processes

*Review*

# Wastewater Treatment in the Diary Industry from Classical Treatment to Promising Technologies: An Overview

**Aws N. Al-Tayawi [1,2], Elias Jigar Sisay [3], Sándor Beszédes [3] and Szabolcs Kertész [3,*]**

[1] Doctoral School of Environmental Sciences, University of Szeged, Tisza Lajos krt. 103, H-6725 Szeged, Hungary; awsaltayawi@uomosul.edu.iq
[2] Faculty of Environmental Science and Technology, University of Mosul, Al-Majmoa'a Street, Mosul 41002, Iraq
[3] Department of Biosystems Engineering, Faculty of Engineering, University of Szeged, Moszkvai krt. 9, H-6725 Szeged, Hungary; eliasjig@gmail.com (E.J.S.); beszedes@mk.u-szeged.hu (S.B.)
* Correspondence: kertesz@mk.u-szeged.hu

**Abstract:** Water pollution caused by population growth and human activities is a critical problem exacerbated by limited freshwater resources and increasing water demands. Various sectors contribute to water pollution, with the dairy industry being a significant contributor due to the high concentrations of harmful contaminants in dairy wastewater. Traditional treatment methods have been employed, but they have limitations in terms of effectiveness, cost, and environmental impact. In recent years, membrane separation technology (*MST*) has emerged as a promising alternative for treating dairy wastewater. Membrane processes offer efficient separation, concentration, and purification of dairy wastewater, with benefits such as reduced process steps, minimal impact on product quality, operational flexibility, and lower energy consumption. However, membrane fouling and concentration polarization present major challenges associated with this technique. Therefore, strategies have been implemented to mitigate these phenomena, including pre-treatment prior to *MST*, coagulation, and adsorption. Recently, 3D printing technology has gained prominence as one of the latest and most notable advancements for addressing these issues. This comprehensive review examines the drawbacks and benefits of conventional methods employed in dairy wastewater treatment and explores the utilization of membrane technology as an alternative to these approaches. Additionally, the latest technologies implemented to mitigate or alleviate the limitations of membrane technology are discussed.

**Keywords:** dairy wastewater; conventional treatment; membrane filtration methods; membrane fouling mitigation; coagulation; 3D-printed promoter/spacer



**Citation:** Al-Tayawi, A.N.; Sisay, E.J.; Beszédes, S.; Kertész, S. Wastewater Treatment in the Diary Industry from Classical Treatment to Promising Technologies: An Overview. *Processes* **2023**, *11*, 2133. https://doi.org/10.3390/pr11072133

Academic Editors: Amilton Botelho Junior and Denise Crocce Romano Espinosa

Received: 29 June 2023
Revised: 13 July 2023
Accepted: 14 July 2023
Published: 17 July 2023



## 1. Introduction

Water is essential to all human activities [1]. Tons and tons of wastewater are produced daily as the human population grows in the domestic, industrial, and agricultural sectors [2,3]. Therefore, water pollution has become a significant concern for the industrial world and a big cause of worry for societies and governments [4–6]. Even though the Earth's surface is more than 70% covered by water, only 3% of this percentage is fit for human consumption, with the other 97% being salt water [7]. Despite these facts, the world's freshwater supply has been under stress recently due to rising water demands and pollution [8]. The water shortage is anticipated to worsen in the upcoming years [9].

Direct discharge of wastewater into water bodies without any prior treatment is the primary cause of water pollution [10,11]. Several factors contribute to water pollution, including energy consumption, radioactive waste [12], the dye industry [13], urban growth [14], sewage and wastewater management [15], industrial waste, mining operations, pesticides, and chemical fertilizers [16,17]. Therefore, water pollution is inevitable simply because it is utilized for many different purposes [18]. In contrast, industrial, household, and agricultural operations create wastewater containing harmful contaminants [19]. Therefore, water resources in this situation must be continuously protected [20,21].

Particularly in developed countries, regulating liquid industrial effluent is getting stricter [20]. Moreover, it is required that all wastewater be treated before being discharged into the environment [22]. The Water Framework Directive of 2000, which specifies standards for protecting surface water, subsurface water, and coastal water in Europe, is the source of the current European water policy [23].

Usually, various contaminations rob us of our natural resources and compel us to prepare to face a more challenging environment [24]. Numerous physical, chemical, and biological procedures, including flotation, oxidation, precipitation, carbon adsorption, solvent extraction, ion exchange, membrane filtration, biodegradation, phytoremediation, and electrochemistry, have been documented over the past three decades [25].

This review aims to shed light on developing the technologies used in dairy factories and the most prominent integrated technologies to achieve the highest efficiency in the extraction processes of dairy derivatives and dairy wastewater treatment.

## 2. Food Wastewater

Annually, a sizable volume of untreated industrial effluent is released into the environment, leading to significant environmental and health problems [26,27]. The food industry, especially dairy, is one of the greatest water users and producers of wastewater overall [9]. Food wastewater has many nutrients, which can greatly impact the biological load [28]. Where chemical oxygen demand (*COD*), biological oxygen demand (*BOD*), high nutrients (nitrogen and phosphorus), and other compounds like solvents and ions are typically present in high concentrations in the wastewater produced by food processing units, which is typically from non-process activities [29]. Additionally, these wastewaters include substantial amounts of products or raw materials in organic loads, nutrients, and suspended particles, which may be distinguished and recovered throughout the treatment process [30].

Despite what has been mentioned, food waste is often regarded as the least polluted water when discussing industrial operations due to the minimal number of harmful compounds typically associated with the industry of metals or intermediate chemicals (petroleum, plastics). However, these fluids have "issues" due to their high concentrations of certain pollutants [31].

## 3. Dairy Wastewater Treatment

The environment is impacted by every step of the dairy industry [32], including the production of milk products, product packaging and storage, effective marketing, and distribution [33]. If the wastewater produced at these levels in the dairy industry is not properly disposed of, it can cause several pollution issues [34]. Large amounts of effluents comprising lactose, protein, ionic content, and fat are produced by the dairy sector (in smaller amounts) [35]. Before entering the sewage system, a sizable volume of dairy wastewater must be treated [36].

Furthermore, dairy industries have a significant impact on water pollution and water quality [37]. Thus, suitable wastewater treatment methods are required to use effective disposal methods because a large amount of water is used during dairy processing and the production of milk-related products [38,39]. This large amount of water is no longer helpful because it contains a high level of contaminants, rendering it non-recyclable [40]. The benefits and shortcomings of the traditional treatment of dairy wastewater will be examined in terms of the principles upon which these procedures are built, which prompted the requirement for the creation of new technologies and their incorporation into the treatment of dairy wastewater.

## 4. Conventional Treatment

Generally, traditional dairy wastewater treatment includes a variety of physical, chemical, and/or biological methods and processes to reduce solids from effluents such as colloids, organic matter, nutrients, and soluble pollutants (metals, organics, etc.) (Figure 1). Many approaches can be applied, including traditional methods, proven recovery processes, and developing removal technologies [41,42]. The advantages and disadvantages of conventional methods are summarized in Table 1.

**Table 1.** Advantages and disadvantages of conventional treatment.

| Process | Main Characteristic(s) | Advantages | Disadvantages | Reference |
|---|---|---|---|---|
| precipitation | Pollutant uptake and separation of the resulting products. | Simplicity, economics, and efficiency in working with high pollutant loads.<br>Very effective in removing metals, phosphorus compounds, and fluorides.<br>Significant decrease in *COD*. | Consumption of chemicals (oxidants, lime, $H_2S$, etc.).<br>pH amendment is prerequisite.<br>At low concentrations, metal ion elimination is ineffective.<br>If the metals are complex, an oxidation step is required.<br>Problems with sludge generation, handling, and disposal (treatment, management, cost). | [18,39,40] |
| Coagulation/ flocculation | Pollutant uptake and separation of the resulting products | Low capital expenditure.<br>Simplicity integrated.<br>Physicochemical methods.<br>A wide variety of chemicals are commercially accessible.<br>Effective for colloidal and S.S particles.<br>Perfect sludge settling and dewatering properties.<br>Significant decrease in *COD* and *BOD*.<br>Bacterial inactivation potential<br>Insoluble pollutants (pigments, for example) can be removed quickly and efficiently. | Non-recyclable chemical addition (coagulants, flocculants, aid chemicals) is required.<br>Effluent physicochemical monitoring.<br>Sludge volume production has increased (cost management, treatment). | [43–46] |
| Adsorption/ filtration | Nondestructive method<br>Utilization of a solid material | Essential in terms of technology (simple equipment) and adaptable to various treatment modalities.<br>A wide selection of commercial items is available.<br>A wide range of pollutants are being targeted (adsorption).<br>Adsorption is a very efficient technique with rapid kinetics.<br>The treated effluent is of exceptional quality.<br>Excellent separation capabilities for a broad spectrum of contaminants, particularly refractory molecules.<br>Highly effective treatment when combined with coagulation to eliminate suspended solids, chemical oxygen demand, and color.<br>Finite use of chemicals. | Investment is relatively high.<br>Materials costs, non-selective processes.<br>The kind of material influences performance.<br>Regeneration is costly and results in material waste.<br>Chemical modification to enhance the adsorption capacity.<br>Adsorbents of various sorts are required.<br>Removal of the adsorbent (requires incineration, regeneration, or replacement of the material).<br>Rapid reactor saturation and blockage (regeneration costly).<br>Inefficient for certain types of dyestuffs and metals. | [20,47,48] |
| Biodegradation | Utilization of a Microorganisms | Capacity to break down hazardous organic contaminants.<br>Less energy is required.<br>May biodegrade organic contaminants via microorganism metabolic activity<br>Because of their specific adaptability to the abiotic circumstances in which they originate, the use of microorganisms isolated from extreme habitats becomes advantageous.<br>As a result of their resilience to pH, temperature, and salinity, they can aid in biodegradation.<br>Depending on the nature of the pollutants, it is possible to work in aerobic or anaerobic conditions. | Because of inhibition, this process is sluggish and occurs only at low concentrations.<br>A large area for development is Required.<br>High energy for aerators is Required.<br>An additional remedy is required. | [42,45,49,50] |

