Journal of Information Systems Engineering and Management
2025, 10(34s)
e-ISSN: 2468-4376
https://www.jisem-journal.com/

Research Article

Analysis of Processes for Olive Oil Mill Wastewater Treatment

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ARTICLE INFO

Received: 30 Dec 2024

Revised: 19 Feb 2025

Accepted: 27 Feb 2025

ABSTRACT

The management and reuse of Olive Oil Mill Wastewater (OOMW) represent a critical challenge and opportunity for promoting sustainable practices in the agro-industrial sector. While OOMW is traditionally viewed as an environmental burden, it also contains valuable organic compounds with potential for recovery and reuse. This study adopts a bibliometric approach supported by information systems to analyze current research trends and emerging technologies for OOMW treatment. By integrating data from the Scopus database and visualizing results with VOSviewer, the analysis identifies thematic clusters and interdisciplinary connections, revealing a growing interest in the digital transformation of wastewater management. Key findings highlight the increasing adoption of smart technologies—such as Internet of Things (IoT) sensors, machine learning algorithms, and real-time decision-support systems—for monitoring, optimizing, and valorizing OOMW. These digital tools not only enhance treatment efficiency but also enable dynamic resource allocation and support circular economy strategies. The study concludes that the convergence between environmental technologies and information systems is reshaping the future of OOMW management, paving the way for intelligent, sustainable, and data-driven solutions in the olive oil industry.

Keywords: Olive oil mill wastewater (OOMW); Information systems; IoT; Machine learning; Smart wastewater management; Circular economy.

INTRODUCTION

In recent years, the convergence between sustainability and digital innovation has driven the development of intelligent frameworks for environmental management. Within this context, information systems are increasingly adopted to collect, process, and visualize both environmental and operational data, thereby enabling more informed decision-making across the agricultural and agro-industrial sectors [1]. In the olive oil industry, where wastewater management constitutes a pressing environmental challenge, IoT-enabled sensing systems have been proposed to monitor water consumption and wastewater generation in real time, supporting both predictive maintenance and adaptive control strategies [2]. This digital transformation is especially relevant given the scale and impact of olive oil production. According to the International Olive Council [3], global olive oil output has increased from 1.8 million tons annually in the 1990s to over 3 million tons in the 2020s, amplifying both the economic significance and environmental footprint of the sector. Although olive oil is rich in bioactive compounds such as phenolics, tocopherols, and antioxidants, the extraction process retains only 1–2% of these compounds in the final product [4]. The remainder is lost in by-products, most notably olive pomace and Olive Oil Mill Wastewater (OOMW), which together can constitute up to 80% of the original biomass. OOMW, the liquid effluent generated during the washing and extraction phases, can account for approximately 50% of the total waste volume [5]. It is characterized by its dark color, acidic pH, and high content of organic matter, lipids, phenolic compounds, and suspended solids, making it both toxic and difficult to manage [6]. Due to its complex physicochemical composition and seasonal generation, OOMW presents serious environmental risks when inadequately treated. Traditional disposal methods—such as land application or uncontrolled discharge—have been associated with soil degradation, groundwater contamination, and pest proliferation [7]. Despite these challenges, OOMW also presents significant opportunities for resource recovery and valorization. Olive mill by-products can be repurposed as biofuels, fertilizers, or as raw materials for the food,

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cosmetics, and pharmaceutical industries [8]. In particular, OOMW is a potential source of high-value compounds, especially polyphenols, which are increasingly used in nutraceutical and biomedical applications. Given its high environmental load and valorization potential, OOMW management is becoming a focal point for sustainable innovation in the agro-food sector. Water, a critical resource in both agriculture and industry [9], is central to this transformation. Recent research highlights the potential of combining emerging treatment technologies—such as nanofiltration membranes and photocatalytic materials—with AI-enhanced information platforms to significantly improve the efficiency of OOMW treatment and compound recovery [10]. In this context, data-driven decision systems can be employed to monitor performance, adjust operational parameters, and support real-time decision-making based on historical patterns and sensor input. These integrated approaches align with circular economy principles and promote industrial symbiosis, enabling the transition from linear waste disposal to a dynamic, intelligent, and sustainable management system. By leveraging both technological innovation and digital intelligence, the olive oil industry can reduce its environmental footprint while unlocking new opportunities for green value creation [11].

