finally, cluster 4 of this analysis represents the growing connection between the "circular Economy" and the "wine Industry", demonstrating how the transition to a circular model is taking hold in wine production. This connection reflects companies' commitment to improving the efficiency of their operations, minimizing waste, and integrating sustainable processes to create economic and environmental value.

The transition to renewable and sustainable energy sources is one of the key challenges for achieving sustainable development goals. In this context, with its by-products, the wine sector offers an opportunity to promote innovative circular economy practices [9]. Among these by-products, grape marc is emerging as a valuable resource that can be converted into energy through gasification.

Research by Ref. [20] explored the potential of grape marc gasification for the production of hydrogen, highlighting how this technology not only allows the recovery of solid waste generated by the wine industry but also contributes to the creation of a clean and renewable energy source.

The analysis of the environmental impact of the gasification process highlights the importance of a systematic and integrated approach. In particular, the reuse of syngas produced during gasification is essential to reduce greenhouse gas emissions and prevent potential negative impacts on the atmosphere. The accumulation of greenhouse emissions also significantly impacts air quality and, consequently, human health and the quality of life of local communities [20].

The adoption of circular economy technologies represents an opportunity for wine businesses to address several global challenges simultaneously: sustainable waste management, energy transition, and climate change mitigation. In addition, the integration of circular solutions such as these allows wineries to increase their competitiveness by improving their operational efficiency and reducing the costs associated with waste management while generating new sources of income through the sale of energy or raw materials derived from by-products [104].

Furthermore, the ability to convert agricultural waste into energy or industrial resources contributes to a virtuous circle that strengthens the resilience of the wine sector in the face of economic and environmental challenges [79]. This approach demonstrates how sustainability and innovation can combine to create tangible benefits not only for businesses but also for the environment and society as a whole, consolidating the role of the circular economy as a strategic pillar for a better and more sustainable future [103].

In this context, synergy with other industries is crucial: collaborations with companies in complementary sectors allow the impact of the circular economy to be extended on a larger scale, stimulating innovation and improving overall environmental performance [15]. The transition to a circular economy enables the transformation of environmental constraints into opportunities for innovation, stimulating the development of skills and knowledge that contribute to making the wine sector increasingly sustainable and competitive and making the wine tradition adapt to new global market demands and long-term sustainability paradigms [79].

The framework in Figure 7 proposes a circular business model in the wine sector, summarising the main points discussed in this section.