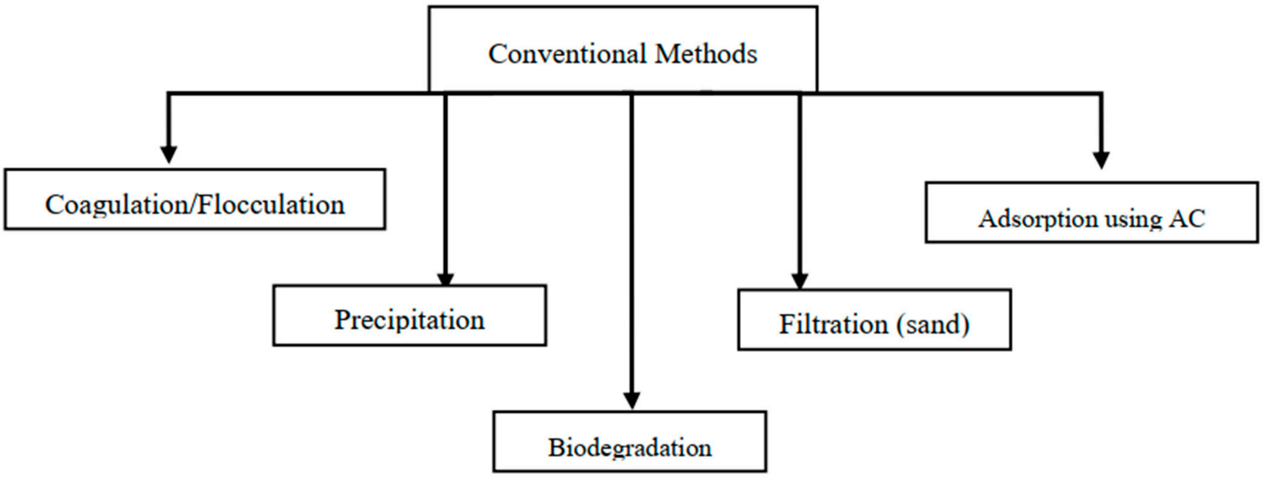


**Figure 1.** Classical wastewater removal technologies.

The drive to reduce waste and energy consumption in various industrial processes is driving the replacement of legacy technology with membrane-based processes [51,52]. Membrane technology is an essential processing tool in the food industry for treating food products, by-products, and food waste [53,54].

## 5. Dairy Wastewater Treatment by Membrane Separation Technology (MST)

In the early 1960s, the first defect-free, high-flux anisotropic reverse osmosis (*RO*) membrane was created at the University of California, Los Angeles (*UCLA*) due to growing worries about the drinking water supply. Two *UCLA* graduate students, Sidney Loeb and Srinivas Sourirajan, found an efficient method for producing *RO* membranes [55,56]. Their lab-scale desalination equipment, the so-called "big dripper", produced tiny volumes of fresh water, but it spawned a global business worth billions of dollars. The discovery of asymmetric membranes by Loeb and Sourirajan is typically considered the beginning of contemporary membrane research. In addition, it is considered the basis of industrial membrane processing [57].

In the food and beverage industry, applying membrane processes as an alternative to classical separation, purification, and concentrated product methods for "sustainable production" and a "zero waste approach" is a popular and rising topic. Depending on the variety of applications, the reasons for the widespread use of suitable membrane processes in the food and beverage industry are as follows: (i) reducing the number of process steps in comparison to traditional methods; (ii) relying on minimized changes in the loss of aroma and nutritional components of food and beverages due to the use of high temperatures in traditional methods and improving end product quality; and (iii) high process selectivity [58]. Also, membrane processes have built-in advantages when making a process more efficient, mainly because they reduce the amount of equipment needed, offer much operational flexibility, and use less energy [59].

### *5.1. Membrane Filtration Methods*

The membrane separation process depends on the nature of the membrane, which divides the liquid into two parts, the permeate part and the retentate part, making it a good instrument for separation, concentration, and purification. The membranes' morphology can be classified according to their porosity, density, symmetries, and asymmetries [60]. Dead end and cross-flow are the typical types of membrane operations. In the dead-end mode, the filtering fluid is typically driven through the membrane pores by applying pressure to the feed side. In cross-flow mode, the feed flows parallel to the membrane surface and permeates the membrane due to a pressure differential. Cross-flow inhibits the production of filter cake, hence maintaining its low level [61].

Membrane processes consist of microfiltration (*MF*), ultrafiltration (*UF*), nanofiltration (*NF*), and reverse osmosis (*RO*) [62] (Figure 2). Typically, membranes are categorized according to the average size of their pores. Dense membranes are those in which the transport of components entails a stage of dissolution and diffusion over the membrane material [60]. The transmembrane pressure is the driving force behind these membrane processes (*TMP*). Furthermore, the molecular weight cut-off is crucial in membrane separation processes (*MWCO*, usually expressed in *Da*) [63]. These two parameters (*TMP* and *MWCO*) can be used to characterize pressure-driven membrane processes [64]. In this regard, *MF* necessitates > 100,000 Da and 0.1–2 bar; *UF* necessitates 1000–100,000 Da and 2–10 bar; *NF* necessitates 100–1000 Da and 5–40 bar, and *RO* necessitates 1–100 Da and 30–100 bar [52]. *MF* can be used as a pretreatment in the dairy industry to remove bacteria and fat and fractionate milk products. *UF* can be used to standardize milk; however, the breakthrough application of *UF* was to convert milk whey into refined proteins for commercial use [65]; *NF* can be used for whey demineralization [66,67], while *RO* can be used for concentration steps [52].

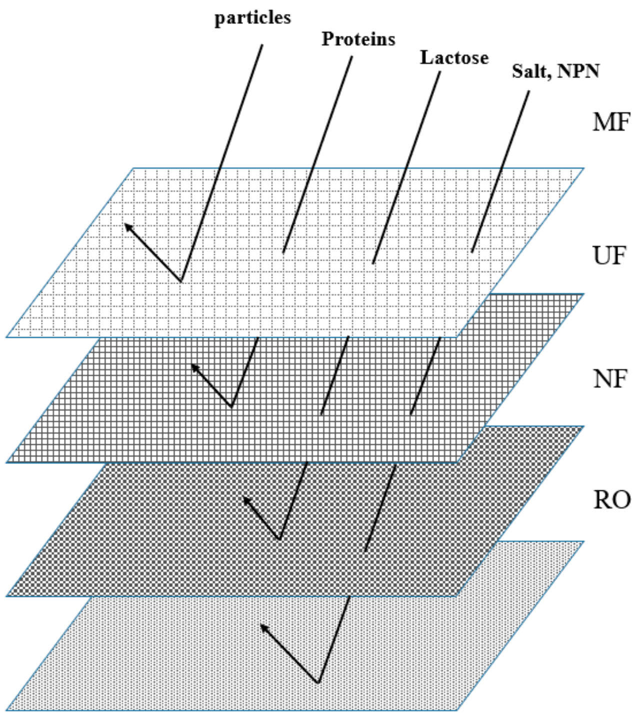


**Figure 2.** Diagram depicting filtering membranes: microfiltration (*MF*), ultrafiltration (*UF*), nanofiltration (*NF*), reverse osmosis (*RO*).