Figure 1. Example of by-products generated during the olive oil production process.

Given the environmental and economic implications, this paper aims to explore current strategies for reusing olive oil mill wastewater, highlighting established and experimental approaches, potential applications, and gaps in the existing literature. Results show the use of information systems and machine learning algorithms to optimize treatment conditions, monitor system performance, and enhance the recovery of bioactive compounds such as polyphenols. The bibliometric analysis also shows that traditional research on membrane technologies, such as mixed matrix membranes and clay-polymer composites, is now intersecting with computational modeling and predictive analytics. The document is organized as follows: Section I discusses the role of water in olive oil production and the methodological approach used for bibliometric analysis. Section II presents the results of this analysis, and Section III concludes with key findings and recommendations.

MATERIALS AND METHODS

Due to the nature of the processes involved, water has long been a vital and essential element in olive oil production [12]. Historically, placing olive mills near water sources such as streams, wells, cisterns, springs, and tanks [13] was a standard and advisable practice until around the mid-1960s. This arrangement was driven by the need for a constant and reliable water supply, minimizing transportation efforts and energy consumption for operations. Olive oil is extracted from olives using various methods in olive mills, including both traditional intermittent (discontinuous) pressing techniques and continuous centrifugal processes, commonly referred to as decanters [5]. The olive oil production process begins with washing the olives in cold tap water, which leads to the generation of liquid effluents. The volume of water used in olive mills can vary depending on the season and the specific characteristics of the extraction method employed [14]. The three-phase process (3PP) yields three distinct products: olive oil, olive pomace (olive cake), and olive oil mill wastewater (OOMW) [15]. The OOMW produced through this method typically contains 3.5–15% organic matter and 83–96% water [16]. In Italy, the amount of wastewater

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https://www.jisem-journal.com/
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generated by the 3PP extraction method is approximately 0.5 to 0.8 m³ per ton of processed olives [14]. Given the high-water consumption and the environmental impact of discharged wastewater, recent studies have highlighted the transformative potential of nanotechnology-based interventions. For example, nanofiltration membranes and nanocomposites offer promising solutions for reducing the organic load and improving the recovery of valuable compounds from wastewater. Additionally, photocatalytic processes using nanomaterials such as TiO2 and Fe2O3 could enhance water recycling efficiency, addressing both sustainability and resource optimization. Coupled with digital monitoring systems, these technologies offer integrated and intelligent pathways for improving water efficiency and sustainability in olive oil production [17]. Figure 2 illustrates the traditional 3PP method while simultaneously highlighting the opportunities for innovation through advanced technologies.

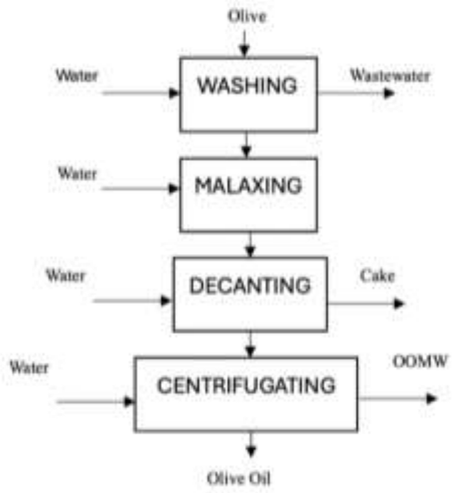

Figure 2. The olive oil production flow chart.

The objective of this methodology is to identify the key topics and application domains related to Olive Oil Mill Wastewater (OOMW) as addressed by the scientific and technical literature. To achieve this, a bibliometric analysis was conducted using the Scopus database, employing a systematic keyword-based query. Specifically, the string "olive oil mill wastewater" was applied to the fields "Article Title," "Abstract," and "Keywords", resulting in 1.584 documents.To further narrow the scope towards studies focused on digital transformation and smart monitoring, a second query was performed by adding the keyword "information system". This refined search retrieved a more specific subset of 14 documents, reflecting a growing but still emerging interest in the application of digital tools, data-driven approaches, and intelligent systems for the management and treatment of OOMW. This two-step methodology not only provides an overview of the scientific landscape on OOMW but also highlights the intersection between environmental sustainability and information systems engineering. The analysis serves as the foundation for identifying research gaps and supporting the development of smart platforms, capable of integrating real-time monitoring, predictive modeling, and cross-sectoral data analysis for more effective decision-making processes. The following figures illustrate the bibliometric findings, offering a visual summary of research evolution, keyword clusters, and thematic trends in this field.

