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Review

Integrated Management of Industrial Wastewater in the Food Sector

Mona A. Abdel-Fatah

Chemical Engineering and Pilot Plant Department, Engineering and Renewable Energy Research Institute, National Research Centre (NRC), 33 El-Bohooth St., Giza 12622, Egypt; monaamin46@gmail.com

Abstract: In 2019, a staggering 931 million tons of food went to waste, which is equal to about 17% of all the food available in stores. Dealing with this waste and managing wastewater from various industries will be among the world's top challenges soon. This is because the global population is expected to grow to around 9 billion people by 2050. Food processing effluent is characterized by valuable material in considerable concentrations, including proteins and lipids with low concentrations of heavy metals and toxicants. Developing an integrated management system for food-processing wastewater should focus on recovering abundant resources, improving the economic value of the process, and mitigating the organic contaminant in the food-processing effluent. This state-of-the-art will review the wastewater management processes of the food processing industry. The latest wastewater treatment processes in different food processing sectors will be reviewed. This review will encompass various physicochemical treatment and recovery techniques, such as precipitation, membrane technology, solvent extraction, foam fractionation, adsorption, and aqueous two-phase systems. Additionally, it will delve into bio-treatment processes that leverage microorganisms and/or enzymes to utilize nutrients found in food-processing wastewater as cost-effective substrates for the production of valuable products. This includes a detailed examination of microalga biomass production within wastewater treatment systems. Finally, the review will put forward future research directions aimed at integrating the principles of the circular economy and developing comprehensive food-processing wastewater management systems.

Keywords: integrated management; food sector; industrial wastewater; sustainable; circular economy

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Citation: Abdel-Fatah, M.A. Integrated Management of Industrial Wastewater in the Food Sector. *Sustainability* **2023**, *15*, 16193. https://doi.org/10.3390/su152316193

Academic Editors: Giovanni De Feo and Agostina Chiavola

Received: 27 August 2023
Revised: 15 October 2023
Accepted: 14 November 2023
Published: 22 November 2023

1. Introduction

The shortage of potable water resources may lead to several problems, including deaths and health-related issues [1,2]. Globally, 2.2 billion individuals lack access to safe drinking water, including 884 million who lack essential water services [3]. In some cities, such as New Delhi, India, there is a massive shortage of water for the inhabitants, leading to deadly competition over limited water resources [4]. The global population is projected to grow to around 9 billion people by 2050. This underscores the urgency of addressing food waste and wastewater management to meet the needs of a growing population [1–8].

Considering the increasing demand for water due to the steady increase in world population and the industrial use of water, reusing water is vital to maintain water resources and to cope with the world's economic growth [5]. The circular economy concept should be implemented in water usage by considering restricted regulations for wastewater discharge to protect natural water reserves. Wastewater reuse schemes should be developed and implemented in all the industrial sectors; nevertheless, more work and development are still needed to ensure sustainable water utilization practices through cost-effective technologies for wastewater treatment [6].

The food industry is a large water consumer. The amount of water used varies considerably in the food and beverages industry according to the nature of the sector, process parameters, unit size, and cleaning process used [7]. Wastewater generated in the food industry may result from processing units, rinsing and cleaning activities, forming byproduct formation streams, including solid and liquid waste [8]. The appropriate water resources and reusing technologies can be selected by evaluating each process's water needs and characteristics. Three different approaches can be implemented to minimize water consumption in the food industry [9]:

- Using production technologies that consume less water.
- Decreasing uncontrolled water usage by implementing spray nozzles and reducing leaks.
- Recycling/reusing water efficiently.

A practical water use reduction strategy can be achieved by recycling and reusing the treated water and recovering valuable materials. Achieving such a strategy requires implementing efficient wastewater treatment methods. Due to the negative perception of using treated water and the possible contamination risk, the concept of circular water use is still not implemented in the food industry [10,11]. Figure 1 illustrates the water consumption by percentage in different sectors of the food industry. Water consumption in industrial food units is affected by many factors, including plant capacity, the manufacturing process, equipment, cleaning operations, and end products. About 4 trillion m^3 is needed, while the freshwater available for these activities is only about 0.01 trillion m^3, which may increase water scarcity [12,13]. With limited water resources, unconventional water resources such as wastewater, rainwater, and saline water must be considered [14,15]. Around 20% of global water consumption is associated with industrial applications, and this is expected to increase annually [16].

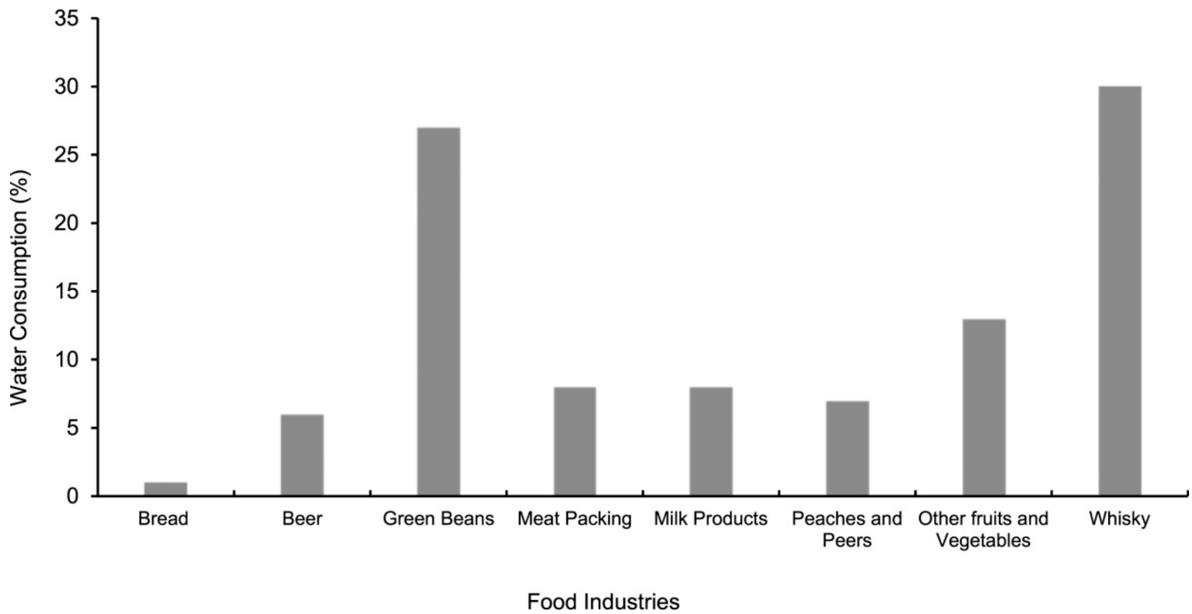

Figure 1. The nominal percentage of water consumed in different food industry sectors [12].

Water reuse is significant for legislative requirements, and it strengthens corporate social responsibility and reputation. Several global companies such as Coca-Cola and Heineken have taken the initiative to reuse treated water. Coca-Cola produces around 804 billion liters of wastewater annually; 173 billion liters are reused. The reuse of this large amount helped the company to meet governmental requirements. Heineken is working on a promising plan to reuse 100% of brewery wastewater by 2030 [17].

Wastewater from the food industry can be toxic to aquatic life, containing organic content 10–100 times that found in domestic water [18]. Due to the versatility of food industries, it is hard to develop one single management method for all the different processing units. The optimum wastewater management approach and treatment method should be chosen based on the food-processing process's nature and the discharged effluent's characteristics [19]. Water is needed in the food industry for process uses and non-process uses. The process uses include any water used as a raw material.

In contrast, the non-process uses include water consumed for washing, cooling, and heating [20]. The non-process uses of water represent the central portion of water use in the food industry [21]. Since water does not significantly impact the raw material or final product within the process uses, wastewater can be used as a sustainable water resource in the food industry after applying efficient treatment and management methods [22,23].

Regarding wastewater creation, management, and recycling in the beverage and food industry, the proficiency of commonly employed technologies for wastewater treatment, including the financial and environmental consequences, will be discussed taking into consideration the following characteristics: (i) legislative necessities regulating the reuse of water, guidelines, and prospective applications of recycled water; (ii) wastewater treatment technologies evaluation, including combining several treatment methods; and (iii) resources recovery during wastewater treatment.

The wastewater generated from non-process uses usually has a high loading of COD, BOD_5, organic contaminants, suspended solids, nutrients such as N_2 and P, solvents, and ions [24]. The circular economy is an interesting framework for wastewater management in the food industry based on reusing and recycling water and other valuable resources [25–28]. The circular economy supports sustainable development in all process-related activities [29]. New methods such as mathematical modeling/optimization and pinch analysis are developed for the sustainable management of resources [30–33]. The primary goal of the circular economy is to develop process integration methods, including redesigning industrial operations to optimize resource management [34].

To implement the optimum wastewater management method, the process data must be considered, including water requirements, operational flow diagram, characteristics and amount of wastewater generated, and feasible methods of wastewater treatment considering the operating conditions. The previous discussion clearly shows the urgent need to develop integrated wastewater management for different industrial applications to reduce environmental harm.

A significant aspect of these challenges is the substantial water consumption by industries such as food processing, which places a strain on our limited sources of clean drinking water. Notably, the food-processing industry is a major contributor to freshwater use. In response, scientists and engineers are actively engaged in developing innovative approaches to enhance wastewater management.

One distinctive aspect of this work is its focus on the valuable components present in food-processing effluent, notably proteins and lipids, alongside low concentrations of heavy metals and toxicants. This integrated approach seeks to harness these valuable resources, thereby elevating the economic viability of the food-processing process. Importantly, this approach aims to address both economic and environmental concerns associated with food-processing effluent.

The focus of this state-of-the-art will be the integrated management of industrial wastewater in the food sector. This paper will review the water consumption and wastewater generation in several food-processing industries and the operating conditions. This paper will discuss the choice of the optimum integrated wastewater management system considering water consumption, sustainable food production, and environmental protection, as shown in Figure 2.