### 5.1.1. Microfiltration

Microfiltration (*MF*), like all other membrane separation procedures, is a technology that permits the differential concentration in the liquid retained by the membrane, known as *MF* retentate, of the components having a pore width larger than the average pore size of the membrane [52]. Membranes with a diameter ranging from 0.1 to 10 µm are used in microfiltration (*MF*). Thus, particles larger than 0.1 µm are included in the retentate, and the pore size can vary depending on the application [67]. The typical TMP ranges between 0.03 and 0.20 MPa [68]. As one of the dairy applications of this process is the retention of bacteria and spores, it is necessary to control the size of the membrane pores, which should be small enough to retain microorganisms without compromising the composition of the permeated milk [60,66,69]. Introduced were commercial ceramic membranes and the idea of uniform transmembrane pressure (*UTP*) for regulating hydrodynamics and fouling during membrane filtration (*MF*) of dairy fluids. This breakthrough led to the resolution of technical issues, including late emmental cheese expansion, spore removal from whey, effective defatting of milk and whey, and casein micelle separation from milk [55].

#### 5.1.2. Ultrafiltration

Ultrafiltration (*UF*) can prevent the passage of molecules larger than 0.001 µm due to membranes with pores ranging from 0.01 to 0.001 µm [67]. Typically, ultrafiltration (*UF*) employs membranes with a cutoff of 1–800 kDa and a *TMP* range of 0.1–1 MPa [68]. *UF* can retain proteins and fat while allowing vitamins, minerals, and lactose to pass through. The use of *UF* in dairy product development improves yield, nutritional functionality, and sensory characteristics [70]. This process is helpful for protein concentration and purification, and it distinguishes itself in cheese production by providing higher protein concentration and better nutritional characteristics to the product. Another common use for *UF* is manufacturing milk protein concentrate (*MPC*) [71,72]. Ultrafiltration (*UF*) was suggested as a potential technology for concentrating milk solids, mainly proteins [55].

#### 5.1.3. Nanofiltration

Membranes with pores ranging from 0.001 to 0.0001 µm are used in nanofiltration (*NF*) processes [67]. *NF* can concentrate small molecules with molecular weights equal to or greater than 100 kDa. Where sugars, amino acids, dyes, and salts can be retained by *NF* membranes [73]. It can also concentrate whey proteins in milk to produce derivatives. Because of the interaction between the membrane, the solution to be filtered, and electrostatic repulsion, the *NF* process is capable of high retention of organic compounds [74]. Nanofiltration (*NF*) employs membranes with a typical cut-off of 150–700 kDa for the concentration and partial demineralization of whey or milk streams, thus removing dissolved mineral salts in inverse proportion to their valence. In ratio to their concentration in the retentate, the demineralization capability is counterbalanced by the partial penetration of low molecular weight components such as lactose. Typical operating pressures for this process are 1–3 MPa [68].

#### 5.1.4. Reverse Osmosis

Reverse osmosis (*RO*) is a process in which membranes with pores smaller than 0.0001 µm are used [65]. Only water can pass through at pressures between 3.5 and 10 MPa [75]. These membranes can retain larger ions and compounds while releasing water into the permeate and can be used for milk preconcentration; this process has increased osmotic pressure and feed stream viscosity, resulting in severe fouling and permeate flow reduction problems. Several studies to promote optimization have focused on the disadvantages of this process [68].

### *5.2. Challenges and Future Perspectives*

#### 5.2.1. Fouling Phenomena

Fouling phenomena refer to the limitations encountered in membrane filtration processes, primarily attributed to membrane fouling and concentration polarization [76,77]. These phenomena lead to a decline in flux, resulting in decreased productivity over time [78]. Concentration polarization occurs due to the preferential passage of certain species across the membrane, accompanied by the accumulation of other species at the membrane surface, which results in a reduction in permeate flux [79]. While concentration polarization is typically reversible by adjusting operational parameters like increasing cross-flow velocity [80], it may also involve the formation of a gel layer at high species concentrations, which cannot be rectified solely through operating condition modifications [81,82]. The development of a gel layer necessitates washing to restore the membrane's characteristics [61].

Fouling remains a significant obstacle in membrane processes [83]. It generally arises through two main routes: foulant adhesion/deposition and the foulant layer filtering process [59]. Fouling occurs due to the interaction between foulants present in the separation solutions, which can include particulate matter, colloidal particles, biomacromolecules, and the membrane surface [84,85]. The foulants physically and chemically interact with the membrane surface, leading to chemical degradation of the membrane material [86,87]. Microorganisms and biomacromolecules non-specifically adhere to the membrane surface, blocking or significantly reducing the membrane pores, thereby causing a notable decline in permeation flux and separation efficiency [88]. The fouling phenomenon can be characterized by different mechanisms, including the complete blocking model, intermediate blocking model, standard blocking model, and cake layer model (Figure 3) [89].

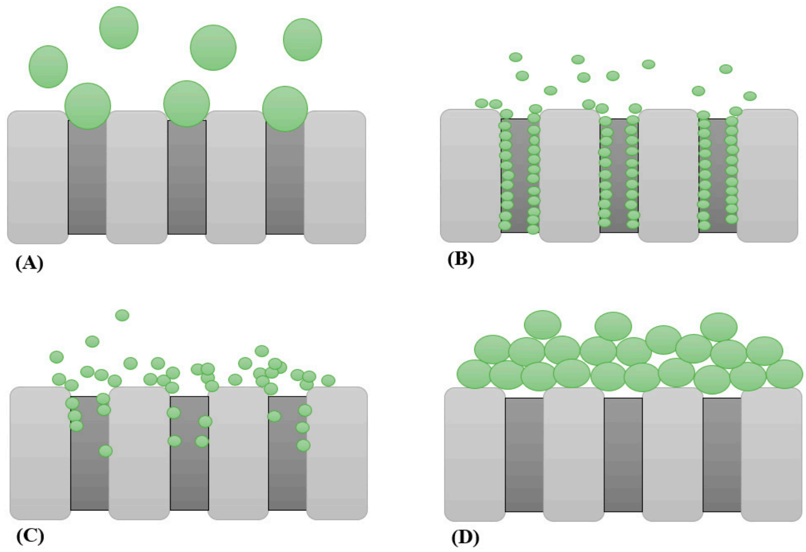


**Figure 3.** Hermia of fouling mechanisms: (**A**) complete blocking model; (**B**) standard blocking model; (**C**) intermediate blocking model; (**D**) cake layer formation model.

Membrane fouling has been examined extensively. Recent trends include in situ real-time monitoring approaches for membrane fouling, sophisticated characterization techniques such as *HPLC* coupled mass spectrometry and advanced simulation methodologies such as molecular simulation [61].

Numerous approaches have been employed in addressing membrane contamination, encompassing chemical and physical treatment modalities. Presently, environmental scientists are actively exploring contemporary and sustainable methodologies that involve the utilization of environmentally benign or recycled materials for the remediation of membrane pollution. The following elucidation highlights several methodologies employed in the treatment of membrane pollution.

#### 5.2.2. Pretreatment before MST

Various pretreatment methods are utilized in membrane filtration. In order to enhance membrane performance, it is crucial to initially identify the primary causes of membrane fouling [53]. The effectiveness of pretreatment in reducing membrane fouling relies heavily on several important factors, which include the type of pretreatment agent employed (such as coagulant, adsorbent, oxidant, or bio-filter), the dosage and mode of dosing (continuous or intermittent), the mixing technique, the temperature, the properties of natural organic matter (NOM) (such as charge density, hydrophobicity, molecular size, and molecular weight), the solution environment (pH and ion strength), and the characteristics of the membrane itself (such as hydrophobicity, membrane charge, and surface morphology) [90].

#### 5.2.3. Coagulation

Coagulation is used as a pretreatment process to increase the rate of particle aggregation. It is the most common and effective pretreatment process due to its low cost and relatively simple operation [91]. It is still a promising method for reducing membrane fouling while improving turbidity, dissolved organic carbon (*DOC*), and microorganism removal [92,93]. It is critical to optimize the coagulation process [94]. To begin, the type of coagulant used can significantly impact the performance of membranes, and under-dosed coagulation could harm membrane performance. An adequate coagulant dose significantly reduced fouling and improved membrane performance, resulting in high removal rates of microorganisms and other waterborne impurities under optimal coagulation conditions. Optimizing operating conditions, such as raw water pH, improves coagulant performance, resulting in less fouling and improved membrane performance. Other coagulants, such as alum or ferric chloride ($FeCl_3$), may necessitate pH adjustments for optimal performance. Coagulant performance may also be affected by the mode of coagulation. Coagulants can be used in-line or in standard mode. In-line coagulation occurs without sedimentation or pre-filtration, whereas standard coagulation does [95].