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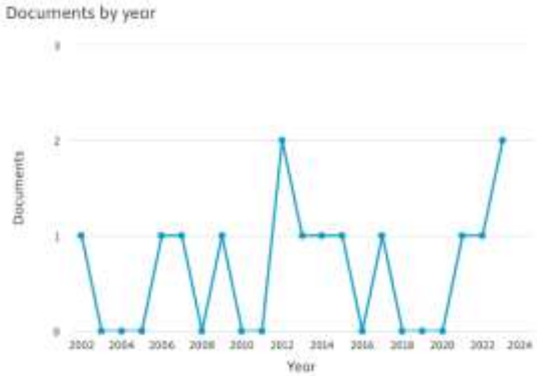

Figure 3. Number of documents published by year.

Figure 3 presents the temporal distribution of scientific publications related to Olive Oil Mill Wastewater (OOMW) and information systems from 2002 to 2024. As shown, the number of documents remains consistently low, with no more than two publications per year, reflecting the emerging nature of this research domain. Despite the limited volume, the presence of studies across two decades suggests early but fragmented academic interest in integrating digital tools into OOMW management. A notable increase appears in 2012 and 2024, which may indicate renewed interest driven by recent technological advancements, particularly in the areas of smart monitoring, IoT-based platforms, and data-driven decision-support systems. This trend aligns with broader transformations in the agro-industrial sector, where digitalization is progressively being adopted as a means to improve resource efficiency, traceability, and environmental performance. Unlike research trends linked to treatment technologies or circular economy policies, which show more consolidated growth, studies focusing specifically on information systems for OOMW remain at a nascent stage. Nonetheless, their temporal persistence and recurrence suggest a solid foundation for future interdisciplinary research that bridges environmental engineering, computer science, and digital innovation in sustainable agriculture. Figure 4 includes a pie chart visualizing the distribution of these documents by subject area of interest, with an emphasis on the growing role of technological advancements, including nanotechnologies, in addressing these challenges.

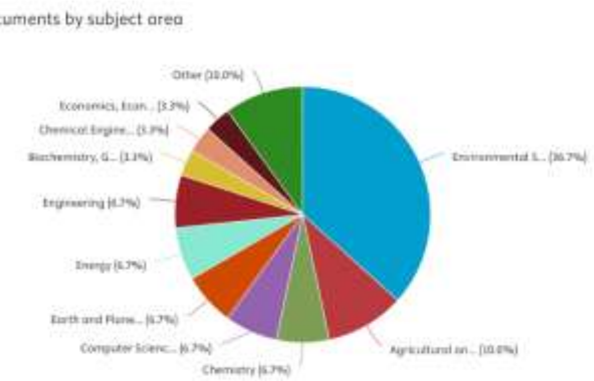

Figure 4. Documents by Thematic Area.

Figure 4 shows the distribution of the 15 documents by subject area. Most publications (36.7%) fall within the field of Environmental Sciences, underscoring the central role of Olive Oil Mill Wastewater (OOMW) as a critical topic in environmental sustainability and waste management. This reflects growing interest in optimizing water reuse, minimizing ecological risks, and supporting circular economy initiatives. A notable proportion of studies is also classified under Agricultural and Biological Sciences (10.0%), further confirming the relevance of OOMW treatment and valorization in agro-industrial systems. Interestingly, the presence of Computer Science (6.7%), Engineering (6.7%), and Energy (6.7%) points to a rising interdisciplinary approach where digital tools, smart sensors, and predictive models are increasingly being used to address environmental challenges. The inclusion of Earth and Planetary Sciences, Chemistry, and Economic, though smaller in percentage, demonstrates that the integration of

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information systems into OOMW-related research is not limited to environmental engineering, but is extending into broader domains concerned with sustainability, energy efficiency, and technological innovation. This thematic distribution reinforces the idea that future research on OOMW treatment should increasingly adopt a cross-disciplinary perspective, leveraging the capabilities of digital transformation to support real-time monitoring, informed decision-making, and data-driven optimization of waste management practices.