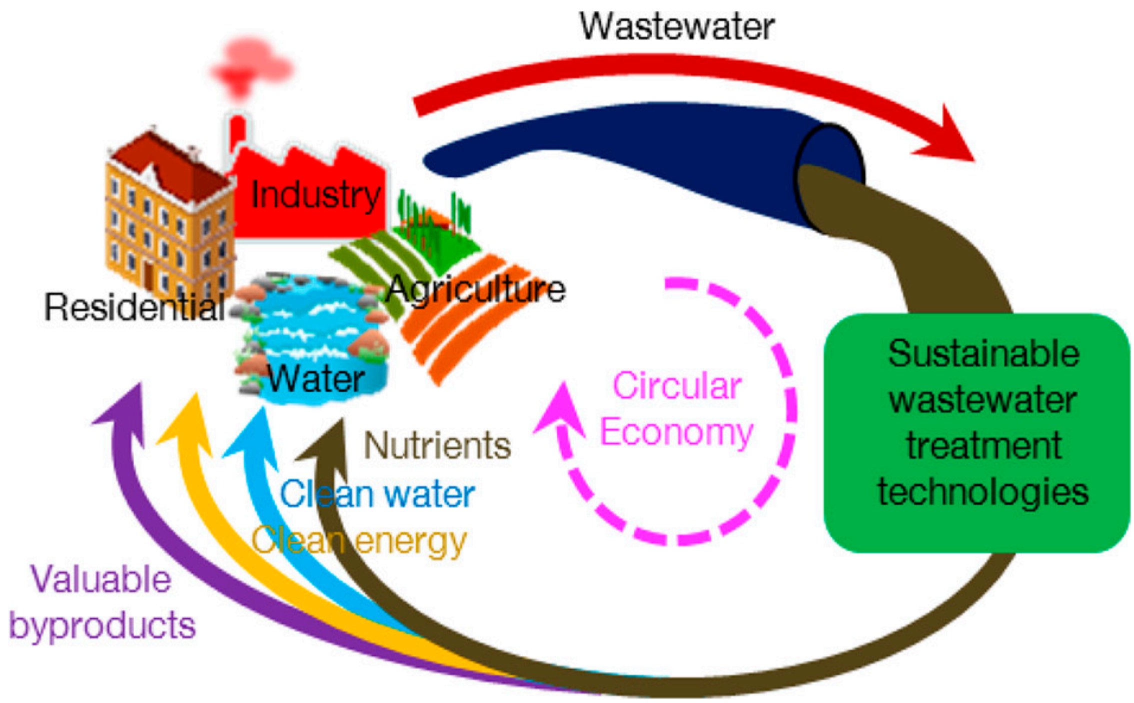

Figure 2. Interconnection between water demand, environmental protection, and enhancing food productivity [35].

2. Integrated Industrial Wastewater Management

Table 1 illustrates the projected wastewater quantities generated by different food products considering water requirements per product and their global production volume. Since washing and cleaning are the steps where the most water is consumed in the food industry, which are considered non-process use, the water consumed is turned into wastewater. In the sugar, edible oil, and grain milling industries, part of the consumed water is used for process-related applications, primarily for adjusting the raw materials' humidity. Humidity levels are crucial in the grain milling and edible oil production industries. In addition, water can be used as a raw material throughout the production process. Creating various sugars such as glucose or fructose starting with the grains is one of the standard processes where water is used as a reactant [36].

Table 1. Estimated volume of wastewater produced for various food products [36].

Product	Wastewater (m^3/ton)	COD (kg/m^3)
Dairy	6.5	1.5–5.2
Fish	13	2.5
Meat and poultry	13	2–7
Sugar refining	11	1–6
Starch	11	1.5–42
Fruits, vegetables, and juices	21	2–10
Vinegar	28.5	0.7–3

2.1. Food Processing Units

The food processing units can be categorized into eight industries, including meat production, fish and seafood, fruit and vegetables, edible oils, dairy products, grain mill products, bakery, and other food products (such as coffee, tea, sugar, and prepared and canned meals). Food industries are the central part of the food supply chain and play an essential role in sustainable development goals and improving the socioeconomic indicators. However, the food industry is a large water consumer and consumes around 30% of the total water used by the industry [37].

2.1.1. Meat Production Industries

Meat represents the essential protein source in the human diet. The meat processing industry is one of the vital industries in the food supply chain, with around 325 million tons annually, including poultry, beef, pork, and sheep raw materials [38]. In a typical meat processing unit, animals are slaughtered and then washed, followed by meat cutting, processing the meat into other products such as sausage or burgers, and finally packing, as shown in Figure 3.

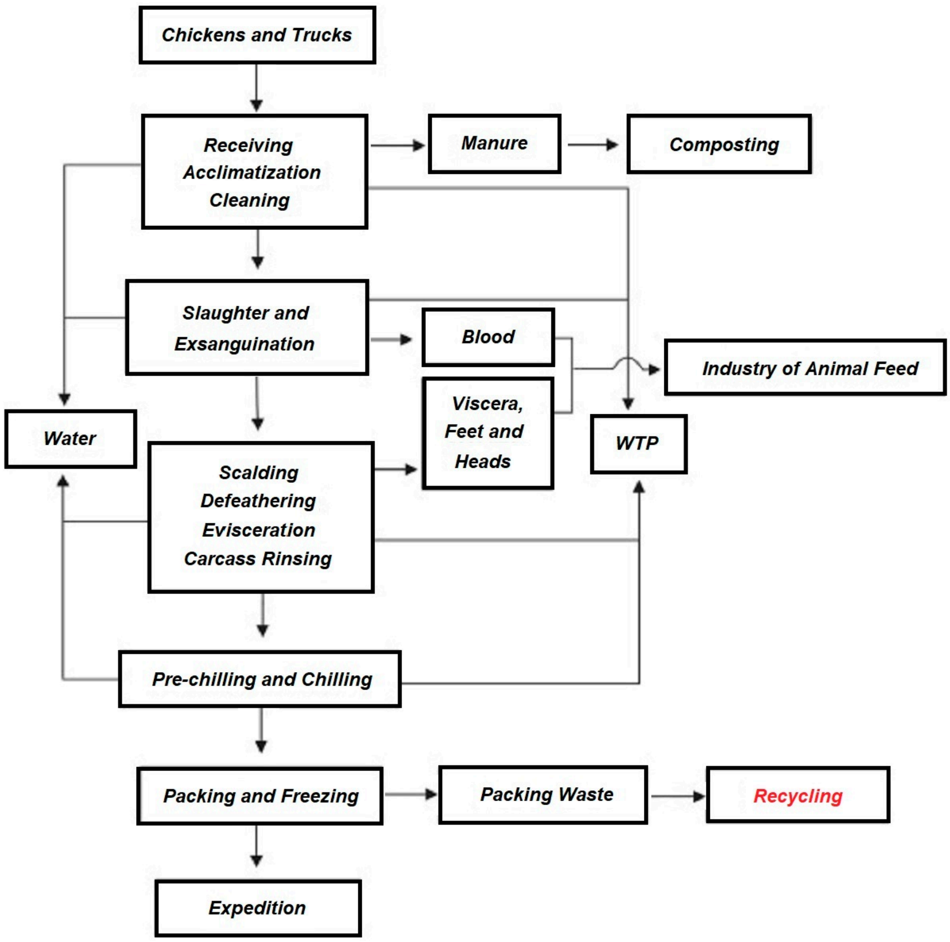

Figure 3. Meat processing industry, water demand, and wastewater generation.

Water demand varies considerably based on the processed animal and the final product. In poultry production, an average of 11.5 L of freshwater is needed per animal, while 1325 L is required per animal in beef processing units. Most of the water is used for washing purposes [39]. As shown in Figure 3, the evisceration step consumes around 44–60% of the unit water demand, subdivided into offal washing, approximately 7–40%, and casings, such as washing hair and fats, with around 9–20%. The animal prewashing step is conducted using water sprays or in water pools, using 7–22% of the process water. Approximately 25–50% of the water is consumed during meat cleaning. Wastewater discharged from meat processing units may reach around 98% of the total water used [40]. Table 2 shows the meat processing unit characteristics for each meat production unit. As shown in Table 2, the wastewater is highly polluted effluent containing organic loads, nutrients, and suspended solids such as blood, debris, meat, and bones.

Table 2. Characteristics of meat production wastewater [40].

Meat	COD mg/L	BOD_5 mg/L	TN mg/L	TSS mg/L	O&G mg/L
Beef	4220	1209	427	1164	na
Poultry	950	400	80	240	120
Pork	4310	na	275	1240	125

Proteins in blood and debris are responsible for high total nitrogen (TN). Biological treatment methods are usually recommended for meat-processing wastewater to facilitate the removal of organic loads and nutrients effectively compared to other treatment methods. Table 3 shows the latest wastewater treatment processes used in the meat production industry [40].

Table 3. Technologies used for the treatment of wastewater in the meat processing industry.

Method	Parameter	Removal Efficiency (%)
Up-flow anaerobic sludge blanket (UASB)	COD Oil and grease (O&G)	78–80 68–70
Coagulation/Floatation	Total Solid (TS) O&G BOD_5 COD	85 85 62–78.8 74.6–79.5
Algal Treatment	(NH_3-N) Total Nitrogen (TN) Total Phosphorus (TP) TN COD	68.75–90.38 30.06–50.94 69 67 91
A_2O Bioreactor	TP TN COD	83.48 90.48 98.33
Algal Treatment	BOD_5 COD TP	97 94 94
Anaerobic Baffled Reactor with Activated Sludge	Total Organic Carbon (TOC) TN Total Suspended Solids (TSS)	85 72 >95
Algal Treatment	NH_3-N Phosphate (PO_4^{3-})	89.74–99.03 92.39–99.93
Sequence Batch Reactor (SBR)	COD BOD_5 TSS TN TP	98 97 89 91 86

Due to their ability to remove all contaminants, biological methods are more effective for treating wastewater from meat processing, such as sequencing batch reactor and algal treatment. However, physiochemical treatment methods, such as filtration, coagulation, and flotation, can be used effectively to reduce grease and oil and total suspended solids. Physiochemical treatment methods are less complicated and cheaper compared to biological processes. Treated wastewater can be reused for washing, which improves water reuse and resource recovery in meat processing.

2.1.2. Fish and Seafood Industries

Fish consumption increased from 9.9 kg to 16.7 kg per person annually from 1960 to 2016 [41]. In the last 10 years, the consumption of processed fish products, representing 90%

of the global market, has increased sharply. During fish processing, chilling and freezing, salting, smoking, drying, and canning are the most popular fish processing steps [42]. In addition, immediate processing steps are needed after catching until processing to facilitate transportation, including slime removal, cutting heads/fins, washing, scaling and gutting, bone separation, and cutting into steaks and fillets. Figure 4 shows the schematic process of fish processing.

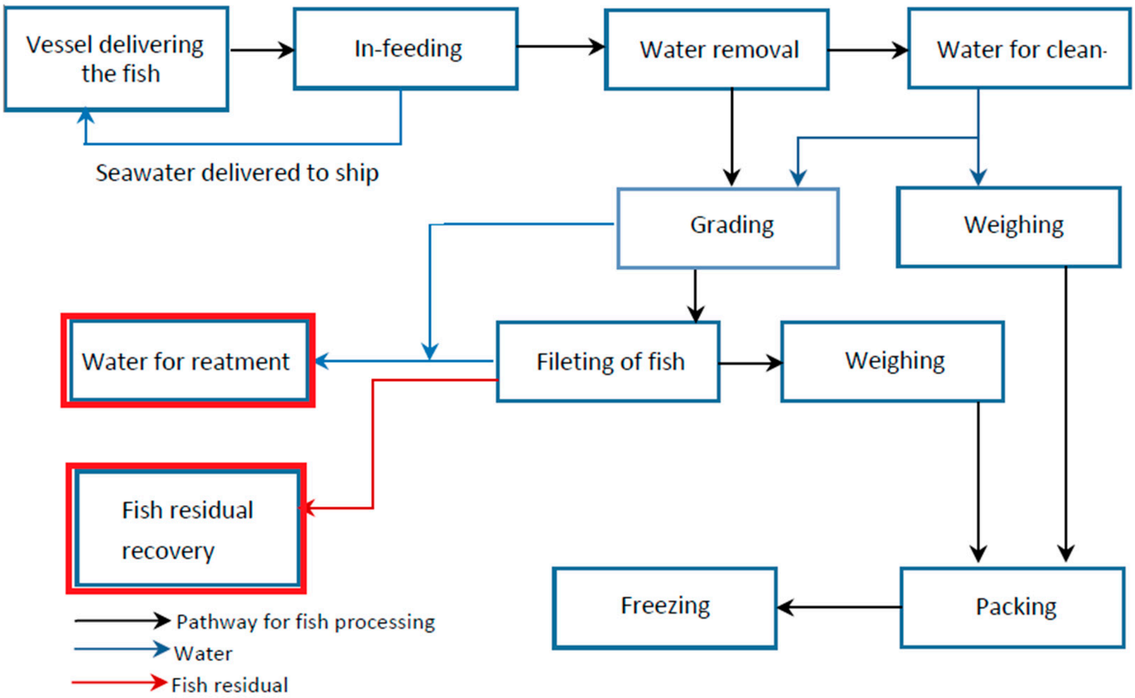

Figure 4. Shows the schematic process of fish processing.