5.2.4. Activated Carbon Adsorption

The process of foulant adhesion to an adsorbent surface, known as "adsorption", is commonly used as a pretreatment method. Adsorbents possess a high porosity and a large specific surface area, allowing them to absorb or accumulate impurities effectively [89]. Among the various adsorbents, powdered activated carbon (PAC) is widely utilized in membrane filtration applications [96]. Adsorption can be combined with membrane filtration in two configurations, similar to pre-coagulation: a unified membrane reactor or a separate reactor following a PAC reactor. Two dosing methods are employed: step input, which introduces PAC into the reactor at a constant rate, and pulse input, which adds all the PAC at the beginning of the filtration cycle. Optimal PAC dosage should be determined through preliminary tests before implementation. Additionally, PAC size must be optimized, considering the potential impact on membrane integrity due to abrasion and the specific material, PAC type, and configuration used. To address the challenges associated with carbon fiber felt (CFF) [96], a separation step has been proposed to prevent direct contact between the PAC and membrane surface. While PAC adsorption is cost-effective [97], its suitability as a pretreatment method in developing countries needs to be evaluated to determine if PAC particles can enter membrane pores and cause fouling. The possibility of some impurities not being absorbed by PAC but readily entering membrane pores may restrict the widespread adoption of PAC [53].

Several authors have explored the theoretical advantages of specific pretreatment methods and integrated multiple approaches to compensate for limitations. Integrated systems often come with high capital costs, which can be challenging for developing countries. However, if such systems effectively control fouling and improve membrane performance, operational costs may be reduced. In situations where poor-quality source water needs to be transformed into high-quality effluent, even if the total costs are high, integrated systems may be the only viable option. However, it is important to note that no single known technique can effectively control fouling [89]. Furthermore, some integrated systems might even exacerbate membrane fouling. One possible explanation for the conflicting performance of integrated pretreatment systems is the formation of precipitates resulting from the combination of certain pretreatment procedures, which can be detrimental to membrane fouling. Therefore, it is crucial to thoroughly evaluate any adverse consequences when implementing integrated systems. Although the capital costs of filtration systems may increase with integrated pretreatment, current research efforts should focus on optimizing specific pretreatment methods to enhance membrane permeability [53].

5.2.5. Mitigate Membrane Fouling Using 3D-Printed Promoters

As mentioned above, fouling removal from membranes continues to be a formidable barrier to their widespread adoption, as cleaning is expensive and generates significant waste [98]. As a result, there is much interest in new membrane materials and/or structures that can reduce fouling and the use of cleaning agents. The main goal in all cases is to reduce interactions between the foulants and the membrane surface [99], either by changing the wetting behavior of the membrane [100] or by promoting fluid turbulence at the membrane surface via surface structuring [101]. As a result, the latter approach is preferred because it applies to commercial membrane materials. Turbulence is created primarily by generating vortices near the membrane surface due to regular or irregularly patterned structures such as pillars, lines, or indents [52]. These patterns are created through various techniques; one of the latest technologies is 3D printing, which is a new membrane fabrication technology that allows the creation of more complex and irregular membrane shapes and structures that are impossible with current methods [52,102].

Ref. [103] state that fouling is frequently controlled by turbulent flow, which requires more energy. In the flow channel of tubular membranes, turbulence promoters or static mixers can be inserted. They deflect the fluid, induce vortices, improve particle back-transport, and increase the shear rate at the membrane surface, all of which help to prevent fouling. However, more is needed to know how the geometry of such turbulence promoters affects fouling reduction.

Ref. [104] explain that changing the hydrodynamic conditions in the membrane module can result in improved mixing efficiency and flow conditions, incorporating three-dimensional (3D)-printed spacers into the module can improve mixing efficiency and flow conditions. Three-dimensional-printed spacers in the module can improve mass transfer through the *UF* membrane by reducing concentration polarization and fouling. Three-dimensional printing has the potential to enable a promising new class of efficient laboratory filtration devices. On the other hand, higher mechanical stirring into the module can reduce membrane fouling by increasing the shear rate on the membrane's surface.

Researchers have taken an interest in adapting variants of 3D printing techniques to membrane manufacturing as their resolution has improved to the micrometer or even nanometer level. Ref. [105] indicate in their research that according to Scopus database statistics (Figure 4), there has been an increase in membrane papers related to 3D printing over the last decade, mirroring the increase in papers on 3D printing overall (Figure 5). Customizing spacers for membrane processes such as *UF*, *RO*, forward osmosis (*FO*), and membrane distillation (*MD*) was the focus of the early work on membrane-related printing technology.

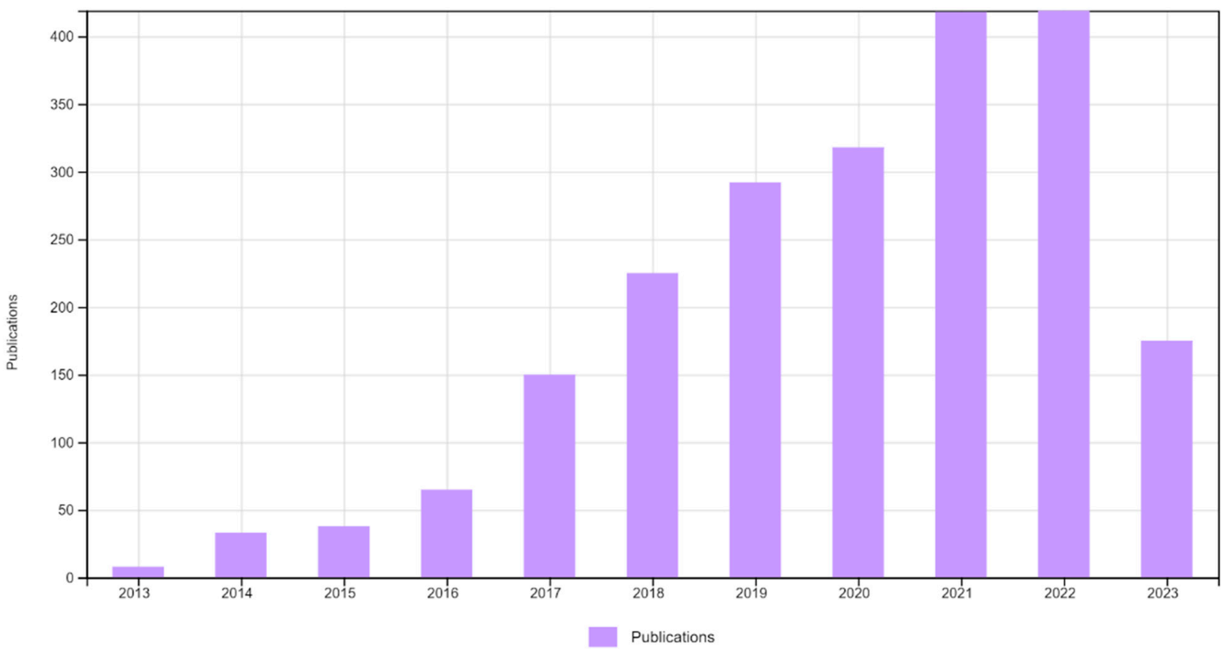


**Figure 4.** Publications on 3D-printed spacer and 3D printing membrane according to Web of Science database from 2013 till 30 June 2023.

Turbulence promoters are a promising alternative for improving hydrodynamic conditions in membrane separation processes [106]. These devices reduce particle deposition by increasing the shear rate on the membrane surface [107]. Turbulence promoter geometry is also essential in their effectiveness in membrane filtration processes. Devices based on 3D printing make significant progress in the design of turbulence promoters because 3D printing technology allows the creation of several complex geometric shapes from various materials [59].

