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ENHANCING WATER RECOVERY IN ROSE OIL PRODUCTION: CERAMIC MEMBRANE APPLICATIONS FOR SUSTAINABILITY AND CIRCULAR ECONOMY

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Abstract
The distillation process in the rose oil production sector produces organically rich, high temperature wastewater. This type of effluent constitutes a serious environmental disposal issue but at the same time contains valuable compounds. The present work investigates a sustainable approach to address this issue by applying ceramic membrane filtration to treat rose processing wastewater and recovery of valuable polyphenols. Characterization of the wastewater showed a complex chemical composition of high organic content and diverse phenolic compounds. Two-stage membrane filtration through a ceramic microfiltration membrane and then a ceramic nanofiltration membrane was employed. The microfiltration process generated higher flux and higher flux recovery ratio compared to nanofiltration. Though the lower flux is typical for denser membranes such as nanofiltration, these ceramic systems are robust and good for efficient pollutant removal and recovering polyphenols. The paper also discusses the application of these ceramic membrane systems to existing rose processing plants, citing their potential to create new sources of income through polyphenol recovery and enable the reuse of water. Inspired by successful applications of membrane systems in similar agro-industrial waste treatment, the economic and energy considerations implies that membrane technology has a lower energy profile and a favourable return on investment. Therefore, this study suggests that ceramic membrane filtration is an economically viable and environmentally sustainable solution for rose processing wastewater.
Keywords: *water recovery, circular economy, sustainability, rose oil distillation wastewater.*
JEL Classification: Q25

1. INTRODUCTION

Roses, includes over a hundred species, grow across Europe, Asia, and North America. While many roses have been cultivated for ages, wild varieties can still be found growing naturally. For thousands of years, rose leaves, flowers, and even their fruits have been used for medicinal purposes (Koczka *et al*., 2018).

Even though there are over a hundred rose varieties globally, the *Rosa damascena* stands out as the most productive for essential oil extraction. This perennial plant, native to Europe and the Middle East, is the type widely grown in Türkiye (Rusanov *et al*., 2014). Türkiye produces about 60% of the world's annual *Rosa damascena*.

After harvesting roses, rose oil and rose water are produced through steam distillation and rose absolute through n-hexane and ethyl alcohol extraction (KGM, 2020). It takes around 3,000 kg of rose blossoms to produce just 1 kg of rose oil, and for every 1 kg of fresh roses, 2 kg of waste is produced. A single two-hour distillation cycle uses 1,000 kg of rose petals and 4,000 liters of water. After the distillation, a hot waste mixture of flower residue and distillation water is left in the tank which includes valuable non-volatile phenolic compounds (Rusanov *et al*., 2014).

Since rose flowers are harvested in May and June, rose oil production follows the same timeline. Polyphenols are present in hot wastewater (around 40 °C) produced during distillation (Avsar *et al*., 2007). Rose oil and water production industry faces a challenge about managing the comparatively high-temperature wastewater generated during distillation.

Polyphenols are becoming increasingly valuable in various industries, so finding a way to recover them from the waste stream of rose processing wastewater is important. Hence, the aim of this work is to investigate the treatability of rose wastewater and the recovery of polyphenols using membrane systems, specifically focusing on ceramic membranes. The key areas covered in this paper are experimental filtration results, integration potential and operational costs of ceramic membranes.

2. POLYPHENOLS

Phenolic compounds are bioactive phytochemicals that occur naturally in plants. These reactive compounds have one or more hydroxyl groups directly attached to an aromatic benzene ring. Many types, such as flavonoids, anthocyanins, and carotenoids, are found in a variety of foods, including medicinal herbs, vegetables, and legumes. They act as antioxidants, by both scavenging free radicals and by chelating metals (Cendrowski *et al*., 2017, Choi *et al*., 2015).

Polyphenols offer a broad range of biochemical and pharmacological benefits because of their antioxidant, anticancer, anti-inflammatory, and lipid-lowering properties, and their protective effects on the cardiovascular system. Specifically, rose petals are known to contain variety of polyphenols such as flavonoids, gallic and protocatechuic acids, and tannins (Rusanov *et al*., 2014).

The global polyphenols market is expected to grow significantly by 7.4% between 2023-2030. This growth is largely driven by the expansion of the global functional food and beverage industry and advancements in polyphenol extraction technologies. As people become more aware of the benefits of herbal products over synthetic drugs, the demand for polyphenols is set to increase. In addition, polyphenols are generally recognized as safe, expanding their use beyond just disease prevention and treatment, to a broader food and beverage industry (GVR, 2025).