Fish processing units are usually near aquatic environments to minimize processing time and transportation costs. Water consumption depends on the process's nature and operating conditions. Around 11 m^3 of water is used to process 1 ton of prepared fish. The generated wastewater is usually discharged directly into aquacultures. Preparation steps, including slime removal, cutting heads, and washing, require considerable water and create an effluent contaminated with blood, high turbidity, BOD_5, and TSS [43,44]. Table 4 shows the typical characteristics of the wastewater generated during fish preparation.

Table 4. Wastewater characteristics of fish preparation [43].

Parameter	R (1)	R (2)	R (3)
BOD_5 (mg/L)	–	3163	858
COD (mg/L)	1518 ± 584.4	3325	–
Total Nitrogen (mg/L)	112 ± 34.5	410	–
Turbidity (NTU))	–	–	64.9
TSS (mg/L)	418 ± 487.2	703	770
pH	7.67	7	5.5–8.5

As shown in Figure 4, a large amount of wastewater is produced from non-process uses. The nature and amount of wastewater are dependent on the nature of the final product. Table 5 recaps the water consumed in fish and seafood canning processing units at distinct stages of the process.

Table 5. Water demand during the production of canned fish.

Product	Water Requirement (m^3/h Normalized for 1 Ton of Raw Fish)				
	Thawing/Washing	Cooking/Can Washing	Sterilization	Additional Use	Total
Tuna	8	4	12	8	32
Sardines	6	4	12	6	28
Salmon	–	4	10	2	16
Shrimp	–	8	6	2	16

The wastewater generated during fish processing is characterized by high salinity and organic loads and ranges between 8 and 18 m^3 per ton of product [45]. Table 6 summarizes the characteristics of wastewater generated during canned fish production.

Table 6. Wastewater characterization in canned fish industries [40].

Product	BOD_5 (mg/L)	COD (mg/L)	Conductivity ($mS \cdot cm^{-1}$)	TSS (mg/L)	TN (mg/L)
Tuna	4569	8313	24.8	3150	471
Tuna	3300	5553	9.21	1575	440
Shrimp	980	1595	na	443	63
Sardines	1065	1320	12.3	4903	36

Fish-processing wastewater contains high organic loading (BOD_5 and COD) and total solids. To meet legislative demands, several treatment methods should be implemented. The high organic content is attributed to the presence of guts, blood, and minces within fish-processing effluent. The cooking stage drains a large number of nutrients into the effluent. At high temperatures, the flesh proteins denature, releasing N_2 [45]. Total solids can be subdivided into dissolved (TDS) from washing with seawater and suspended (TSS) solids from discharging fish flesh minces, debris, skin, and scales. Combining physiochemical and biological methods is required to eliminate all fish-processing wastewater contaminants effectively. Table 7 shows the developed treatment methods used for fish-processing wastewater.

Table 7. Wastewater treatment processes in fish-processing industries [45].

Treatment Process	Parameter	Removal %
Crystallization	COD	40.1
	TSS	21.6
	TN	93.8
Sedimentation/Floatation	BOD_5	90
	COD	60
	TSS	95
	NH_4^+-N	50
Ultrafiltration (UF)	BOD_5	24.4
	COD	35.2
Reverse Osmosis (RO)/UV Disinfection	DOC	99.9
	O&G	99.8
	TSS	98.4
	Hetero-trophics	100
Ring Fixed Bed Bioreactor (RFBB)	BOD_5	77
	COD	80
	NH_4^+-N	42
Algal Treatment	COD	99.9
	TDS	19.4
	NH_4^+-N	93.1

Table 7. *Cont.*

Treatment Process	Parameter	Removal %
Moving Bio-Bed Reactor/UASB/Fluidized Immobilized Catalytic Carbon Oxidation/Chemo Autotrophic Activated Carbon	COD Protein Lipid O&G	99 99 100 100

2.1.3. Fruit and Vegetable Processing Industry

With valuable vitamins and minerals, fruits represent a remarkable portion of everyday diets. Processed fruits and vegetables represent a considerable share of the food market. In 2021, the global market of processed fruits and vegetables was around USD 105 billion, which is forecasted to increase steadily [46]. Fruit and vegetable processing aims to produce juice and other products and to extend the lifetime of raw materials through canning and drying. Figure 5 presents the various steps in the processing of fruits and vegetables.

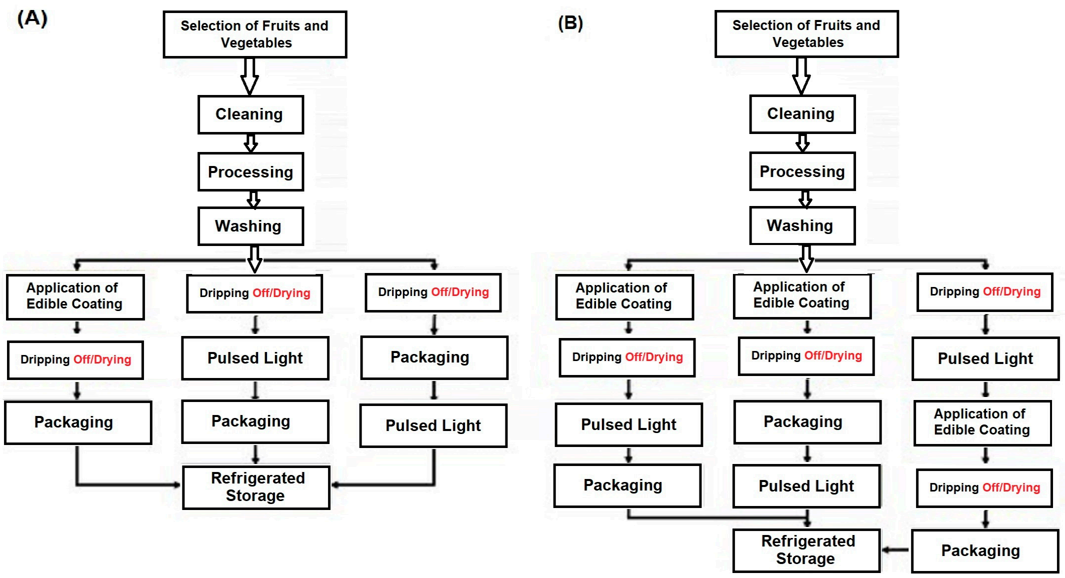

Figure 5. Diagram of fruit (**A**) and vegetable (**B**) processing.

The washing steps are the water-consuming steps in fruit and vegetables processing units, as shown in Figure 5. Primary washing, main washing, and rinsing consume around 18%, 53%, and 17% of the process water consumption, respectively. Domestic use and equipment cleaning are approximately 12% of the total water consumption. The water consumption in fruit and vegetable processing may range 1.5–5 m^3 for each ton of product according to the feedstock and final product characteristics.

The wastewater contains suspended solids from soil and dirt, organic loads from biological elements such as leaves, branches, and rotten fruits, TN and TP from fertilizers, and COD from pesticides [47,48]. Table 8 recaps the characterizations of the wastewater produced during fruit and vegetable processing. Wastewater from fruit and vegetable processing units is highly polluted and requires efficient treatment before it can be discharged into the environment or recycled for further use. Combining biological and chemical treatment methods are needed to accomplish the desired removal and treatment efficiency. Table 9 displays wastewater treatment processes used in fruit and vegetable processing units. The highest removal efficiency can be achieved using hybrid biological-physiochemical methods.

Table 8. Characterizations of wastewater generated during fruit and vegetable processing.

Parameter	R (1)	R (2)	R (3)
COD (mg/L)	22,300	21,040	10,913
BOD_5 (mg/L)	14,300	13,900	6900
TS (mg/L)	12,400	4590	2100
TN (mg/L)	220	na	252
TP (mg/L)	46	512.4	20.8

Table 9. Technologies employed in fruit and vegetable industry for the treatment of wastewater.

Method	Parameter	Removal (%)
Aqueous phase reforming	COD	79.7
	TOC	94.9
Fenton	COD	70.2
	Polyphenol	36.1
Electrocoagulation	COD	66
	Color	98
Fenton/Coagulation	COD	80
	Turbidity	99
	TSS	95
Up-flow anaerobic stage reactor and Activated sludge	COD	97.5
	BOD_5	99.2
	TSS	94.5
	O&G	98.9
Aerobic with Coagulation	COD	99.6
	Turbidity	94.4
Immobilized Cell Bioreactor	COD	89.5
Plasma	COD	93.3
	Endotoxin	90.2

2.1.4. Edible Oils Industry

Edible oils are used for daily cooking, produced from natural or synthetic sources (synthesized fats). Edible oils from natural sources are more widely used since they are associated with fewer health risks and a simple production process compared to edible oils from synthetic fats [49]. Statistics indicate an increasing demand for soybean, palm, and rapeseed oil. In 2019, the consumption of palm, soybean, and rapeseed reached 71.48, 55.46, and 45.27 million tons, respectively [50,51].

Extraction of edible oil from seeds and vegetables takes place in three main steps, including pretreatment (preparation), pressing (extraction), and refining [52,53]. Figure 6 shows a diagram of the general procedure of edible oil extraction from seeds and vegetables.

During the pretreatment step, biological and chemical substances that may interfere with oil extraction are removed, including optimizing the humidity content and cell wall breakage. During the pressing/extraction step, lipids are separated from the seeds, which can be achieved using high-pressure extraction, thermal treatment, milling, solvent extraction, milling, or enzymatic extraction. Finally, the smoking point, color, and clarity are improved during the refining step, which can be achieved using physical and chemical processes such as bleaching, neutralization, degumming, dewaxing, and deodorizing [54,55]. Water consumption mostly takes place in the pretreatment and refining steps. The process water is used for steam generation, cooling, and washing. Table 10 summarizes the average water consumption and wastewater generation in the edible oil extraction process.