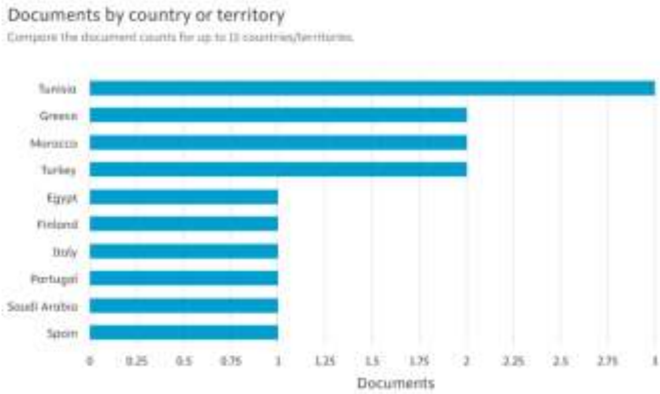

Figure 5. Documents country or territory.

Figure 5 illustrates the geographic distribution of scientific publications on Olive Oil Mill Wastewater (OOMW) in relation to information systems and digital technologies. Although the total number of documents is limited, the dataset highlights the emergence of several countries, Tunisia, Greece, Morocco, and Turkey, as pioneers in exploring the digital dimension of OOMW treatment and monitoring. These countries, all significant olive oil producers, are beginning to incorporate IoT frameworks, data analytics, and smart decision-support tools into the management of agro-industrial waste. Tunisia, in particular, leads the list, reflecting an institutional interest in advancing sustainable and data-driven practices in the olive oil sector. Interestingly, countries with traditionally strong research output on OOMW, such as Spain and Italy, appear less represented in this digital subset. This may indicate a gap between conventional environmental engineering approaches and digital integration strategies, suggesting an opportunity for further interdisciplinary development in Mediterranean countries with mature olive oil industries. Overall, the figure underscores the global yet uneven emergence of smart solutions in the OOMW domain. Overall, this distribution reflects the global production of olive oil, as shown in Figure 6.

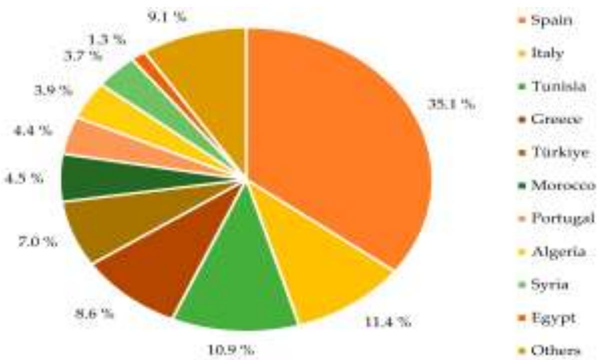

Figure 6. Distribution of world olive oil production by countries in the 2019/2020 season [20].

Subsequently, a comprehensive bibliometric analysis was performed using VOSviewer to construct and visualize bibliometric maps, providing graphical representations of publication networks that aid in interpreting relationships and trends within the scientific literature [18,19]. These maps highlight the interconnectedness between various disciplines and the growing interest in applying advanced technologies, including nanotechnologies, to address OOMW challenges.

In this study, VOSviewer was used to create three types of maps:

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- Co-occurrence map (network visualization): This map displays clusters where keywords are strongly correlated, allowing the definition of specific research topics.
- Co-occurrence map (overlay visualization): This map illustrates the frequency with which keywords co-appear in analyzed documents, helping to identify the main connections between various topics over time.
- Co-citation map by source: This map shows how different bibliographic sources are cited together in documents, enabling researchers to identify journals, books, or other works that are frequently co-cited. These co-citations reveal key sources of information and influences within the field.