After functional beverages, functional foods are the second largest area where polyphenols are used (Fig. 1). Functional foods play an important role in preventive healthcare by strengthening the immune system and helping to prevent diseases. Dietary supplements have become increasingly popular among consumers looking for natural solutions to various health problems (GVR, 2025). In addition to food industry, polyphenols are also used in polishes, medicines, pesticides, and in the production of cosmetics and synthetics (Mudimu *et al*., 2012).

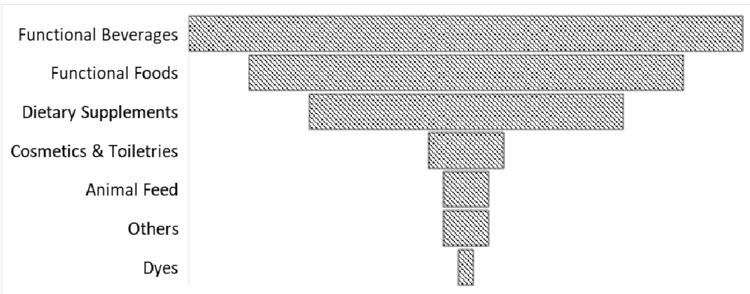

Figure 1. Global Polyphenol Market Share by Application, 2022 (GVR, 2025)

The increasing use of polyphenols in functional food, beverage, and nutritional supplement production, along with their application in cosmetics, dyes, and animal feed, is transforming the market. Their widespread use in different industries, leading to high sales values, makes the recovery of polyphenols from wastewater highly desirable. Therefore, it is very important to recover valuable products such as polyphenols from waste streams such as rose oil production wastewater. Polyphenols have shown promising results in preventing a number of health issues, including cardiovascular diseases, cancer, diabetes, neurodegenerative conditions, aging and skin problems. They also have an important prebiotic effect. Therefore, the use of polyphenols is expected to increase in the functional food market (GVR, 2025).

3. ROSE PROCESSING WASTEWATER TREATMENT

Studies by Tosun *et al*. (2002) revealed that classic coagulation wasn't effective for treating rose processing wastewater, while Fenton's reagent achieved a 76% chemical oxygen demand (COD) removal, and electrocoagulation provided an 81% COD removal (Avsar *et al*., 2007).

In their review paper Slavov *et al*. (2017) summarized studies on the valorisation of rose oil production waste. They grouped these studies into categories like obtaining new aromatic products/increasing essential oil yield, isolating biologically active substances, composting, biosorption of pollutants, using it as feed or feed additives, gasification and biogas production, and other recovery methods. Rusanov *et al*. (2014) recovered polyphenols from rose processing wastewater using activated resins.

Pulido (2016) suggested on their review that feeding raw wastewater into membrane systems without pretreatment leads to serious fouling problems. Effective antifouling solutions are crucial to make membrane systems more technically and economically viable. However, it's important to note that olive mill wastewaters are different from rose processing wastewaters because it does not emerge at high temperatures. This limits the applicability of polymeric membranes, which have proven effective with olive mill wastewater, to rose processing wastewater at high temperatures.

4. MEMBRANE TECHNOLOGY

Membranes are divided into two main groups: inorganic and organic. Among organic membranes, polymeric membranes dominate the market. Inorganic membrane materials typically consist of oxide mixtures and sintered metals. Oxides like alumina, silica, and titania, or mixtures of these compounds, are commonly used in commercial ceramic membranes (Goh and Ismail, 2018).

Inorganic membranes are gaining a lot of attention due to their chemical, thermal, and mechanical stability. This makes ceramic membranes an ideal choice for treating challenging wastes, such as industrial wastewater treatment and oil/water separation processes that involve harsh conditions. Because inorganic membranes can withstand aggressive chemical and thermal cleaning methods and backwashing, it's easier to recover flux after cleaning (Chen *et al*., 2017).

While organic membranes currently hold the largest share of the membrane market, their limited thermal and chemical stability can sometimes lead to lower performance compared to inorganic membranes for certain types of wastewaters. Hence, research on inorganic membranes is growing every day. In 1985, 474 articles were published on inorganic membranes and in 2016, 3682 were published. This clearly shows the rapid development of academic work in this area (Chen *et al*., 2017).