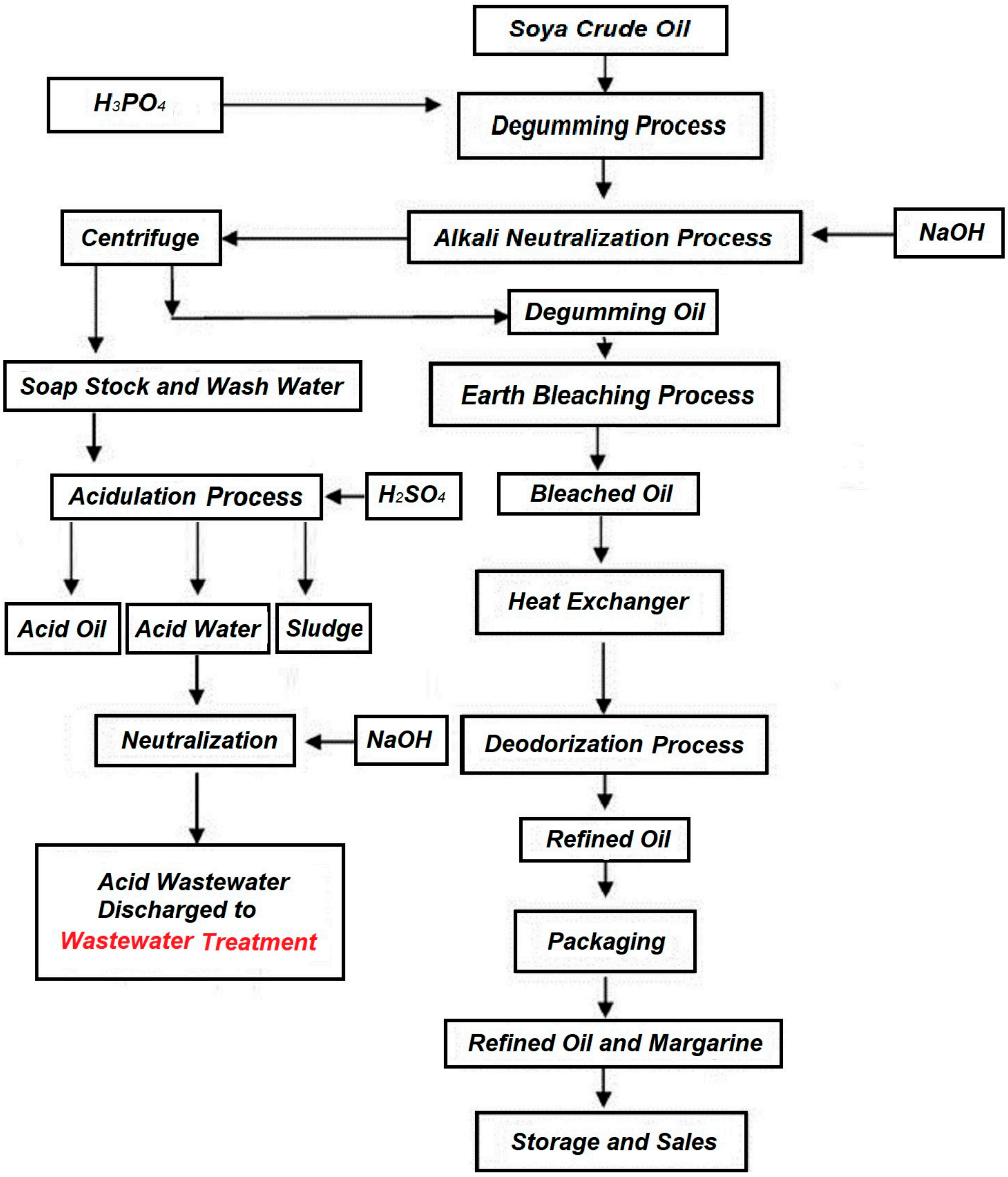

Figure 6. Edible oil production diagram.

Table 10. Average water requirement and wastewater generation.

Oil	Water Needed for Each Ton of Produced Oil (m^3)	Wastewater Generated per Ton of Seed (m^3)
Palm	2.450	0.87
Soybean	3.365	8.5
Rapeseed	1.860	0.85

The wastewater generated during edible oil extraction is characterized by high levels of COD, BOD_5, TN, TP, TDS, TSS, oil, and grease. Wastewater generated during edible oil extraction is a nontoxic waste since edible oil extraction does not involve any chemical use. Table 11 shows characterizations of wastewater in various oil extraction units. Due to the existence of fatty acids in edible oils, BOD_5, COD, oil, and grease levels are quite high in the edible oil extraction effluent. In contrast, proteins in seeds lead to a higher level of TN. Higher levels of TN and TP are attributed to the fertilizers used during seed/vegetable farming. The presence of TSS is attributed to soil, debris from trees, fruit, and dust washed out during the washing step.

Table 11. Characteristics of edible oil wastewater [51].

Parameter	Palm Oil	Soybean Oil	Rapeseed Oil
pH	3.4–5.2	4.2	6.3–7.2
BOD_5 (mg/L)	10,250–43,750	4340	4300–4650
COD (mg/L)	15,000–100,000	17,000	13,800–15,000
TS (mg/L)	5000–54,000	6700	3800–4100
TN (mg/L)	180–1400	na	na
TP (mg/L)	180	na	62
O&G (mg/L)	4000	1550	3600–3900

A combination of biological and physiochemical treatment methods is necessary for developing an efficient treatment of wastewater generated during edible oil extraction. As indicated by the low biodegradability index of wastewater (low ratio of BOD_5/COD), a single-step biological treatment method will not be enough to achieve efficient wastewater treatment [50]. Table 12 indicates various treatment methods in this field.

Table 12. Edible oil effluent treatment processes.

Process	Oil	Parameter	Removal (%)
Magnetic field and Adsorption	Palm	Color TSS COD	39 61 46
Microbial fuel cells + Biological aerated filters	Palm	NH_3-N COD	93.6 96.5
UASB–Hollow-centered packed bed (HCPB)	Palm	COD	86.7
UASB-HCPB	Palm	BOD_5 COD	90 88
Flocculation	Palm	TSS Turbidity COD Color	82.97 88.62 53.23 91.76
Algal Treatment	Palm	COD	71
Fenton advanced oxidation process (AOP)	Palm	COD	85
Electrocoagulation—Peroxidation	Palm	Color TSS COD	96.8 100 71.3
SBR	Palm	BOD_5 COD TSS	96 98 99
Ultrafiltration + Adsorption	Palm	TDS TSS COD BOD_5 Turbidity	47 71 42 63 63.3
Algal Process	Palm	TN Phosphate TOC COD	86 85 77 48
The integrated 2-phase anaerobic reactor	Soybean	COD	80
Yeast Treatment	Soybean	COD	94
Internal circulation-anoxic/oxic coupling reactor	Soybean	COD TN	90 98

Table 12. *Cont.*

Process	Oil	Parameter	Removal (%)
Continuous aerobic/anaerobic in MBBR	Soybean	COD TN	94.4 76
Algal treatment	Soybean	COD TN	77.8 89
Electrocoagulation and Electro-oxidation	Rapeseed	CODs TSS DOC	99 100 95
Electrochemical Peroxidation	Rapeseed	CODs TSS DOC	77 100 86
Photo-Fenton	Rapeseed	COD TOC	80 70
Hybrid TiO_2/UV/ultrafiltration	Rapeseed	COD O&G	82 86
Microbial fuel cell	Vegetable	COD TSS Phosphate Turbidity	90 64 73.6 91.5

2.1.5. Dairy Industries

Due to the significant variation in dairy products, including, milk, cheese, cream, butter, yogurt, and powdered milk, several production methods and processes are used. Figure 7 illustrates the flow diagram of a dairy production process to produce primary dairy products [56–60]. To understand the variety in dairy processes, around 500 types of cheese are produced globally, resulting in several wastewater treatment processes based on the initial feedstock and the final product. The whey generated in the cheese industry varies in quantity based on the type of cheese produced; for hard cheese such as cheddar cheese, whey is produced in large amounts, whereas the whey generated during soft cheese production is quite limited.

The wastewater generated during the dairy industry may range between 0.5 and 20.5 L per kg of the dairy product. The wide range of wastewater production indicates significant variation in the dairy industry based on the composition and variety of the ultimate products. Table 13 shows water consumption and wastewater generation for different dairy production units [61–65]. Developing wastewater management methods and strategies is essential due to the large water consumption and the contaminants' varying load and nature. Table 14 shows the characteristics of a multi-product dairy processing factory effluent, as the typical specifications of wastewater in milk processing units [66].

Table 13. Water demand in dairy processing.

Product	Water Utilization	Unit
Milk and dairy drinks	0.5–4.1	L W/L milk
Cheese	0.6–2.9	L W/L milk
Powdered products	0.1–2.7	L W/L milk
Frozen milk products	15.7	L W/kg of product
Cream	3.3	L W/kg of product
Butter	4	L W/kg of product
Yogurt and fluid products	1.2	L W/kg of product

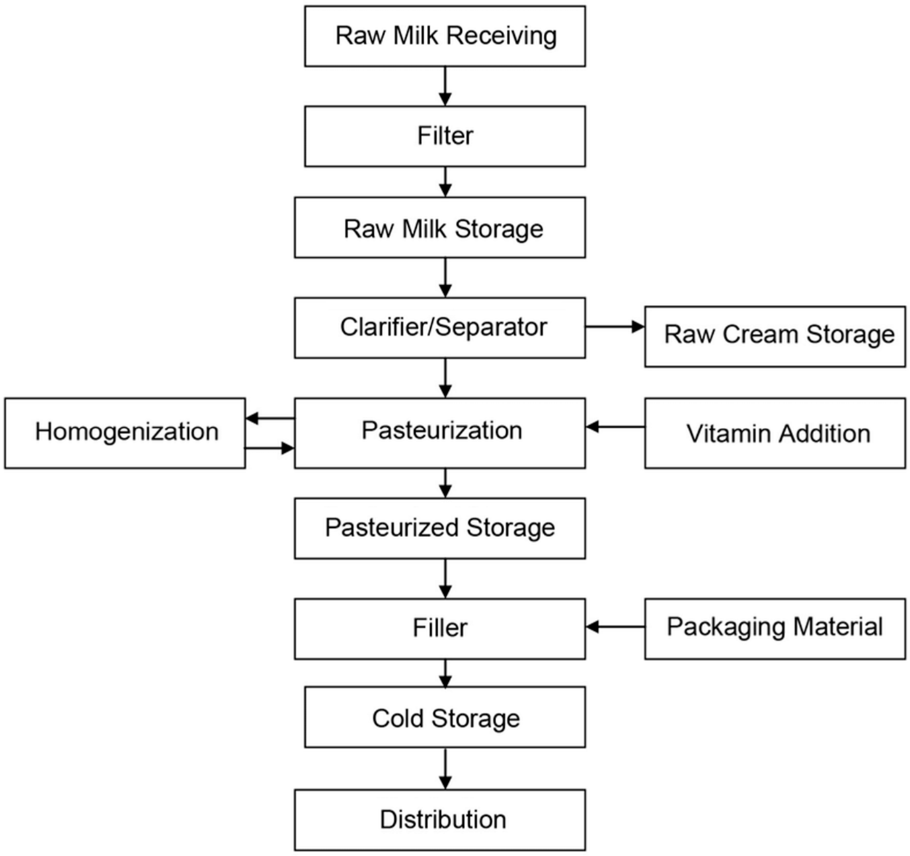

Figure 7. Process diagram of the dairy industry.