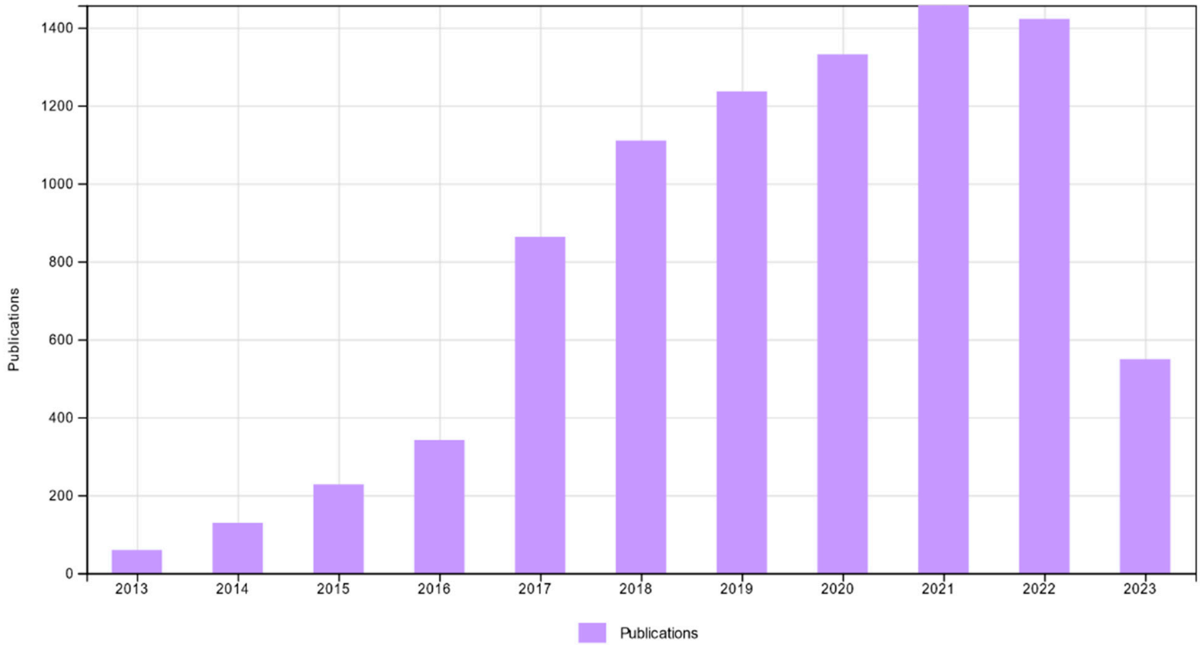


**Figure 5.** Publications on 3D printing technology according to Web of Science database from 2013 till 30 June 2023.

Ongoing research endeavors aim to identify viable strategies for mitigating membrane contamination, a critical concern in the realm of alternative approaches to conventional treatment methods. The forthcoming scientific investigations will emphasize the utilization of physical techniques in conjunction with 3D printing methodologies, specifically targeting the treatment of dairy waste within wastewater management.

## 6. Conclusions

Water pollution is a significant concern due to the increasing population and various human activities, leading to the generation of tons of wastewater every day. The limited availability of freshwater resources and the rising water demands exacerbate the water shortage issue. Water pollution arises from multiple sources, such as industrial, domestic, and agricultural sectors, which release harmful contaminants into water bodies. To mitigate water pollution, strict regulations have been imposed, especially in developed countries, to ensure the proper treatment of industrial effluents before discharge. Among the various industries, the food sector, particularly the dairy industry, is a significant contributor to water pollution. Dairy wastewater contains high concentrations of organic matter, nutrients, and suspended particles, posing environmental and health risks if not properly treated. Traditional treatment methods, including precipitation, coagulation/flocculation, adsorption/filtration, and biodegradation, have been used to treat dairy wastewater. These methods have their advantages and disadvantages in terms of effectiveness, cost, and environmental impact.

In recent years, membrane separation technology has gained popularity as an alternative to dairy wastewater treatment. Membrane processes, such as microfiltration, ultrafiltration, nanofiltration, and reverse osmosis, offer efficient separation, concentration, and purification of dairy wastewater. These processes provide advantages such as reduced process steps, minimal changes in the quality of the end product, operational flexibility, and lower energy consumption. The integration of advanced technologies, including membrane-based processes, in the treatment of dairy wastewater can help achieve higher efficiency and improve the sustainability of the dairy industry. The adoption of these technologies is crucial for minimizing water pollution, conserving water resources, and ensuring the production of safe and environmentally friendly dairy products. Continued research and development in this field are essential to further enhance the effectiveness and applicability of dairy wastewater treatment technologies.

**Author Contributions:** Conceptualization, methodology, validation, formal analysis, investigation, data curation, A.N.A.-T. and S.K.; writing—original draft, review, S.B.; editing and visualization, E.J.S.; project administration, S.K. All authors have read and agreed to the published version of the manuscript.

**Funding:** This study was financed by National Research, Development and Innovation Office, NKFI-FK-142414 project. Sz. Kertész is grateful for the financial support of the János Bolyai Research Scholarship of the Hungarian Academy of Sciences (BO/00576/20/4) and the ÚNKP-22-5-SZTE-210 New National Excellence Program of the Ministry for Culture and Innovation from the Source of the National Research, Development and Innovation Fund.

**Institutional Review Board Statement:** Not applicable.

**Data Availability Statement:** Data are contained within the article.

**Conflicts of Interest:** The authors declare no conflict of interest.

## References

1. Elliott, H. Alabama's Water Crisis. *Ala. L. Rev.* **2011**, *63*, 383.
2. Obotey Ezugbe, E.; Rathilal, S. Membrane Technologies in Wastewater Treatment: A Review. *Membranes* **2020**, *10*, 89. [PubMed]
3. Ighalo, J.O.; Adeniyi, A.G.; Adeniran, J.A.; Ogunniyi, S. A Systematic Literature Analysis of the Nature and Regional Distribution of Water Pollution Sources in Nigeria. *J. Clean. Prod.* **2021**, *283*, 124566.
4. Rathoure, A.K. *Toxicity and Waste Management Using Bioremediation*; IGI Global: Hershey, PA, USA, 2015; ISBN 1466697350.
5. Li, Y.; Ni, L.; Guo, Y.; Zhao, X.; Dong, Y.; Cheng, Y. Challenges and Opportunities to Treat Water Pollution. In *Paths to Clean Water Under Rapid Changing Environment in China*; Springer: Singapore, 2022; pp. 13–42.
6. Dharwal, M.; Parashar, D.; Shuaibu, M.S.; Abdullahi, S.G.; Abubakar, S.; Bala, B.B. Water Pollution: Effects on Health and Environment of Dala LGA, Nigeria. *Mater. Today Proc.* **2022**, *49*, 3036–3039. [CrossRef]
7. Ahmad, M.; Yousaf, M.; Nasir, A.; Bhatti, I.A.; Mahmood, A.; Fang, X.; Jian, X.; Kalantar-Zadeh, K.; Mahmood, N. Porous Eleocharis@ MnPE Layered Hybrid for Synergistic Adsorption and Catalytic Biodegradation of Toxic Azo Dyes from Industrial Wastewater. *Environ. Sci. Technol.* **2019**, *53*, 2161–2170. [CrossRef]
8. Hettiarachchi, S.; Wasko, C.; Sharma, A. Do Longer Dry Spells Associated with Warmer Years Compound the Stress on Global Water Resources? *Earth's Futur.* **2022**, *10*, e2021EF002392. [CrossRef]
9. Asgharnejad, H.; Khorshidi Nazloo, E.; Madani Larijani, M.; Hajinajaf, N.; Rashidi, H. Comprehensive Review of Water Management and Wastewater Treatment in Food Processing Industries in the Framework of Water-Food-Environment Nexus. *Compr. Rev. Food Sci. Food Saf.* **2021**, *20*, 4779–4815.
10. El Messaoudi, N.; El Mouden, A.; Fernine, Y.; El Khomri, M.; Bouich, A.; Faska, N.; Ciğeroğlu, Z.; Américo-Pinheiro, J.H.P.; Jada, A.; Lacherai, A. Green Synthesis of $Ag_2O$ Nanoparticles Using *Punica granatum* Leaf Extract for Sulfamethoxazole Antibiotic Adsorption: Characterization, Experimental Study, Modeling, and DFT Calculation. *Environ. Sci. Pollut. Res.* **2022**, 1–18. [CrossRef]
11. El Khomri, M.; El Messaoudi, N.; Dbik, A.; Bentahar, S.; Lacherai, A.; Faska, N.; Jada, A. Regeneration of Argan Nutshell and Almond Shell Using $HNO_3$ for Their Reusability to Remove Cationic Dye from Aqueous Solution. *Chem. Eng. Commun.* **2022**, *209*, 1304–1315.
12. Chang, Y.-C.; Zhao, X.; Han, Y. Responsibility under International Law to Prevent Marine Pollution from Radioactive Waste. *Ocean Coast. Manag.* **2022**, *227*, 106294.
13. El Messaoudi, N.; El Khomri, M.; Chegini, Z.G.; Dbik, A.; Bentahar, S.; Iqbal, M.; Jada, A.; Lacherai, A. Desorption of Crystal Violet from Alkali-Treated Agricultural Material Waste: An Experimental Study, Kinetic, Equilibrium and Thermodynamic Modeling. *Pigment. Resin Technol.* **2022**, *51*, 309–319.
14. Afolalu, S.A.; Ikumapayi, O.M.; Ogedengbe, T.S.; Kazeem, R.A.; Ogundipe, A.T. Waste Pollution, Wastewater and Effluent Treatment Methods—An Overview. *Mater. Today Proc.* **2022**, *62*, 3282–3288. [CrossRef]
15. Jadeja, N.B.; Banerji, T.; Kapley, A.; Kumar, R. Water Pollution in India—Current Scenario. *Water Secur.* **2022**, *16*, 100119.
16. Singh, J.; Yadav, P.; Pal, A.K.; Mishra, V. Water Pollutants: Origin and Status. In *Sensors in Water Pollutants Monitoring: Role of Material*; Springer: Berlin/Heidelberg, Germany, 2020; pp. 5–20.
17. Akhtar, N.; Syakir Ishak, M.I.; Bhawani, S.A.; Umar, K. Various Natural and Anthropogenic Factors Responsible for Water Quality Degradation: A Review. *Water* **2021**, *13*, 2660.
18. Hannah, D.M.; Abbott, B.W.; Khamis, K.; Kelleher, C.; Lynch, I.; Krause, S.; Ward, A.S. Illuminating the 'Invisible Water Crisis' to Address Global Water Pollution Challenges. *Hydrol. Process.* **2022**, *36*, e14525. [CrossRef]