Using inorganic membranes offers an attractive alternative for challenging water treatment processes where polymeric membranes might fail or be ineffective due to fouling or material instability. This includes desalination, wastewater treatment, handling radioactive substances, concentrated organic waste, and wastewaters containing oil and grease (Goh and Ismail, 2018). In recent years, inorganic membranes have been successfully applied in a wide range of industries because of their thermal and chemical stability. Key applications include producing drinking water, desalination, textile wastewater treatment, oily wastewater treatment, electronic industry wastewater treatment, fruit juice concentration, and wastewater treatment.

Inorganic membranes can compete with polymeric membranes, which are often unstable in long-term applications, because of the advantages listed above. As a result, inorganic membranes are considered cost-effective and efficient water treatment alternative compared to polymeric membranes in long-term (Chen *et al.*, 2017). Nowadays, inorganic membranes, with their exceptional chemical and physical properties, are attracting increasing attention due to their adaptability to different conditions and their reusability (Goh and Ismail, 2018). Inorganic membranes can withstand harsh conditions in wastewater treatment and aggressive cleaning methods. They not only reduce the frequency of membrane cleaning, hence replacement, but also increase process efficiency. Metawater (Tokyo, Japan) has installed more than hundred water treatment plants using inorganic membranes shows their competitiveness. In an era where sustainability is increasingly important, inorganic membranes hold great promise for more efficient water and wastewater treatment, offering long-term cost savings and water conservation (Chen *et al.*, 2017).

Considering the high temperature, complex composition, and fouling potential of rose processing wastewater, ceramic membranes offer an ideal solution that allows both efficient wastewater treatment and polyphenol recovery due to their exceptional thermal, chemical, and mechanical stability.

5. ROSE PROCESSING WASTEWATER FILTRATION

5.1. Methodology

Rose processing wastewater was collected directly from a rose oil production facility in Isparta, Türkiye. Before ceramic membrane filtration, rose processing wastewater was subjected to a pre-treatment by using mesh-filter to remove large rose petal fragments. For characterization of the rose processing wastewater, alkalinity, dissolved organic carbon (TOC), COD, biochemical oxygen demand (BOD), and total Kjeldahl nitrogen (TKN) were determined following the Standard Methods for the Examination of Water and Wastewater (APHA, 2005).

The core of the methodology involves a two-stage ceramic membrane filtration process, microfiltration and nanofiltration. The prefiltered rose processing wastewater first filtered via microfiltration membranes. The microfiltration membranes used were 2.5 mm thick, 90 mm in diameter, and consisted of zirconium oxide with a pore size of 150 kDa. The filtration was carried out at room temperature for 4 hours at a constant pressure of 0.5 bar.

After microfiltration the permeate was filtered via nanofiltration membranes. The nanofiltration membranes used had a thickness of 2.5 mm, a diameter of 90 mm, and were composed of zirconium oxide with a pore size of 1 kDa. The nanofiltration was carried out for 4 hours at a constant pressure of 1 bar under room temperature.

A tangential flow membrane test unit was used for all filtration experiments. The system was equipped with a pump, relief valves and a pressure gauge. Flux, the amount of water passes through per unit area of membrane per unit time, flux recovery ratio (FRR), the ratio of the flux recovered after backwashing to the initial flux were determined as described elsewhere (Celik Madenli *et al*., 2025).

5.2. Filtration Results

As shown in Table 1, rose processing wastewater is dense in organic content with high COD, BOD values. These high values indicate a pollution load that requires significant effort for treatment. High TOC content indicates the presence of a wide variety of carbon-based compounds. High TKN concentration indicates a significant nitrogen content that may contribute to environmental problems if not treated. High total solids content, a significant portion of which is volatile solids, indicates a high organic particle content. These characteristics emphasize the need for effective treatment.

Table 1. Rose Processing Wastewater Characterization

Parameter	**Value**
pH	4.77
Alkalinity (mg $CaCO_3$/L)	300
Total solids (mg/L)	6,620
Suspended solids (mg/L)	1,005
Volatile solids (mg/L)	5,760
COD (mg/L)	47,800
TKN (mg/L)	3,080
BOD (5 days, mg/L)	23,920
TOC (mg/L)	21,210

Source: Tosun *et al*., 2002; Celik Madenli *et al*., 2025

Rose processing wastewater is a rich source of several polyphenols. It has high concentrations of quinic acid and gallic acid, which are known for their antioxidant properties. It also includes a number of other phenolic compounds, such as quercetin, ellagic acid, cyanidin-3-o-glucoside (Celik Madenli *et al*., 2025). The presence of these polyphenols demonstrates the potential of rose processing wastewater for polyphenol recovery. This polyphenol content strongly strengthens the economic value for the treatment and valorisation of wastewater. In addition, this supports the development of circular approaches in the rose oil industry.