Table 14. Wastewater characterization in dairy production.

Parameter (mg/L)	Range	Average
COD	1906–2513	2131
BOD_5	1372–1809	1536
TN	246–297	273
TP	55–73	60
TN	218–241	233
NO_3-N	22–48	38

The wastewater generated from the dairy processing units will include high COD, BOD_5, and TN, resulting primarily from cheese production [67]. Several parameters may affect the nature and loading of wastewater, including the processed milk amount, product type, production processes, and washing mechanism [68–70]. Due to the high TN, COD, and BOD_5, biological treatment methods are very common in the dairy processing unit. Physicochemical treatment methods, including gravitational methods, membrane-based methods, and adsorption, are used to improve the effectiveness of the treatment method as an auxiliary process for biological treatment methods [71].

Advanced oxidation processes can efficiently treat the high COD effluent from dairy wastewater units. Activated sludge, SBRs, aerated lagoons, up-flow anaerobic sludge blankets (UASB), and anaerobic filters are biological methods that can efficiently reduce TN [72,73]. Algal treatment and microalgae cultivation units are necessary for managing dairy processing unit wastewater treatment to reduce the high concentration of nutrients. Table 15 summarizes the biological methods used for dairy processing wastewater treatment.

Table 15. Biological treatment processes employed in dairy wastewater treatment.

Method	Parameter	Treatment (%)
Algal Treatment	COD TN Phosphate COD $NO_3{}^{-}$-N TP TDS	76.77 92.15 100 95.1 79.7 98.1 22.8
Algal Treatment	COD TN Phosphate	64.47 86.21 89.83
SBBR	COD Phosphate NH_3-N	81.8 94 85.1
SBR	COD Phosphate $NH_4{}^{+}$-N	63.5 88 66
UAASB	COD Phosphate $NH_4{}^{+}$-N	71.27 96.54 95.88
Airlift reactor with aerobic granular sludge	COD BOD_5 TN	81–93 85–94 52–80
Combined UASB and Membrane bioreactor (MBR)	COD	95–99
Hybrid MBR	COD	95
MBR	COD BOD_5 $NH_4{}^{+}$-N	94.1 98 100
Floating activated sludge	COD	77
Up-flow anaerobic/aerobic/anoxic bioreactor	COD TN TP	>90 >50 >50
Aerobic sequencing batch flexible fiber biofilm reactor	COD TSS	98 99
Airlift bioreactor	COD TN TP	99 79 63

2.1.6. Grain Milling Industry

Corn, wheat, and rice, the most consumed grains, produced globally in 2019 were about 1100, 735, and 496 $\times$ 10^6 tons, respectively. Grains are used to produce starch, flour, proteins, carbohydrates, and animal food. Milled grains are produced and used in several types of foods, such as pasta and bread [74].

Grain milling can be categorized into dry milling using cylinder or disc mills; wet milling using cylinder or disc mills; and wet milling with stone mills. Water demand and wastewater generation vary considerably based on the nature of the grain milling process. Figure 8 illustrates the schematic of the general grain milling process.

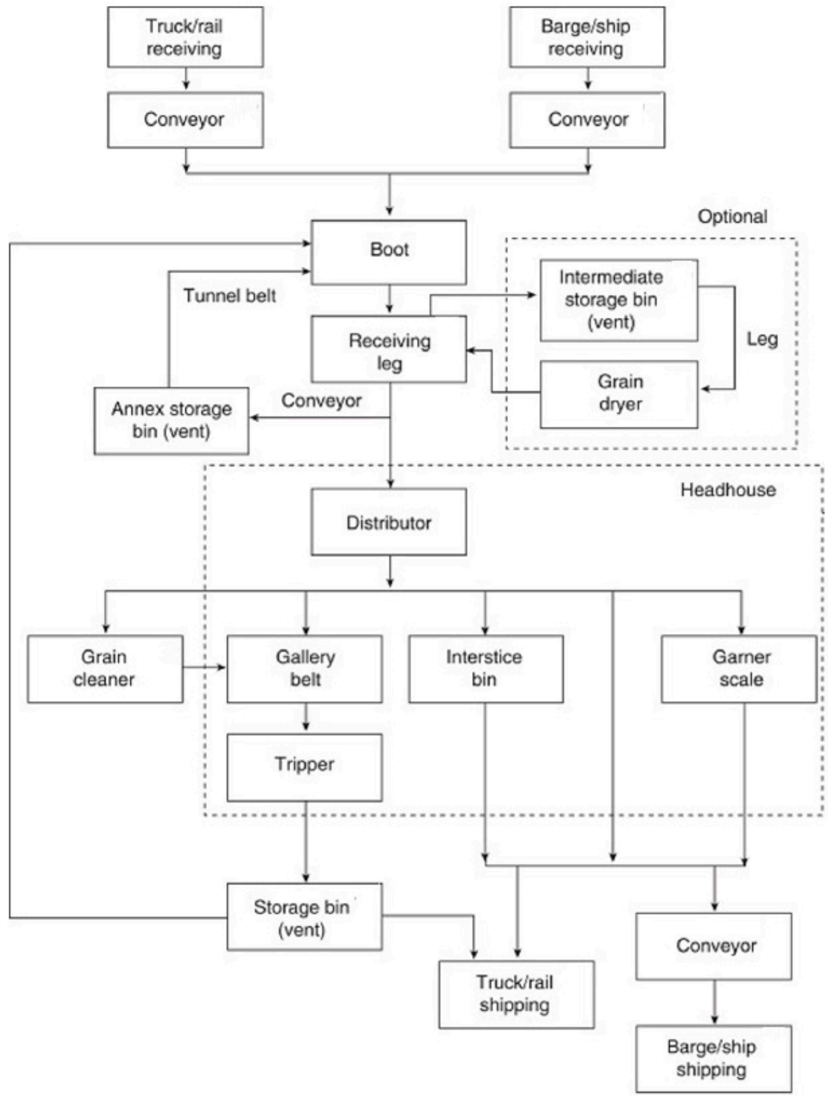

Figure 8. Diagram of the grain milling process.

Water demand is determined based on seed humidity. The grain humidity should be in the range of 14–16% by weight. In dry grain milling, water is used for product tempering and conditioning and the seeds are separated from the endosperm. Wastewater generation in dry mills is lower compared to wet milling, and water use is limited to site and device washing. In wet milling, a huge quantity of water is used in the washing stage, generating a large quantity of wastewater. Table 16 displays water demand and wastewater generation during the corn, wheat, and rice wet milling [75,76].

Table 16. Water demand and wastewater generation in grain wet milling units.

Grain	Water Requirement (m^3 per Ton of Grain)	Wastewater Generation (m^3 per Ton of Grain)
Corn	4	3.6
Wheat	0.07	0.06
Rice	1.3	0.3

The wastewater generated from grain milling contains high loadings of COD, BOD_5, TDS, TSS, oil, and grease. The high loadings are expected due to the presence of proteins and carbohydrates mainly produced during the washing step. Table 17 summarizes the wastewater characteristics for different grain seed milling processes.

Table 17. Wastewater characteristics for different grain milling processes.

Grain	Process	BOD_5 (mg/L)	COD (mg/L)	TSS (mg/L)	TDS (g/L)	O&G (mg/L)	pH
Corn	Wet	26,000	106,600	–	109	–	5.2
Wheat	Wet	614	1680	818	1.8	1038	7
Wheat	Dry	80	154	94	0.3	Nil	7.5
Rice	Wet	1200	1350	1100	0.7	–	7.5

Wastewater generated during grain milling is characterized by high loadings of organics, chemicals, and solids; different treatment methods are needed to achieve efficient treatment of wastewater, as shown in Table 18. Corn contains higher concentrations of carbohydrates and protein, leading to higher concentrations in the generated wastewater during corn milling, which requires more extensive wastewater treatment. The ion exchange process can be used to enhance the glucose and fructose syrup's clarity in corn refineries, resulting in higher TDS [12].

Table 18. Wastewater treatment processes in grain milling units.

Grain	Process	Source of Wastewater	Parameter	Efficiency of Removal (%)
Wheat	Filtration+ centrifugation+ filtration column + UV	Washing wastewater	BOD_5 DO Conductivity Turbidity	45 71 13 82
Wheat	Ozone oxidation	Entire wastewater	Phenols	80
Wheat	Coagulation	Entire wastewater	Turbidity	98
Corn	micro-electrolysis + two-phase anaerobic-aerobic + electrolysis	Modified and oxidized starch wastewater	COD	96
Corn	Internal circulation anaerobic + two-stage AO biochemical + modified Fenton	Starch wastewater	COD NH_3-N TN	99.8 98.7 99
Corn	Sedimentation + microfiltration + reverse osmosis	Starch washing wastewater	TSS TS BOD_5	99.3 99.6 100
Corn	Algal treatment	Cationic starch wastewater	TSS TP	80 33
Rice	Ultrafiltration	Total wastewater	COD Color	63 67
Rice	Algal treatment	Parboiled rice wastewater	TP NH_3-N BOD_5 COD TDS	93.9 100 98.7 91.6 93.5
Rice	Algal treatment	Entire wastewater	TP TN	68.12 49.32

As shown in Table 18, biological treatment methods are more efficient for corn milling wastewater treatment, while physical treatment methods are more appropriate for wheat milling wastewater treatment. Algal treatment methods are proposed for grain processing wastewater characterized by high levels of nutrients and almost no heavy metals. Algal biomass can be used in several industries such as the food and pharmaceutical industries and as a feedstock for biofuel production.

2.1.7. Bakery Industry

The bakery industry has a remarkable place in daily diets around the globe [77]. The bakery industry is estimated at USD 311 billion in the United States. The feedstock used in the bakery industry includes sugar, flour, yeast, oil, water, salt, and preservatives [78]. Figure 9 shows the diagram of a typical bakery industry process.