RESULTS AND DISCUSSION

To design the co-occurrence maps using VOSviewer, a minimum threshold of 2 co-occurrences per keyword was set, resulting in a manual refinement to 31 keywords after duplicate removal. Figure 7 presents the network visualization, while Figure 8 illustrates the overlay visualization.

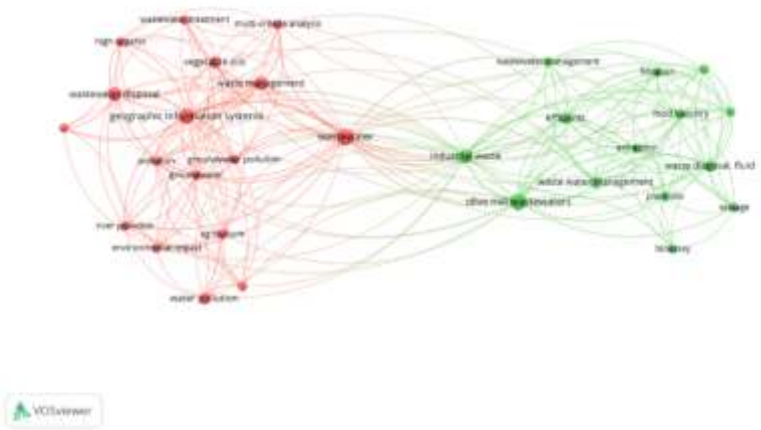

Figure 7. Network Visualization (different colours define 2 clusters).

Figure 7 visualizes the co-occurrence of keywords related to Olive Oil Mill Wastewater (OOMW) research, as identified through bibliometric mapping using VOSviewer. Each circle represents a distinct keyword, with larger circles indicating higher frequency across the analyzed literature. The spatial proximity between terms reflects the strength of their bibliographic relationship: keywords positioned closer together tend to co-occur in the same publications or are frequently cited in similar contexts. Colors are used to differentiate clusters of closely associated terms, revealing thematic groupings within the field.

The software identified two primary clusters, each representing a different perspective on the study and management of OOMW:

- Red cluster (left side): This group includes keywords such as *"wastewater", "pollution", "geographic information systems", "groundwater", "environmental impact"* and *"wastewater disposal."* It reflects a territorial and environmental focus, emphasizing the impact of OOMW on soil, water bodies, and ecosystems. Of particular interest is the inclusion of "geographic information systems" (GIS), which signals the growing role of spatial data management and digital mapping tools in analyzing pollution sources, monitoring discharge areas, and supporting policy decisions.
- Green cluster (right side): This cluster encompasses terms like *"olive mill wastewaters", "filtration", "effluents", "food industry"* and *"extraction."* It reflects a more process-oriented perspective, centered on treatment technologies, industrial applications, and waste valorization strategies. The presence of keywords such as *"wastewater management"* and *"bioassay"* suggests that researchers are increasingly integrating real-time monitoring, process optimization, and data analytics into OOMW-related operations.

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Although separated into two clusters, the map reveals interconnecting paths between environmental impact assessment and technological innovation. This convergence highlights the potential for information systems and IoT-based solutions to bridge the gap between monitoring and action, enabling more adaptive and intelligent responses to the environmental challenges posed by OOMW.

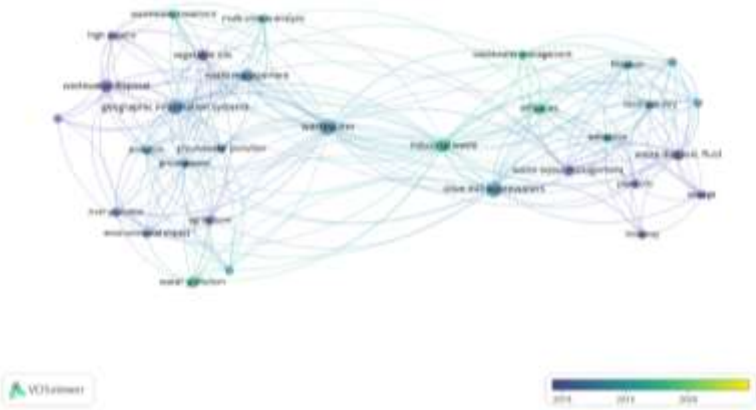

Figure 8. Overlay Visualization (coloured bar indicates the average year of publication).