19. Chandnani, G.; Gandhi, P.; Kanpariya, D.; Parikh, D.; Shah, M. A Comprehensive Analysis of Contaminated Groundwater: Special Emphasis on Nature-Ecosystem and Socio-Economic Impacts. *Groundw. Sustain. Dev.* **2022**, *19*, 100813.
20. Crini, G.; Lichtfouse, E. Advantages and Disadvantages of Techniques Used for Wastewater Treatment. *Environ. Chem. Lett.* **2019**, *17*, 145–155.
21. Walker, D.B.; Baumgartner, D.J.; Gerba, C.P.; Fitzsimmons, K. Surface Water Pollution. In *Environmental and Pollution Science*; Elsevier: Amsterdam, The Netherlands, 2019; pp. 261–292.
22. Ahmad, I.; Ibrahim, N.N.B.; Abdullah, N.; Koji, I.; Mohamad, S.E.; Khoo, K.S.; Cheah, W.Y.; Ling, T.C.; Show, P.L. Bioremediation Strategies of Palm Oil Mill Effluent and Landfill Leachate Using Microalgae Cultivation: An Approach Contributing towards Environmental Sustainability. *Chin. Chem. Lett.* **2023**, *34*, 107854.
23. Morin-Crini, N.; Crini, G.; Roy, L. Eaux Industrielles Contaminées. *PUFC Besançon* **2017**, *513*, 37–47.
24. Rashid, R.; Shafiq, I.; Akhter, P.; Iqbal, M.J.; Hussain, M. A State-of-the-Art Review on Wastewater Treatment Techniques: The Effectiveness of Adsorption Method. *Environ. Sci. Pollut. Res.* **2021**, *28*, 9050–9066.
25. Crini, G.; Lichtfouse, E.; Wilson, L.D.; Morin-Crini, N. Conventional and Non-Conventional Adsorbents for Wastewater Treatment. *Environ. Chem. Lett.* **2019**, *17*, 195–213. [CrossRef]
26. Pathak, U.; Das, P.; Banerjee, P.; Datta, S. Treatment of Wastewater from a Dairy Industry Using Rice Husk as Adsorbent: Treatment Efficiency, Isotherm, Thermodynamics, and Kinetics Modelling. *J. Thermodyn.* **2016**, *2016*, 3746316. [CrossRef]
27. Shahedi, A.; Darban, A.K.; Taghipour, F.; Jamshidi-Zanjani, A. A Review on Industrial Wastewater Treatment via Electrocoagulation Processes. *Curr. Opin. Electrochem.* **2020**, *22*, 154–169. [CrossRef]
28. Wang, C.; Huang, Z.; Lee, X.; Tang, Y.; Zeng, L.; Chen, Y. Screening of Composite Flocculants for Food Wastewater Treatment. *J. Water Chem. Technol.* **2022**, *44*, 88–95. [CrossRef]
29. Saxena, G.; Purchase, D.; Bharagava, R.N. Environmental Hazards and Toxicity Profile of Organic and Inorganic Pollutants of Tannery Wastewater and Bioremediation Approaches. In *Bioremediation of Industrial Waste for Environmental Safety*; Springer: Berlin/Heidelberg, Germany, 2020; pp. 381–398.
30. Udugama, I.A.; Petersen, L.A.H.; Falco, F.C.; Junicke, H.; Mitic, A.; Alsina, X.F.; Mansouri, S.S.; Gernaey, K.V. Resource Recovery from Waste Streams in a Water-Energy-Food Nexus Perspective: Toward More Sustainable Food Processing. *Food Bioprod. Process.* **2020**, *119*, 133–147. [CrossRef]
31. Barbera, M.; Gurnari, G. *Wastewater Treatment and Reuse in the Food Industry*; Springer: Berlin/Heidelberg, Germany, 2018; ISBN 3319684426.
32. Bhuvaneshwari, S.; Majeed, F.; Jose, E.; Mohan, A. Different Treatment Methodologies and Reactors Employed for Dairy Effluent Treatment—A Review. *J. Water Process Eng.* **2022**, *46*, 102622.
33. Sar, T.; Harirchi, S.; Ramezani, M.; Bulkan, G.; Akbas, M.Y.; Pandey, A.; Taherzadeh, M.J. Potential Utilization of Dairy Industries By-Products and Wastes through Microbial Processes: A Critical Review. *Sci. Total Environ.* **2022**, *810*, 152253.
34. Kushwaha, J.P.; Srivastava, V.C.; Mall, I.D. Organics Removal from Dairy Wastewater by Electrochemical Treatment and Residue Disposal. *Sep. Purif. Technol.* **2010**, *76*, 198–205. [CrossRef]
35. Mehrotra, R.; Trivedi, A.; Mazumdar, S.K. Study on Characterisation of Indian Dairy Wastewater. *Int. J. Eng. Appl. Sci. Technol.* **2016**, *1*, 77–88.
36. Kertész, S.; László*, Z.; Forgács, E.; Szabó, G.; Hodúr, C. Dairy Wastewater Purification by Vibratory Shear Enhanced Processing. *Desalin. Water Treat.* **2011**, *35*, 195–201. [CrossRef]
37. Scarsbrook, M.R.; Melland, A.R. Dairying and Water-Quality Issues in Australia and New Zealand. *Anim. Prod. Sci.* **2015**, *55*, 856–868. [CrossRef]
38. Sonawane, A.V.; Murthy, Z.V.P. Dairy Industry Wastewater Treatment by MOF and 2D Nanomaterial Engineered PVDF Membranes Based Aerobic MBR: Membrane Fouling Mitigation and Stability Study. *Process Saf. Environ. Prot.* **2023**, *171*, 680–693. [CrossRef]
39. Stasinakis, A.S.; Charalambous, P.; Vyrides, I. Dairy Wastewater Management in EU: Produced Amounts, Existing Legislation, Applied Treatment Processes and Future Challenges. *J. Environ. Manage.* **2022**, *303*, 114152. [CrossRef] [PubMed]
40. Kaur, N. Different Treatment Techniques of Dairy Wastewater. *Groundw. Sustain. Dev.* **2021**, *14*, 100640. [CrossRef]
41. Zinicovscaia, I. Conventional Methods of Wastewater Treatment. In *Cyanobacteria for Bioremediation of Wastewaters*; Springer: Cham, Switzerland, 2016; pp. 17–25.
42. Chan, S.S.; Khoo, K.S.; Chew, K.W.; Ling, T.C.; Show, P.L. Recent Advances Biodegradation and Biosorption of Organic Compounds from Wastewater: Microalgae-Bacteria Consortium—A Review. *Bioresour. Technol.* **2022**, *344*, 126159. [CrossRef]
43. Litu, L.; Ciobanu, G.; Cîmpeanu, S.M.; Kotova, O.; Ciocinta, R.; Bucur, D.; Harja, M. Comparative Study between Flocculation-Coagulation Processes in Raw/Wastewater Treatment. *AgroLife Sci. J.* **2019**, *8*, 139–145.
44. Zhao, C.; Zhou, J.; Yan, Y.; Yang, L.; Xing, G.; Li, H.; Wu, P.; Wang, M.; Zheng, H. Application of Coagulation/Flocculation in Oily Wastewater Treatment: A Review. *Sci. Total Environ.* **2021**, *765*, 142795. [CrossRef]
45. Anderson, A.; Anbarasu, A.; Pasupuleti, R.R.; Sekar, M.; Praveenkumar, T.R.; Kumar, J.A. Treatment of Heavy Metals Containing Wastewater Using Biodegradable Adsorbents: A Review of Mechanism and Future Trends. *Chemosphere* **2022**, *295*, 133724.
46. Kurniawan, S.B.; Imron, M.F.; Chik, C.E.N.C.E.; Owodunni, A.A.; Ahmad, A.; Alnawajha, M.M.; Rahim, N.F.M.; Said, N.S.M.; Abdullah, S.R.S.; Kasan, N.A. What Compound inside Biocoagulants/Bioflocculants Is Contributing the Most to the Coagulation and Flocculation Processes? *Sci. Total Environ.* **2022**, *806*, 150902. [CrossRef]