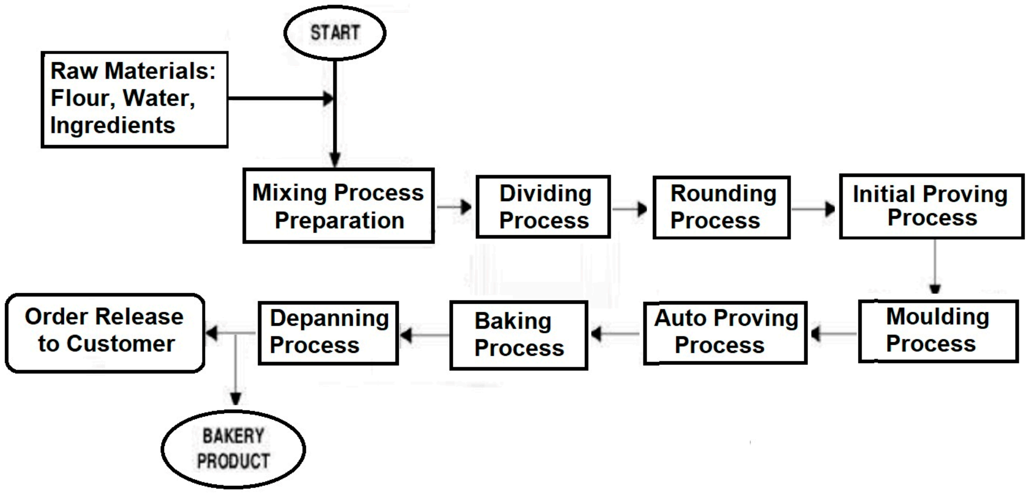

Figure 9. Diagram of the bakery industry.

The bakery unit usually includes the following production steps: mixing, fermentation, baking, and storage. Equipment washing is the main wastewater-producing activity. Based on the factory capacity and the products' range, water demand varies from 38 to 1140 m^3/day [78]. The ratio of water used for the bakery product in weight is around 10. Half of the water demand is used for non-process functions such as washing and cooling, usually discharged as wastewater. The bakery industry wastewater is biodegradable, containing an elevated organic loading resulting from a high proportion of BOD_5:N:P and BOD_5/COD. Carbohydrates and lipids are the major contaminants in wastewater from bakery industries, with a weight percentage of around 70% carbohydrates and 20% lipids, indicating the presence of high loadings of BOD_5 and COD. However, the carbohydrates and lipids recovered provide an excellent opportunity to develop an economical/cost-saving treatment method [79–81]. Table 19 displays the specification of wastewater from the bakery unit.

Table 19. Wastewater characteristics of the bakery industry.

Parameter, ($mg{\cdot}L^{-1}$)	[82]	[83]	[84]
pH	6	4.7–5.1	3.5–3.8
TSS	1180	6000	881–1124
TDS	3600		
BOD	2250	3200	1603–3389
COD	5700	7000	3984–9672
TN	60–90	36	
TP	30–100	7	
O&G	96	820	

The ratio of BOD_5/COD for bakery effluent is usually around 0.5; this ratio indicates the wastewater's biodegradability and the effectiveness of biological treatment of the effluent. The presence of high TSS and TDS indicates the need for pretreatment methods and physical treatment methods. Aerobic and anaerobic biological treatment will be needed, as noted in the TN and TP levels, as shown in Table 19. Table 20 demonstrates the outstanding accomplishments in bakery wastewater treatment [85].

Table 20. Technologies for treating wastewater from bakery industry.

Process	Stage	Parameter	Removal Efficiency (%)
Electrochemical	Pre-treatment	COD Turbidity	6–8 32–98
Constructed wetland	Biological treatment	TKN TP BOD_5 TSS O&G	57 65 92 69 99
UASB	Biological treatment	COD	83.1
UASB	Biological treatment	COD	92

Bakery effluent treatment is not discussed in the literature in detail, which raises the need for more work to implement the circular economy concept for treating the bakery units' wastewater. This wastewater could be a source of valuable materials such as fats, oils, and carbohydrates.

2.2. Other Food Processing Industries

In addition to the seven main food industry categories discussed previously, other food industries such as tea, sugar, cocoa, seasoning coffee, and prepared meals are usually classified as other food processing industries. Sugar, tea, and coffee will be reviewed due to their potential importance in the world food chain supply. Each industry is unique regarding water demand and wastewater generated through the process.

2.2.1. Sugar Production

A total of 174 million tons of sugar is produced annually. Around 80% of global sugar is produced from cane, and the remaining originates from beets [86,87]. The nature of the sugar extraction process may vary depending on the feedstock, affecting water demand and wastewater generation. Figure 10 shows the sugar production process from cane and beets, including water consumption and wastewater generation.

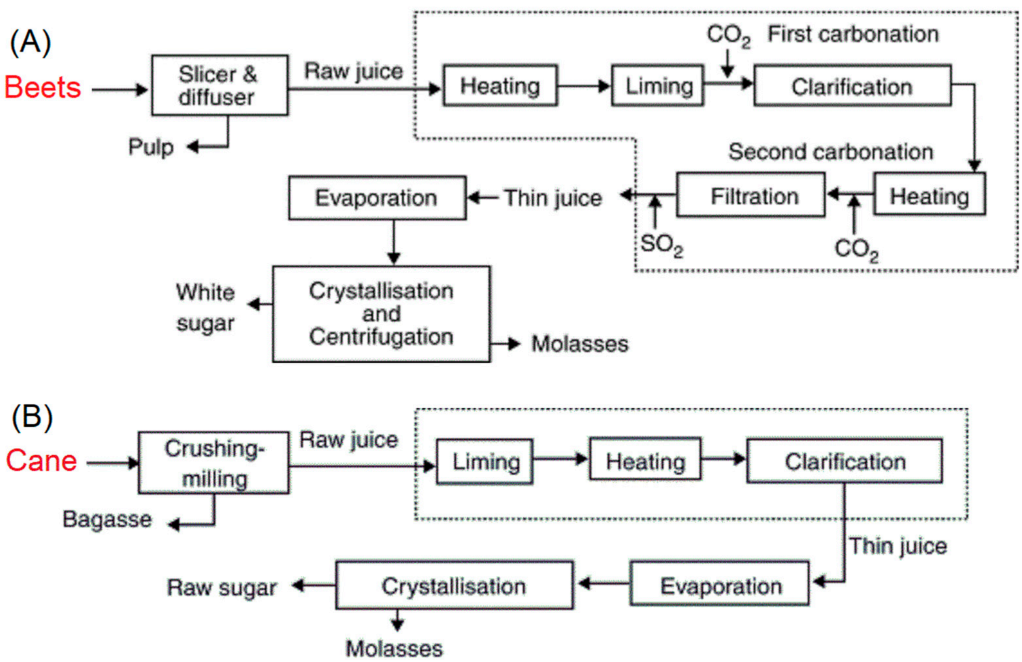

Figure 10. Sugar production from (**A**) beets and (**B**) sugarcane.

During sugar extraction from beets, water is used for beet washing and transportation, generating an effluent that contains high levels of BOD_5 and TSS (from beetroots covered with mud and soil). Recently, dry cleaning and mechanical conveyors have been developed to minimize energy and water demand. During sugar extraction from sugarcane, water consumption occurs mostly during the wet milling of sugarcane when the imbibition water is added [88]. The water consumption in sugar production may range from 1.3 to 4.36 and from 3 to 10 m^3 per ton for sugarcane and beet extraction, respectively. The water demand varies according to the initial conditions of the feedstock, involving humidity and dust. Around 20% of the water demand is discharged as wastewater when sugar is extracted from sugarcane, whereas 80% is discharged when sugar is produced from beets. High COD, BOD_5, COD, TSS, and unpleasant odor characterize the wastewater generated during sugar extraction from beets. Table 21 shows the wastewater characteristics generated in sugar processing factories [88].

Table 21. Wastewater characteristics in the sugar production industry.

Parameter	Beet	Cane
CODt (mg/L)	6621 ± 113.2	965–11,640
CODs (mg/L)	6165 ± 517.1	799–10,640
BOD_5 (mg/L)	3837	1939–2347
TKN (mg/L)	10	20–43
TP (mg/L)	2.7	3–31
TSS (mg/L)	665 ± 21.2	288–5030
VSS (mg/L)	335 ± 7.1	110–1990
pH	6.82	4.4–4.6

Biological treatment methods or a combination of physiochemical and biological treatment methods should be employed for treating the wastewater generated from the sugar industry since this wastewater is characterized by high levels of BOD_5, COD, and TSS.

2.2.2. Tea Industry

Tea is produced from the leaves of the tea plant [89]. Tea leaves are the primary feedstock for producing tea products, including post-fermented and black tea. Figure 11 indicates the tea production process schematically. Around 1.4 m^3 of water is consumed for each ton of tea produced, usually during oxidation and machine cleaning. The consumed water is discharged chiefly as wastewater. The wastewater is usually characterized by intense color and turbidity, including organic/inorganic chemicals starting from unprocessed and treated tea, grease/oil, detergents, and metallic particles, as demonstrated in Table 22.

Table 22. Wastewater characteristics in tea industries.

Parameter	R (1)	R (2)
Turbidity (NTU)	11,549	9210
COD (mg/L)	9850	628
BOD_5 (mg/L)	na	193.4
TSS (mg/L)	8945	na
TOC (mg/L)	5057	na
pH	na	6.69
Conductivity ($\mu S \cdot cm^{-1}$)	na	317

Physiochemical treatment methods are recommended for treating in the tea industry, considering the low COD and BOD_5 and associated minimal operating cost. For removing dyes and other components, such as phenols, AOPs showed the best removal efficiency [89].

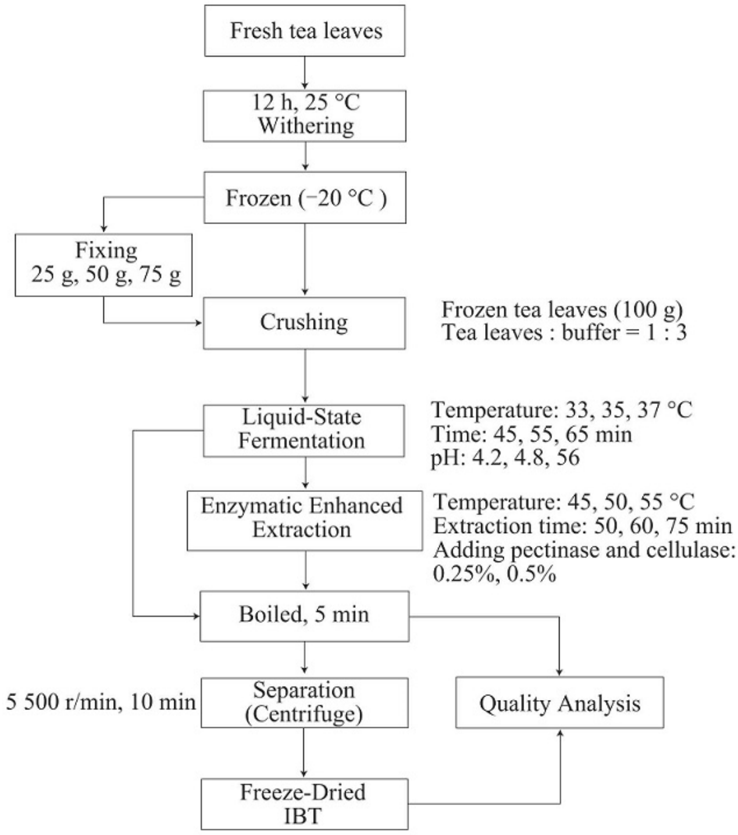

Figure 11. Diagram of tea production.