Figure 8 illustrates the temporal evolution of research topics related to Olive Oil Mill Wastewater (OOMW), as revealed by a co-occurrence overlay map. Each keyword is color-coded according to its average year of appearance in the literature, based on data spanning from 2002 to 2024. The darker tones (purple–blue) represent earlier publications, while lighter tones (green–yellow) indicate more recent trends. From 2010 to 2015, the dominant focus centered on conventional environmental concerns, as reflected by terms such as *"wastewater treatment", "pollution"* and *"wastewater disposal."* These early studies primarily addressed mitigation strategies through chemical and biological processes, with limited incorporation of digital tools or systems-based approaches. Starting around 2016, the field began to shift toward resource valorization and integrated waste management, as seen in the appearance of terms like *"industrial waste", "food industry"* and *"extraction"*. This transition aligns with the growing interest in circular economy models and the potential of OOMW as a source of high-value compounds. More recently, from 2020 onward, the map shows a gradual emergence of keywords linked to digital transformation, including *"geographic information systems"* and *"multi-criteria analysis."* These terms suggest an increasing adoption of information systems and decision-support frameworks to enhance monitoring, evaluation, and planning processes in OOMW treatment. Although still limited in volume, this digital dimension reflects a new frontier in the research, where IoT-based sensing, smart data analytics, and GIS platforms are progressively entering the discourse. Overall, the overlay visualization reveals a field in evolution moving from basic environmental mitigation toward data-driven, systemic, and intelligent approaches to OOMW management, in line with the global shift toward sustainable and smart agriculture.

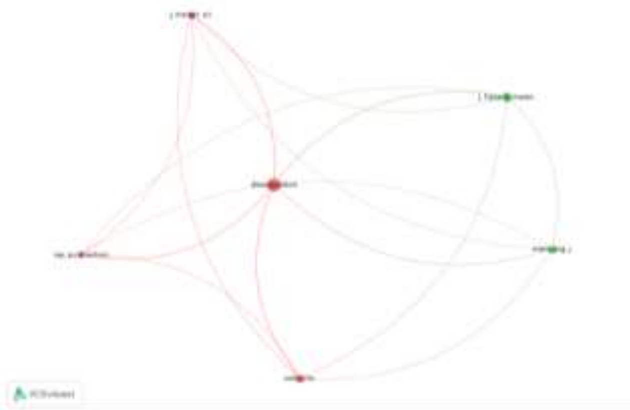

Figure 9. Network Visualization (different colours define 2 clusters).

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Figure 9 presents the journal co-citation network derived from the bibliometric analysis. Each node represents a scientific journal, with the size of the node indicating its number of citations within the selected corpus. The lines connecting journals represent the frequency with which they are cited together, highlighting intellectual relationships and shared research themes. Despite the smaller volume of documents, the journal Desalination emerges as the most frequently co-cited source, with 26 citations and 5 direct links to other journals in the network. Its centrality underscores its continued relevance in the field of wastewater treatment, membrane technologies, and water resource management, particularly within contexts like Olive Oil Mill Wastewater (OOMW) where advanced purification solutions are required.

The co-citation map reveals two main thematic clusters:

- The red cluster, which includes journals such as *Journal of Membrane Science*, *Separation and Purification Technology*, and *Water Research*, reflects a strong focus on technological innovations in water treatment. These journals are commonly associated with the development of filtration systems, effluent quality monitoring, and system optimization.
- The green cluster, comprising journals like *Journal of Hazardous Materials* and *Chemical Engineering Journal*, leans toward interdisciplinary research at the intersection of environmental risk, chemical processing, and resource recovery.

Although the current network does not yet include specialized journals in information systems or smart agriculture, the structure of the map indicates an increasing convergence between traditional engineering disciplines and digital innovation. As research on OOMW progresses, especially with the incorporation of IoT monitoring, machine learning analytics, and real-time decision systems, new bridges are expected to form between environmental engineering and information systems–oriented publications. This evolving co-citation structure highlights the potential for interdisciplinary dialogue and the emerging role of digital platforms in shaping the future of wastewater management research. The analysis of recent literature on Olive Oil Mill Wastewater (OOMW) treatment highlights a growing convergence between technological innovation and digital transformation. While nanotechnology-based solutions such as photocatalytic nanomaterials and nanofiltration membranes continue to play a crucial role in improving purification efficiency and resource recovery, emerging trends point to the integration of these technologies within smart, data-driven management frameworks.