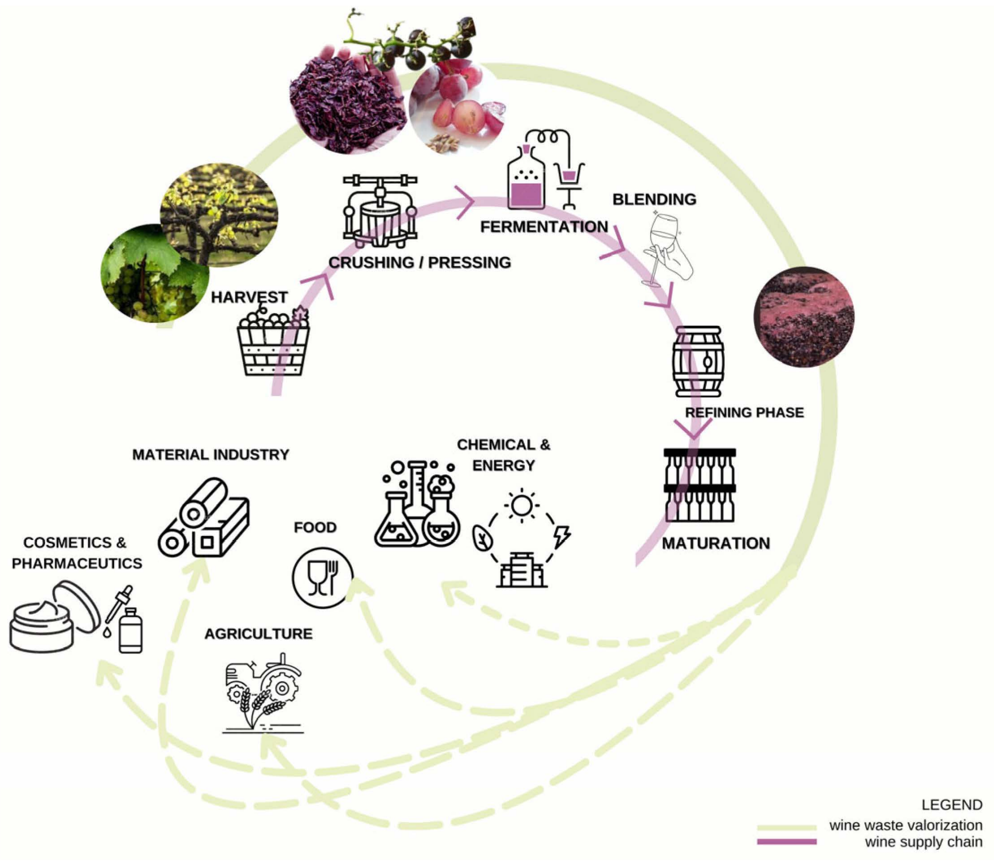

Figure 7. Circular business model framework. Source: authors' elaboration.

6. Conclusions

The study carried out an in-depth analysis of the main wastes generated along the wine production chain and identified the economic sectors in which they are reused. The study showed that the sectors most involved in the valorization of these by-products are the agricultural, energy, and food sectors. Among the most frequently used by-products are grape marc, grape seeds, and general canteen waste. Grape marc, for example, is used to produce compost, biogas, or bioethanol, as well as for the extraction of bioactive compounds for the nutraceutical and cosmetic industries [31,74,89]. Grape seeds, rich in natural oils and antioxidants, are used to produce essential oils, protein flours, or food supplements [75], while general cellar waste is often used for energy production through anaerobic digestion or waste-to-energy processes [90,108].

From a management point of view, this study provides a tool to assist agricultural enterprises in the decision-making process related to managing and valorizing waste from the wine supply chain by identifying sectors in which the waste can be reused [35]. In addition, businesses can benefit from guidance on how to turn by-products into economic opportunities by creating new revenue streams through the sale of valorized products such as bioactive compounds, organic fertilizers, or biomass for energy [31,74,89].

From a scientific point of view, this review aims to fill existing gaps in the literature and make an important contribution to outlining the state of the art on this topic. The article provides an overview of the main strategies studied for the reuse of by-products of wine production. The identification of new products, such as bioactive compounds, biogas, and compostable materials, is a fundamental starting point for further studies.

However, the search has limitations. Although this search is one of the first systematic reviews in this field, the manual search method used may have excluded or omitted potentially relevant articles. While this approach provides more direct control over the selection of sources, there is a risk that important contributions will be missed. Secondly, although Scopus is one of the most comprehensive and reliable platforms for academic literature, the use of a single database is another major limitation. For this reason, the next steps of the research include the use of other databases, such as Web of Science, to expand the sample of articles.

In addition, future research developments will focus on developing methods and tools to evaluate the effectiveness of circular economy strategies in wine businesses. This will include the analysis of environmental impacts through metrics such as emission reduction, improved waste management, and economic benefits, focusing on return on investment, savings from reduced disposal costs, and the creation of new value streams through by-product valorization.

To this end, the study of existing case studies related to the valorization of waste in the wine sector will be useful as they provide concrete examples of the application of circular economy practices. The analysis of these cases will make it possible to assess the environmental and economic impact of the strategies adopted, understand the critical success factors, and identify operational and technological barriers. In fact, the integration of innovative technologies, such as anaerobic fermentation for biogas production and the extraction of bioactive compounds from grape residues, not only favors the reduction of environmental impacts but also creates new markets for by-products, thus increasing the value of the supply chain [105].

Collaborative models between the different actors in the wine supply chain, such as producers, researchers, policymakers, and practitioners, are needed to get a holistic view of the circular supply chain model. Collaboration could facilitate the development of synergies and accelerate the implementation of sustainable and technological practices [38]. The interaction between different actors can provide additional insights to identify best practices and improve management approaches, allowing farms to optimize their waste reuse strategies in an economically and environmentally beneficial way.

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