2.2.3. Coffee Industry

Around 10 million tons of coffee is consumed annually worldwide, and this is increasing annually by 1.5% [90]. Two different methods of coffee processing are used: (1) the dry process and (2) the wet process, which varies considerably in terms of water and energy demands. Figure 12 shows the coffee processing phases.

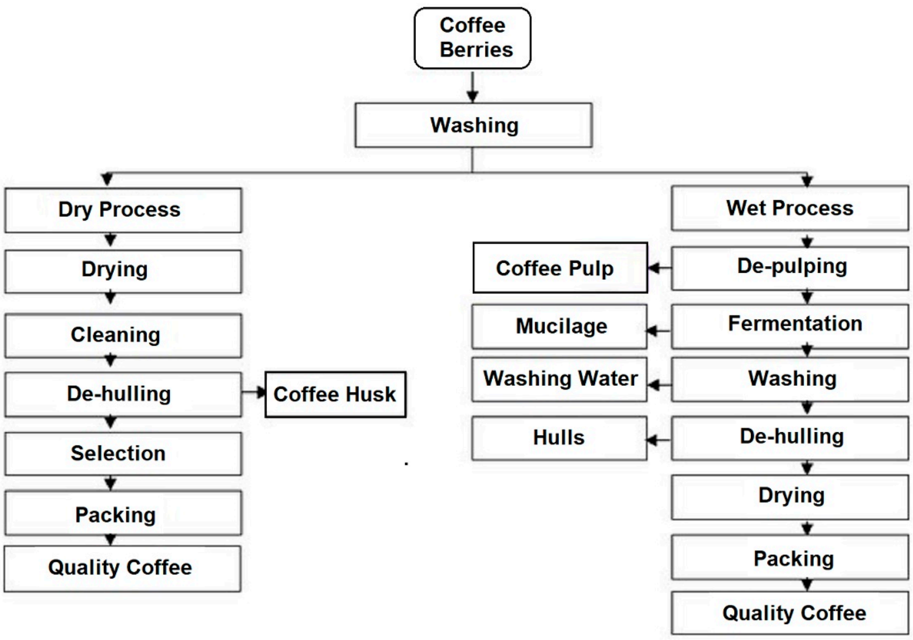

Figure 12. Diagram of coffee processing.

Coffee bean processing involves the husks of coffee cherries removal and the beans drying. In dry coffee production, the husks of cherries are removed mechanically, and the drying is achieved using solar energy over two weeks. During wet coffee production, water is used in large amounts for sorting, skin removal, and washing coffee cherries [91]. Then, pulp removal can be achieved using machine-assisted aqua-pulping or the classic ferment-and-wash method. In the ferment-and-wash method, a large amount of water is used for bean fermentation and washing. Finally, coffee beans are washed in tanks or washing machines. During the wet process, around 12.5 m^3 of water is used per ton of green coffee. The amount of wastewater generated is estimated at 3 m^3 of highly polluted wastewater per ton of green coffee used. Table 23 shows the wastewater characteristics of coffee processing [92].

Table 23. Characteristics of wastewater from coffee processing.

Type	pH	BOD_5 (g/L)	COD (g/L)	TS (g/L)	TP (mg/L)	TN (g/L)
Arabica	3.9–4.1	3.6–15.2	6.2–31.5	5.4–13.4	5–8.8	0.1–0.12
Robusta	4.1–4.6	10.8–13.2	15–18.1	6.3–12	4–7.3	0.02–0.04

A perceptible quantity of BOD_5 and COD generated during coffee processing necessitates advanced methods for wastewater treatment compared to the treatment method used in tea factories. Table 24 shows the most recent research on sugar, tea, and coffee processing/production wastewater treatment.

Table 24. Technologies used for treating wastewater generated in sugar, tea, and coffee industries [50].

Characteristics of Wastewater	Method	Parameter	Removal Efficiency (%)
Sugar	UASB	COD	78–82
Sugar	Electrochemical	COD Turbidity	84 86
Sugar	Anaerobic granular sludge	COD	92–95
Sugar	Electrochemical peroxidation	COD COD TOC TOC	65 64 66 63
Sugar	Chemical oxidation + electro-oxidation	COD Turbidity	81 83.5
Sugar	Electrochemical reactor	COD Turbidity	90 93.5
Sugar	Algal treatment	COD BOD_5 TDS Turbidity	37.91 25.69 48.51 39.2
Tea	Membrane treatment	Turbidity COD TOC	>99.9 >99.9 >99.9
Tea	Photo-Fenton	COD	88–99.3
Tea	UV photo-Fenton	TOC COD Polyphenol	96 100 97
Tea	Adsorption + AOP	Color	98
Coffee	UV photo-Fenton	TOC	93

Table 24. *Cont.*

Characteristics of Wastewater	Method	Parameter	Removal Efficiency (%)
Coffee	Photo-Fenton + UASB	BOD_5	95
Coffee	Chemical flocculation + AOP	COD	87
Coffee	Adsorption	COD BOD_5	99 99
Coffee	Membrane treatment	COD Conductivity	97 99
Coffee	Chemical coagulation + electro-oxidation	TOC COD	95 97
Coffee	Fenton's + coagulation	TOC COD BOD_5	76.2 76.5 66.3

2.3. Different Wastewater Treatment Solutions

2.3.1. Treatment Unit Inlet Composition

The primary contaminants in food-processing wastewater are the organic molecules, which can be considered a nontoxic effluent [93]. However, low concentrations of cleaning products and other toxic compounds could be found unsuitable for regular treatment methods. For example, soybean processing generates around 10 L of wastewater, and tofu curd residues as a solid waste around 0.25 kg. Tofu-containing wastewater contains complex polysaccharides rich in nitrogen and contains low carbon, requiring a pretreatment step before conventional biological and physical treatment methods. Whey produced during cheese production is rich in lactose that cannot be fermented using traditional fermentation methods [94].

During potato processing, wastewater contains remarkable levels of starch, which can be used for alcohol production [95]. Tomato, grape, and apple processing waste generate a pomace that can be used as animal feed [96]. However, many of these wastes have some degree of utilization. Recently, several technologies have been developed to reduce pomace [97]. One of the most promising technologies is converting pomace into alcohol. However, choosing the optimum treatment method depends on the waste's organic composition, which is vital for producing valuable products. Higher oxygen demand and carbohydrate content substrate will require an extensive treatment process, and the substrate can be used for generating alcohol. The optimum sugar concentration of substrates used for alcohol production should be 15–20%. Higher sugar concentration substrates can be diluted or pretreated using acid hydrolysis, heat treatment, or enzymatic hydrolysis [98].

A balanced carbon-to-nitrogen ratio (C/N) should be maintained before the substrate is fed to fermentation to avoid antagonistic effects. The balance can be kept by mixing several wastewater streams, such as the co-fermentation of corn with soy skim milk [99,100]. In many cases, food-processing wastewater does not have enough nitrogen content, which may require the addition of other supplements to ensure a balanced substrate for microorganisms during the fermentation process. Adding lipids improves the production of ethanol by around 14% [101]. However, adding lipids to the substrate should be considered based on the nature of the wastewater; for example, a low concentration of lipids in molasses stimulated ethanol production. In general, studying the composition of the wastewater will help in the careful design of an optimum process.

The following Tables 25–27 show the primary physical and chemical properties and composition of organic molecules usually found in wastewater generated during food processing. Wastewater rich in carbohydrates is an ideal substrate for alcohol production—usually, carbohydrates in food-processing wastewater range from 0.45% w/v

to 4.3% w/v. thus, sugar or nitrogen sources should be added to provide enough nutrients for the microorganisms. The solid-containing wastewater contains a higher carbohydrate content of 29.2% w/w to 54.6% w/w; this wastewater represents an excellent raw material for alcohol production. Liquid effluents with low hydrocarbon content act as dilution agents or replacements for process water. However, nitrogen supplements could be needed to meet the growth requirements of the microorganism [102].

Solid-rich waste and liquid wastewater establish a perfect medium for producing alcohol. An economic analysis should be conducted before developing such an industrial-scale process.

Organic Contents

The organic content of food-processing waste is affected by several metal ions, which play a primary part in the metabolism of microorganisms. Metal ions participate in biocatalytic reactions within growth enzymes, keeping the cell osmotic pressure. The deficiency or overload of mineral ions may result in cell death and limit alcohol production. Consequently, the concentration of minerals in the waste directly affects alcohol production. Whey substrate requires the addition of ferrous sulfate or ferric chloride, which could increase the butanol yield from 0.06 to 7.13 g/L and 4.32 g/L, respectively [103].

Inorganic Content (Minerals)

Adding minerals to the substrate is essential to maintain a high yield and to increase the selectivity of the desired product, such as the butanol-to-acetone ratio in whey fermentation. Minerals are essential for yeast strain stability and for improving ethanol production. A higher yield of the desired product is essential for reducing the energy demand of the process. The optimum concentration of mineral ions can be determined using the statistical design of the experiment. To optimize the concentration, several studies were found in the literature exploring ethanol production from molasses, seaweed, and bagasse [103].

Metal absorption is the limiting step in alcohol tolerance levels [103]. The tables above show the mineral composition of various FPWs. Mineral concentrations are higher in waste streams rich in solids; such waste can be used as a complete production medium for alcohol, with a limited need for adding mineral ions. Magnesium and zinc play a significant role in the glycolytic pathway and cell stability and regulate yeast stress during ethanol fermentation. Usually, solid waste does not have enough zinc to maintain the microorganisms' growth, except grape pomace. For all food wastes listed except grape pomace, zinc supplements must be added to streams that may contain some solid waste.

2.3.2. Technologies for Food Industry Wastewater Treatment and Reuse

Water is a crucial component in various industrial processes worldwide. However, it is important to implement appropriate treatment techniques to prevent the release of contaminants into the environment [103–105]. Shockingly, nearly 80% of global wastewater remains insufficiently treated. Industrial pollutants such as suspended solids, grease, oil, and particles contribute to elevated COD, pH, BOD_5, and turbidity, ultimately leading to surface and groundwater pollution. Such hazardous pollution poses a severe threat to human health. Therefore, it is imperative to develop effective treatment methods to avoid the discharge of industrial pollutants into the environment.

Figure 13 gives a brief outline of the different technologies currently being used to process food industry wastewater. As described by the Council Directive 2020/741/EC [106], a single technology or a group of numerous technologies can be used in conjunction with one another to meet the discharge criteria established for various physical, chemical, and biological parameters. The technology to be used typically depends on the extent of contaminants present in the wastewater [104].

Table 25. Characteristics of food processing liquid effluent.