The comparative performance of ceramic microfiltration and nanofiltration membranes in terms of flux and FRR are shown in Fig. 2. The microfiltration membrane had a higher flux compared to the nanofiltration. The higher flux is expected for membranes with larger pores whereby water undergoing treatment passes but larger compounds are blocked. But the most significant measure of membrane sustainability is the FRR, which explains the extent to which the permeability of the membrane is restored upon fouling and cleaning. In the microfiltration membrane, the FRR was 25%. While it indicates some recovery, it also reveals that much of the initial flux was lost, attributed to irreversible fouling. This result highlights the treatment difficulties of rose processing wastewater due to the complex structure.

The nanofiltration membrane had a lower flux compared to the microfiltration. Lower flux in nanofiltration is expected with its smaller pore size, allowing more selective fractionation of smaller molecules including polyphenols. However, higher selectivity usually leads to a lower permeation rate. Similar to microfiltration, the nanofiltration membrane also had a lower FRR. This decreased recovery, is expected for membranes with smaller pore sizes handling complex feeds. The smaller pores are more susceptible to fouling by still smaller molecules that pass through the microfiltration step, and the foulants can be more difficult to be removed completely. While nanofiltration provides improved separation, more aggressive or optimized cleaning protocols should be explored to achieve maximum long-term flux stability and lower overall operating costs.

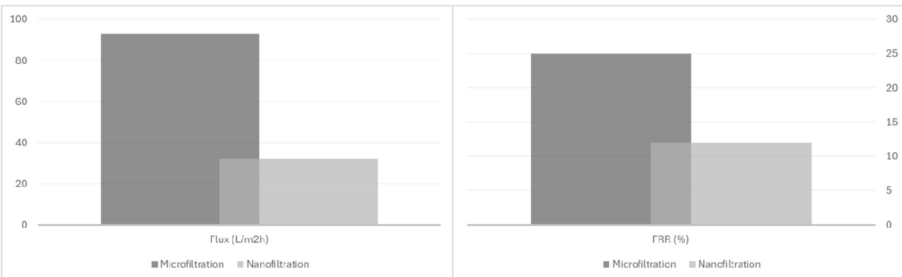

Figure 2. Flux and FRR results of the filtration

Mudimu *et al*. (2012), in their review, explored the use of membrane processes for treating olive mill wastewater and recovering polyphenols. Their findings indicated that microfiltration and ultrafiltration could be used for COD removal, while nanofiltration and reverse osmosis systems were effective for polyphenol recovery from olive mill wastewater. Garcia-Castello *et al*. (2010) used an Al_2O_3 microfiltration membrane with a 200 nm pore size, a Nadir N30F nanofiltration membrane with a 578 Da pore size, osmotic distillation, and vacuum membrane distillation for polyphenol recovery from olive mill wastewater. Their work showed that a microfiltration-nanofiltration and osmotic distillation system recovered 56% of low molecular weight polyphenols.

Gebreyohannes *et al*. (2015) studied treating olive mill wastewater with a forward osmosis system. They showed that a system with only a forward osmosis unit achieved a 71% volume reduction and a 98% removal of colour, biophenols, and ions. When a membrane bioreactor was used as a pretreatment, they saw a 30% increase in flux and a 92.3% pectin removal. They also demonstrated 83% recovery from the ultrafiltration system and 92% recovery from the nanofiltration system for polyphenol recovery from the forward osmosis concentrate, using ultrafiltration (100 kDa) and nanofiltration (10 nm) membranes.

6. INTEGRATING CERAMIC MEMBRANES INTO ROSE PROCESSING PLANTS

Beyond the lab scale tests, the practical benefit of developed ceramic membrane system depends on its ability to adapt to the intense and challenging operational environment of a rose oil production facility. In an industrial rose processing facility, a significant amount of hot, polyphenol-rich wastewater is generated after the distillation. The ceramic membrane system is proposed to be integrated into the existing production flow. The wastewater resulting from distillation can be directed to the membrane unit. The microfiltration step used in this study may be useful for removing larger suspended solids and particles. This critical step prevents fouling of downstream membranes. This will ensure optimum performance and longevity during continuous operation.