47. Moreno-González, M.; Keulen, D.; Gomis-Fons, J.; Gomez, G.L.; Nilsson, B.; Ottens, M. Continuous Adsorption in Food Industry: The Recovery of Sinapic Acid from Rapeseed Meal Extract. *Sep. Purif. Technol.* **2021**, *254*, 117403. [CrossRef]
48. Shrivastava, V.; Ali, I.; Marjub, M.M.; Rene, E.R.; Soto, A.M.F. Wastewater in the Food Industry: Treatment Technologies and Reuse Potential. *Chemosphere* **2022**, *293*, 133553. [CrossRef] [PubMed]
49. Yu, M.; Wang, J.; Tang, L.; Feng, C.; Liu, H.; Zhang, H.; Peng, B.; Chen, Z.; Xie, Q. Intimate Coupling of Photocatalysis and Biodegradation for Wastewater Treatment: Mechanisms, Recent Advances and Environmental Applications. *Water Res.* **2020**, *175*, 115673. [CrossRef]
50. Mustafa, S.; Bhatti, H.N.; Maqbool, M.; Iqbal, M. Microalgae Biosorption, Bioaccumulation and Biodegradation Efficiency for the Remediation of Wastewater and Carbon Dioxide Mitigation: Prospects, Challenges and Opportunities. *J. Water Process Eng.* **2021**, *41*, 102009. [CrossRef]
51. Daufin, G.; Escudier, J.-P.; Carrère, H.; Bérot, S.; Fillaudeau, L.; Decloux, M. Recent and Emerging Applications of Membrane Processes in the Food and Dairy Industry. *Food Bioprod. Process.* **2001**, *79*, 89–102.
52. Al-Shimmery, A.; Mazinani, S.; Ji, J.; Chew, Y.M.J.; Mattia, D. 3D Printed Composite Membranes with Enhanced Anti-Fouling Behaviour. *J. Memb. Sci.* **2019**, *574*, 76–85. [CrossRef]
53. Arhin, S.G.; Banadda, N.; Komakech, A.J.; Kabenge, I.; Wanyama, J. Membrane Fouling Control in Low Pressure Membranes: A Review on Pretreatment Techniques for Fouling Abatement. *Environ. Eng. Res.* **2016**, *21*, 109–120. [CrossRef]
54. Reig, M.; Vecino, X.; Cortina, J.L. Use of Membrane Technologies in Dairy Industry: An Overview. *Foods* **2021**, *10*, 2768. [CrossRef]
55. Glater, J. The Early History of Reverse Osmosis Membrane Development. *Desalination* **1998**, *117*, 297–309. [CrossRef]
56. Matsuura, T. Progress in Membrane Science and Technology for Seawater Desalination—A Review. *Desalination* **2001**, *134*, 47–54. [CrossRef]
57. Pouliot, Y. Membrane Processes in Dairy Technology—From a Simple Idea to Worldwide Panacea. *Int. Dairy J.* **2008**, *18*, 735–740. [CrossRef]
58. Celikten, C.; Mavus, R.; Kemec, S.; Unlu, U.; Ergun, A.; Deligoz, H. Membrane Technologies in the Food and Beverage Industry. *J. Fac. Eng. Archit. Gazi Univ.* **2022**, *37*, 1713–1733.
59. Ferreira, F.B.; Ullmann, G.; Vieira, L.G.M.; Cardoso, V.L.; Reis, M.H.M. Hydrodynamic Performance of 3D Printed Turbulence Promoters in Cross-Flow Ultrafiltrations of Psidium Myrtoides Extract. *Chem. Eng. Process. Intensif.* **2020**, *154*, 108005.
60. da Cunha, T.M.P.; Canella, M.H.M.; da Silva Haas, I.C.; Amboni, R.D.; Prudencio, E.S. A Theoretical Approach to Dairy Products from Membrane Processes. *Food Sci. Technol.* **2022**, *42*. [CrossRef]
61. Charcosset, C. Classical and Recent Applications of Membrane Processes in the Food Industry. *Food Eng. Rev.* **2021**, *13*, 322–343.
62. Saboyainsta, L.V.; Maubois, J.-L. Current Developments of Microfiltration Technology in the Dairy Industry. *Lait* **2000**, *80*, 541–553. [CrossRef]
63. Castro-Muñoz, R.; Yáñez-Fernández, J.; Fíla, V. Phenolic Compounds Recovered from Agro-Food by-Products Using Membrane Technologies: An Overview. *Food Chem.* **2016**, *213*, 753–762.
64. Bazinet, L.; Doyen, A. Antioxidants, Mechanisms, and Recovery by Membrane Processes. *Crit. Rev. Food Sci. Nutr.* **2017**, *57*, 677–700.
65. Kravtsov, V.; Kulikova, I.; Mikhaylin, S.; Bazinet, L. Alkalinization of Acid Whey by Means of Electrodialysis with Bipolar Membranes and Analysis of Induced Membrane Fouling. *J. Food Eng.* **2020**, *277*, 109891. [CrossRef]
66. Nath, K.; Dave, H.K.; Patel, T.M. Revisiting the Recent Applications of Nanofiltration in Food Processing Industries: Progress and Prognosis. *Trends Food Sci. Technol.* **2018**, *73*, 12–24.
67. Carter, B.G.; Cheng, N.; Kapoor, R.; Meletharayil, G.H.; Drake, M.A. Invited Review: Microfiltration-Derived Casein and Whey Proteins from Milk. *J. Dairy Sci.* **2021**, *104*, 2465–2479. [PubMed]
68. Blais, H.N.; Schroën, K.; Tobin, J.T. A Review of Multistage Membrane Filtration Approaches for Enhanced Efficiency during Concentration and Fractionation of Milk and Whey. *Int. J. Dairy Technol.* **2022**, *75*, 749–760.
69. Debon, J.; Prudêncio, E.S.; Petrus, J.C.C.; Fritzen-Freire, C.B.; Müller, C.M.O.; de, M.C. Amboni, R.D.; Vieira, C.R.W. Storage Stability of Prebiotic Fermented Milk Obtained from Permeate Resulting of the Microfiltration Process. *LWT-Food Sci. Technol.* **2012**, *47*, 96–102.
70. Faion, A.M.; Becker, J.; Fernandes, I.A.; Steffens, J.; Valduga, E. Sheep's Milk Concentration by Ultrafiltration and Cheese Elaboration. *J. Food Process Eng.* **2019**, *42*, e13058. [CrossRef]
71. Gavazzi-April, C.; Benoit, S.; Doyen, A.; Britten, M.; Pouliot, Y. Preparation of Milk Protein Concentrates by Ultrafiltration and Continuous Diafiltration: Effect of Process Design on Overall Efficiency. *J. Dairy Sci.* **2018**, *101*, 9670–9679. [PubMed]
72. Ng, K.S.Y.; Dunstan, D.E.; Martin, G.J.O. Influence of Processing Temperature on Flux Decline during Skim Milk Ultrafiltration. *Sep. Purif. Technol.* **2018**, *195*, 322–331.
73. Chen, Z.; Luo, J.; Hang, X.; Wan, Y. Physicochemical Characterization of Tight Nanofiltration Membranes for Dairy Wastewater Treatment. *J. Memb. Sci.* **2018**, *547*, 51–63. [CrossRef]
74. Prudêncio, E.S.; Müller, C.M.O.; Fritzen-Freire, C.B.; Amboni, R.D.M.C.; Petrus, J.C.C. Effect of Whey Nanofiltration Process Combined with Diafiltration on the Rheological and Physicochemical Properties of Ricotta Cheese. *Food Res. Int.* **2014**, *56*, 92–99. [CrossRef]
75. Blais, H.; Ho, Q.T.; Murphy, E.G.; Schroën, K.; Tobin, J.T. A Cascade Microfiltration and Reverse Osmosis Approach for Energy Efficient Concentration of Skim Milk. *J. Food Eng.* **2021**, *300*, 110511. [CrossRef]