Results show the use of information systems and machine learning algorithms to optimize treatment conditions, monitor system performance, and enhance the recovery of bioactive compounds such as polyphenols. Intelligent platforms capable of analyzing real-time data from IoT-enabled sensors, installed at various stages of the treatment process, can inform dynamic decision-making and enable adaptive responses to fluctuating wastewater characteristics [21]. The bibliometric analysis also shows that traditional research on membrane technologies, such as mixed matrix membranes and clay-polymer composites, is now intersecting with computational modeling and predictive analytics. For example, recent applications of machine learning in membrane performance evaluation have allowed researchers to identify key structural variables influencing filtration efficiency, leading to more targeted material design and operational control [22]. These developments align closely with the principles of the circular economy and the Agenda 2030 goals, as they not only reduce environmental risks but also enable resource valorization and cost-effective reuse. Furthermore, pilot-scale implementations demonstrate that digital integration significantly improves scalability and cross-sector applicability, particularly when combining environmental technologies with real-time monitoring infrastructures. Taken together, these findings suggest that the future of OOMW management lies in the development of hybrid systems that couple advanced treatment technologies with intelligent information management architectures. Such systems can facilitate data harmonization across plants, automate decision-making, and foster industrial symbiosis within the agro-industrial ecosystem. Continued research should focus on designing scalable digital platforms, enhancing interoperability among data sources, and embedding AI-based optimization tools to support a sustainable and digitally empowered olive oil sector.

CONCLUSIONS

This study has analyzed current scientific developments in the management, treatment, and valorization of Olive Oil Mill Wastewater (OOMW), emphasizing the transition from traditional approaches toward digitally integrated, smart, and sustainable systems. Through a bibliometric methodology supported by information systems, the research identified emerging trends, thematic clusters, and the growing role of digital technologies in environmental management. The findings underscore the increasing relevance of information systems, IoT-based monitoring, and machine learning models as essential enablers of adaptive, real-time wastewater treatment workflows. These tools are not only capable of enhancing operational efficiency but also support the recovery of valuable bioactive compounds, such as polyphenols, thus contributing to the goals of circular economy and industrial symbiosis. Although physical and chemical technologies, including nanofiltration membranes and photocatalytic materials, continue to offer promising results, their true potential emerges when integrated within data-centric architectures that allow dynamic process optimization, predictive maintenance, and cross-sector interoperability. The combination of environmental engineering and digital innovation is paving the way for intelligent treatment ecosystems capable of responding to complex and variable wastewater conditions. However, significant challenges remain. The development of scalable digital platforms, the harmonization of regulatory frameworks, and the promotion of interdisciplinary collaboration between technology developers, environmental scientists, and decision-makers are critical to unlocking the full potential of these innovations. Future research should focus on designing end-to-end digital infrastructures for wastewater management, capable of collecting, harmonizing, and analyzing multi-source data in real time. Moreover, applications in new sectors such as sustainable construction could further expand the impact of treated OOMW, turning waste into a strategic resource for eco-innovation. In this context, the integration of information systems into OOMW management is not just a technological advancement it is a necessary shift toward a resilient, intelligent, and sustainable agro-industrial future.

Acknowledgements:

The present work was financially supported by the projects:

NODES “Nord-Ovest Digitale E Sostenibile” - Spoke 7 “Secondary Agroindustry”, progetto bandiera Plant which has received funding from the MUR—M4C2 1.5 of PNRR funded by the European Union—Next Generation EU. Grant Agreement No. ECS00000036 – CUP: E13B22000020001.

“3A- ITALY - FORWARD”, Spoke 4: Smart and sustainable materials for circular and augmented industrial products and processes, Project code PE00000004, Concession Decree No. 341 of 15.3.2022 adopted by Ministero dell’Università e della Ricerca (MUR), CUP B73C22001270006, funded by the European Union – NextGenerationEU.

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