The scope of this work goes beyond wastewater treatment and aims to create new income streams and promote operational sustainability. The polyphenols recovered using membranes are high-value bioactive compounds that are in great demand in the functional food, cosmetics and pharmaceutical sectors. Projected uses include reintegrating recovered polyphenols back into existing rose-based products to increase their worth or marketing them as an independent commercial product. Moreover, depending upon permeate quality obtained, treated water can be recycled within the plant for non-critical purposes as well. Usage of treated water in industry will reduce the need for fresh water, reduce waste discharge, and close the loop.

Membrane technology is a new solution to wastewater treatment from agriculture and food industries. These technologies are flexible, presenting new ways of extracting valuable compounds, protecting the environment, and recycling water. Membranes do not generally require complex phase transitions, so they are quite energy efficient. They are also relatively simple to control and need less physical space for a given separation task. When membrane processes are integrated into industrial operations, they can unlock solutions that are both economically sound and environmentally sustainable on a larger scale. They promise a high recovery of precious, added-value chemicals from waste streams, while keeping energy consumption low. By efficient and successful recycling of valuable biomolecules and water, membranes ultimately lead to better environmental protection and a positive impact on society as a whole (Papaioannou *et al*., 2022; Teodora *et al*., 2022).

Even though this paper is about rose processing wastewater, results can be applied to other agro-industrial sectors as well. Innocenzi *et al*. (2021) applied membrane processes in the olive oil wastewater and have proved to be efficient for both water recovery and valorisation of polyphenols. This provides a strong and relevant comparison for the rose industry, demonstrating that successful industrial application of ceramic membranes is not a theoretical promise, but has a proven track record of success in similar industrial applications.

7. ECONOMIC AND ENERGY CONSIDERATIONS

In comparison to traditional and advanced treatment systems, one of the advantages of membrane technology is that it is less energy intensive (Keyvan Hosseini *et al*., 2022). Long-term sustainability of any industrial solution depends on initial capital cost and operating and maintenance cost. The maintenance and operating cost for membrane technology would be energy consumption, replacement of the membranes, cleaning chemicals cost, and personnel cost. While fouling would be a concern for any membrane system, leading to increased transmembrane pressure and increased frequency of cleaning, there are certain benefits ceramic membranes possess in this area. Their increased longevity and resistance to strong cleaning agents mean that they don't need to be replaced quite so often and can survive more severe cleaning practices, potentially saving overall maintenance costs compared to their polymeric counterparts (Chen *et al*., 2024).

Innocenzi *et al*. (2021) applied membrane processes to treat olive oil wastewater and carried out life cycle assessment to examine the economic feasibility of the membrane-based treatment scheme. They showed an overall cost of treatment equal to 253 €/m³. Cost analysis also showed that the utility and personnel cost was a substantial factor in the total annualized cost. The economic analysis shows that the suggested membrane scheme is feasible economic solution for the olive processing industry.

The true measure of the value of this technology is its capacity to give a strong return on investment for rose oil and water producers. The value of extracting high-purity polyphenols from a stream that was otherwise considered waste is significant. Ceramic membrane filtration not only reduce disposal costs, but it generates entirely new income streams from an otherwise saleable product. Secondly, aside from the benefits to the environment, such as reduced wastewater outflow and possible water reuse, the public image is also boosted, possibly making producers eligible for environmental incentives or certification. This complete resource management strategy, turning waste into assets, of ceramic membrane technology makes it a very economically sound and favourable technique for achieving a more sustainable, profitable rose industry.

8. CONCLUSION

This study demonstrates the potential of ceramic membrane filtration as an economical solution for the treatment of rose processing wastewater and recovery of polyphenols.

Rose oil production wastewater characterization showed that it is a highly rich organic effluent, with varying polyphenols. This further verified the necessity of efficient treatment. The two-stage ceramic membrane filtration process, microfiltration and nanofiltration, was used. Our findings suggest that ceramic membranes have the potential to be used for polyphenol recovery and wastewater filtration in the rose oil production industry. These membranes have potential for recovery of water used in distillation during rose oil production, thus reducing freshwater demand and wastewater discharge. Therefore, ceramic membrane filtration supports the circular and sustainable practices in the rose oil production industry. The wider implications of scaling up ceramic membranes is also examined by taking into consideration the potential for integration into existing production systems, energy requirements, and operational costs. As a result, this study supports sustainability goals and circular economy by highlighting the potential of ceramic membranes usage for water recovery in rose oil production.

Further research shall be focused on the optimization of operating conditions of the membrane for maximizing stability of flux as well as the recovery efficiency of polyphenols. Pilot-scale operations over a long-term duration are also necessary to support these findings under continued industrial operating conditions and to generate more precise data for the overall life cycle assessment.

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