76. Saffarimiandoab, F.; Gul, B.Y.; Tasdemir, R.S.; Ilter, S.E.; Unal, S.; Tunaboylu, B.; Menceloglu, Y.Z.; Koyuncu, İ. A Review on Membrane Fouling: Membrane Modification. *Desalin. Water Treat* **2021**, *216*, 47–70. [CrossRef]
77. AlSawaftah, N.; Abuwatfa, W.; Darwish, N.; Husseini, G. A Comprehensive Review on Membrane Fouling: Mathematical Modelling, Prediction, Diagnosis, and Mitigation. *Water* **2021**, *13*, 1327.
78. Leu, M.; Marciniak, A.; Chamberland, J.; Pouliot, Y.; Bazinet, L.; Doyen, A. Effect of Skim Milk Treated with High Hydrostatic Pressure on Permeate Flux and Fouling during Ultrafiltration. *J. Dairy Sci.* **2017**, *100*, 7071–7082. [CrossRef]
79. Sutrisna, P.D.; Kurnia, K.A.; Siagian, U.W.R.; Ismadji, S.; Wenten, I.G. Membrane Fouling and Fouling Mitigation in Oil–Water Separation: A Review. *J. Environ. Chem. Eng.* **2022**, *10*, 107532.
80. Krishnan, S.; Nasrullah, M.; Kamyab, H.; Suzana, N.; Munaim, M.S.A.; Wahid, Z.A.; Ali, I.H.; Salehi, R.; Chaiprapat, S. Fouling Characteristics and Cleaning Approach of Ultrafiltration Membrane during Xylose Reductase Separation. *Bioprocess Biosyst. Eng.* **2022**, *45*, 1125–1136. [PubMed]
81. Mohammad, A.W.; Ng, C.Y.; Lim, Y.P.; Ng, G.H. Ultrafiltration in Food Processing Industry: Review on Application, Membrane Fouling, and Fouling Control. *Food Bioprocess Technol.* **2012**, *5*, 1143–1156.
82. Deka, A.; Rasul, A.; Baruah, A.; Malakar, H.; Basumatary, A.K. Treatment of Dairy Wastewater with Tubular Ceramic Membrane. *Mater. Today Proc.* **2023**, *72*, 2773–2779. [CrossRef]
83. Sisay, E.J.; Kertész, S.; Fazekas, Á.; Jákói, Z.; Kedves, E.Z.; Gyulavári, T.; Ágoston, Á.; Veréb, G.; László, Z. Application of $BiVO_4/TiO_2$/CNT Composite Photocatalysts for Membrane Fouling Control and Photocatalytic Membrane Regeneration during Dairy Wastewater Treatment. *Catalysts* **2023**, *13*, 315.
84. Hepsen, R.; Kaya, Y. Optimization of Membrane Fouling Using Experimental Design: An Example from Dairy Wastewater Treatment. *Ind. Eng. Chem. Res.* **2012**, *51*, 16074–16084. [CrossRef]
85. Zhang, B.; Feng, X. Assessment of Pervaporative Concentration of Dairy Solutions vs. Ultrafiltration, Nanofiltration and Reverse Osmosis. *Sep. Purif. Technol.* **2022**, *292*, 120990.
86. Shi, X.; Tal, G.; Hankins, N.P.; Gitis, V. Fouling and Cleaning of Ultrafiltration Membranes: A Review. *J. Water Process Eng.* **2014**, *1*, 121–138.
87. Gul, A.; Hruza, J.; Yalcinkaya, F. Fouling and Chemical Cleaning of Microfiltration Membranes: A Mini-Review. *Polymers* **2021**, *13*, 846. [CrossRef]
88. Ladewig, B.; Al-Shaeli, M.N.Z. Fouling in Membrane Bioreactors. In *Fundamentals of Membrane Bioreactors*; Springer: Berlin/Heidelberg, Germany, 2017; pp. 39–85.
89. Hermia, J. Constant Pressure Blocking Filtration Laws: Application to Power-Law Non-Newtonian Fluids. *Inst. Chem. Eng. Trans.* **1982**, *60*, 183–187.
90. Pezeshk, N.; Narbaitz, R.M. More Fouling Resistant Modified PVDF Ultrafiltration Membranes for Water Treatment. *Desalination* **2012**, *287*, 247–254.
91. Huang, H.; Schwab, K.; Jacangelo, J.G. Pretreatment for Low Pressure Membranes in Water Treatment: A Review. *Environ. Sci. Technol.* **2009**, *43*, 3011–3019.
92. Fiksdal, L.; Leiknes, T. The Effect of Coagulation with MF/UF Membrane Filtration for the Removal of Virus in Drinking Water. *J. Memb. Sci.* **2006**, *279*, 364–371. [CrossRef]
93. Xiangli, Q.; Zhenjia, Z.; Nongcun, W.; Wee, V.; Low, M.; Loh, C.S.; Hing, N.T. Coagulation Pretreatment for a Large-Scale Ultrafiltration Process Treating Water from the Taihu River. *Desalination* **2008**, *230*, 305–313.
94. Jung, J.; Kim, Y.-J.; Park, Y.-J.; Lee, S.; Kim, D. Optimization of Coagulation Conditions for Pretreatment of Microfiltration Process Using Response Surface Methodology. *Environ. Eng. Res.* **2015**, *20*, 223–229.
95. Matsushita, T.; Shirasaki, N.; Tatsuki, Y.; Matsui, Y. Investigating Norovirus Removal by Microfiltration, Ultrafiltration, and Precoagulation–Microfiltration Processes Using Recombinant Norovirus Virus-like Particles and Real-Time Immuno-PCR. *Water Res.* **2013**, *47*, 5819–5827. [PubMed]
96. Stoquart, C.; Servais, P.; Bérubé, P.R.; Barbeau, B. Hybrid Membrane Processes Using Activated Carbon Treatment for Drinking Water: A Review. *J. Memb. Sci.* **2012**, *411*, 1–12.
97. Khan, M.M.T.; Takizawa, S.; Lewandowski, Z.; Jones, W.L.; Camper, A.K.; Katayama, H.; Kurisu, F.; Ohgaki, S. Membrane Fouling Due to Dynamic Particle Size Changes in the Aerated Hybrid PAC–MF System. *J. Memb. Sci.* **2011**, *371*, 99–107.
98. Wei, Y.; Qi, H.; Gong, X.; Zhao, S. Specially Wettable Membranes for Oil–Water Separation. *Adv. Mater. Interfaces* **2018**, *5*, 1800576.
99. Ding, Y.; Maruf, S.; Aghajani, M.; Greenberg, A.R. Surface Patterning of Polymeric Membranes and Its Effect on Antifouling Characteristics. *Sep. Sci. Technol.* **2017**, *52*, 240–257.
100. Padaki, M.; Murali, R.S.; Abdullah, M.S.; Misdan, N.; Moslehyani, A.; Kassim, M.A.; Hilal, N.; Ismail, A.F. Membrane Technology Enhancement in Oil–Water Separation. A Review. *Desalination* **2015**, *357*, 197–207.
101. Maruf, S.H.; Wang, L.; Greenberg, A.R.; Pellegrino, J.; Ding, Y. Use of Nanoimprinted Surface Patterns to Mitigate Colloidal Deposition on Ultrafiltration Membranes. *J. Memb. Sci.* **2013**, *428*, 598–607.
102. Low, Z.-X.; Chua, Y.T.; Ray, B.M.; Mattia, D.; Metcalfe, I.S.; Patterson, D.A. Perspective on 3D Printing of Separation Membranes and Comparison to Related Unconventional Fabrication Techniques. *J. Memb. Sci.* **2017**, *523*, 596–613.
103. Armbruster, S.; Cheong, O.; Lölsberg, J.; Popovic, S.; Yüce, S.; Wessling, M. Fouling Mitigation in Tubular Membranes by 3D-Printed Turbulence Promoters. *J. Memb. Sci.* **2018**, *554*, 156–163.

104. Fodor, E.; Šereš, Z.; Gergely, G.; Hodúr, C.; Kertész, S. Investigation of Ultrafiltration Parameters of Different Organic Load Wastewater Types. *Analecta Tech. Szeged.* **2022**, *16*, 129–135.
105. Qian, X.; Ostwal, M.; Asatekin, A.; Geise, G.M.; Smith, Z.P.; Phillip, W.A.; Lively, R.P.; McCutcheon, J.R. A Critical Review and Commentary on Recent Progress of Additive Manufacturing and Its Impact on Membrane Technology. *J. Memb. Sci.* **2022**, *645*, 120041.
106. Liu, J.; Liu, Z.; Xu, X.; Liu, F. Saw-Tooth Spacer for Membrane Filtration: Hydrodynamic Investigation by PIV and Filtration Experiment Validation. *Chem. Eng. Process. Process Intensif.* **2015**, *91*, 23–34.
107. Tsai, H.-Y.; Huang, A.; Luo, Y.-L.; Hsu, T.-Y.; Chen, C.-H.; Hwang, K.-J.; Ho, C.-D.; Tung, K.-L. 3D Printing Design of Turbulence Promoters in a Cross-Flow Microfiltration System for Fine Particles Removal. *J. Memb. Sci.* **2019**, *573*, 647–656.