Parameters	Tofu Processing Effluent				Sweet Whey				Acid Whey				Potato Processing Effluent				Sweet Beverage (Soda)			
	Med	**Mean**	**SD**	**N**	**Med**	**Mean**	**SD**	**N**	**Med**	**Mean**	**SD**	**N**	**Med**	**Mean**	**SD**	**N**	**Med**	**Mean**	**SD**	**N**
Carbohydrates [g/L]	6.6	8.3	7.1	4	33.5	33.1	13.1	10	43.7	41.5	6.0	8	16.8	16.8	0.3	2	4.5	8.0	8.8	3
Proteins, g/L	1.2	1.2	0.8	6	4.5	4.9	2	11	7.9	7.6	1.7	8	2.4	3.3	2.5	4		0.2		1
Lipids, g/L		3.8		1	3.9	3.9	2.6	10	5.5	5.6	2.5	7		0.2		1				0
pH	5	5.2	0.4	5	4.2	4.4	0.9	9		4.7		1	5.8	5.5	0.7	5	9.8	9.8	0.8	6
Ash, %*w*/*w*	1.7	1.7	0.4	3	0.7	1.0	0.6	7	0.5	0.5	0.1	7	0.2	0.2	0	2	0.1	0.1	0.1	5
Total solids,% *w*/*w*		1.7		2	6.7	6.3	0.9	6	6.4	6.6	0.5	6	0.8	1.0	1.0	4		0.1		2
COD, g/L	19.9	22.6	13.3	7	69.3	67.1	4.8	4		79.5		1	5.9	6.0	3.8	4	7.4	1.3	1.3	8
Parameters	**Tomato Pomace**				**Apple Pomace**				**Grape Pomace**				**Spent Coffee Grounds**				**Bread Waste**			
	Med	**Mean**	**SD**	**N**	**Med**	**Mean**	**SD**	**N**	**Med**	**Mean**	**SD**	**N**	**Med**	**Mean**	**SD**	**N**	**Med**	**Mean**	**SD**	**N**
Carbohydrates, %*w*/*w*	33.9	36.1	10.3	9	42.8	44	6	10	29.2	28.1	5.0	5	49.5	51.2	6.5	6	54.6	58.9	14.4	6
Proteins, %*w*/*w*	21	16.4	9.1	13	4.3	4.3	1.3	11	10.5	9.9	2.5	7	16.4	17	4.6	8	11.8	11	2.1	8
Lipids, %*w*/*w*	13.4	11.3	5.3	7	2.7	2.9	1.2	9	6.7	6.9	1.8	7	24	22.2	5.7	8	1.8	1.8	0.4	4
pH		2.9		1		3.9		1		4.4	0.8	2		5.3	0.6	2				
Ash, %*w*/*w*	4.1	5.0	2.1	6	1.5	1.5	1.0	9	4.8	4.8	2.0	6	1.5	1.5	0.2	5	1.80	1.7	0.5	7
Total solids, % *w*/*w*	14.5	17.8	7.1	3	27.7	28.3	2.2	4		35.0		1	29.2	28.3	7.7	4	89	80.7	13.4	7
COD, g/kg	87.0	86.7	9.5	3	14.3	14.4	6.1	3		14.4		1		160		1				

Med: Median, SD: Standard deviation, N: number of reported values.

Table 26. Mineral content associated with liquid effluents.

Mineral Content, mg/L	Tofu Processing Effluent				Sweet Whey				Acid Whey				Potato Processing Effluent				Sweet Beverage (Soda)			
	Med	Mean	SD	N	Med	Mean	SD	N	Med	Mean	SD	N	Med	Mean	SD	N	Med	Mean	SD	N
Calcium		34.6		1	341	340	84	4	1100	1110	85	4		100		1		3.7		1
Magnesium		16.3	2	2	49	55	22	3		230		1		91.2		1		3.1		1
Sodium		127		1	386	366	82	4		1785	2	2		40		1		21.6		1
Potassium		861		1	1300	1250	240	3	1400	1367	153	3		35		1		4.3		1
Iron		9	1	2		2		1				0		0.2		1		0		1
Manganese		0		1				0		0.1		1		0.2		1		0		1
Phosphorous		15	1	2	440	700	521	3	540	540	198	3	169	268	295	3		1.3		1
Sulfur		2240	1	1				0				0	58	67	30	3		300		1
Zinc		0.5	0	2		0.3		2		2.2		1		0.5		1		0		1

Table 27. Minerals in water-rich solid stream.

Mineral Content, mg/kg	Tofu Processing Effluent				Sweet Whey				Acid Whey				Potato Processing Effluent				Sweet Beverage (Soda)			
	Med	Mean	SD	N	Med	Mean	SD	N	Med	Mean	SD	N	Med	Mean	SD	N	Med	Mean	SD	N
Calcium	5700	5297	1922	7	675	808	366	6	4400	4570	1164	3	777	1020	625	5	1358	1252	553	6
Magnesium		2310		2	388	390	174	6	1500	1643	682	4	1900	1515	820	5	700	731	519	4
Sodium		1820		2	100	855	1045	5	440	420	92	3	267	317	282	4	3150	3438	644	4
Potassium		8740		2	2300	3098	2649	5	1880	2027	711	3	8100	7635	3062	5	1600	2270	1521	5
Iron		384		2	30	30	6	3	50	41.3	31	3	85	136	131	4	93	230	239	5
Manganese		366		2	6	7	2	4	106	106	34	3	33	34	6.7	4		1.7		1
Phosphorous	4750	5466	1921	8	850	973	435	5	3400	3077	1120	3	1534	1442	394	5	1890	1945	420	4
Sulfur				0		1100		1		890		1	1600	2000	872	5				
Zinc		54		1	13	11	6	4		9800		1	12	12	3			20.5	8	2

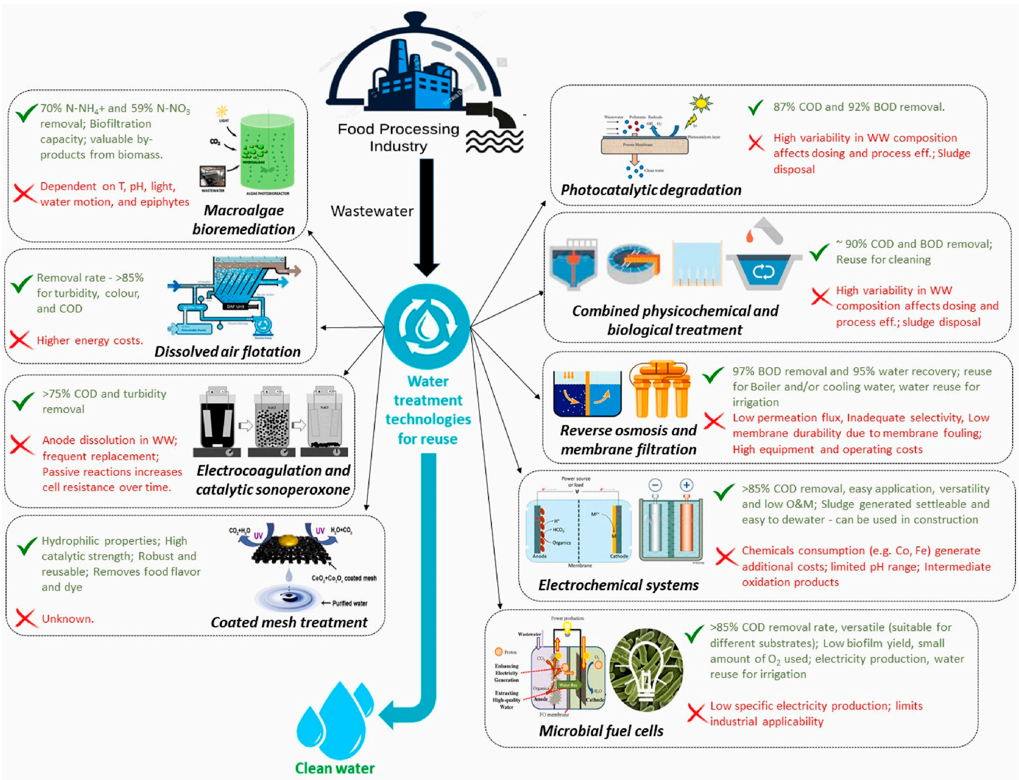

Figure 13. An outline of the different wastewater treatment technologies [12].

Figure 13 provides a concise overview of the various technologies presently employed for food industry wastewater treatment. According to Council Directive 2020/741/EC, either a single technology or a combination of multiple technologies can be employed synergistically to achieve compliance with the set discharge standards concerning diverse physical, chemical, and biological parameters. The selection of the appropriate technology usually hinges on the concentration of contaminants found in the wastewater [104].

Food industry wastewater treatment technologies and reuse, including physical, chemical, and biological treatment methods, are shown in Figure 13. Physical treatment involves the removal of large particles through sedimentation or filtration. The chemical treatment uses chemicals such as coagulants and flocculants to remove dissolved contaminants. Biological treatment uses microorganisms to break down organic pollutants. Advanced treatment technologies such as membrane filtration and ozone treatment can further treat wastewater to meet stringent reuse standards. The processed water can be reprocessed for non-potable purposes such as irrigation or industrial processes, thus reducing the strain on freshwater resources and promoting sustainable water management practices in the food industry [103–105].

2.4. Challenges and Factors for Selecting the Optimum Treatment Method

When selecting the optimum treatment method for wastewater, several challenges and factors must be considered: the wastewater characteristics, the type and amount of contaminants present, the size and scale of the treatment facility, and the available resources. Factors such as cost, energy requirements, and maintenance needs must also be considered, as they can affect the long-term viability and sustainability of the chosen treatment method. Furthermore, regulatory requirements and environmental concerns are critical factors that must be considered when selecting a wastewater treatment method. Wastewater management is a crucial part of food industries to enhance productivity and reduce environmental effects. Process integration methods are practical tools to decrease water demand and wastewater generation by considering the physiochemical characteristics of the system under study, including water demand and minimum acceptable threshold for particular contaminants [104].

Water pinch analysis and mathematical optimization are standard process integration methods to reduce water demand and wastewater generation [98]. To achieve sustainability in food industries, the process should be modified to ensure higher productivity, lower resource consumption, and minimal environmental destruction [104,105]. Recently, process integration methods have attracted significant attention in food industries. Mixed integer nonlinear programming to manage water/wastewater in milk-processing units reduced water demand and wastewater generation by around 33 and 85%, respectively, by examining each unit's needs and integrating the overall process [82]. The literature highlights the necessity to gather complete qualitative and quantitative information on water/wastewater flow rates, quality, and placement in the production unit. By employing water pinch analysis and mathematical optimization, 30% of water demand and wastewater generation were reduced in a corn refinery by developing a wastewater management system, which could be an ideal start for other food processing units [105]. Using a similar analogy, BOD_5 was used as the critical contaminant for developing a wastewater management system, reducing water demand and wastewater generation by around 43 and 66%, respectively [82,107]. Figure 14 Advantages and disadvantages of the different nutrient recovery processes.

Conventional wastewater treatment has the following advantages: conventional methods such as sedimentation and primary treatment are often cost-effective and require less complex infrastructure. These methods effectively remove solid particles and suspended solids from wastewater. They generally have lower energy requirements compared to advanced treatment methods. On the other side, conventional methods are less effective at removing contaminants such as nutrients (nitrogen and phosphorus) and organic matter. They may not completely eliminate pathogens and microorganisms from the water.

Conventional treatment processes produce significant amounts of sludge, which must be managed properly.

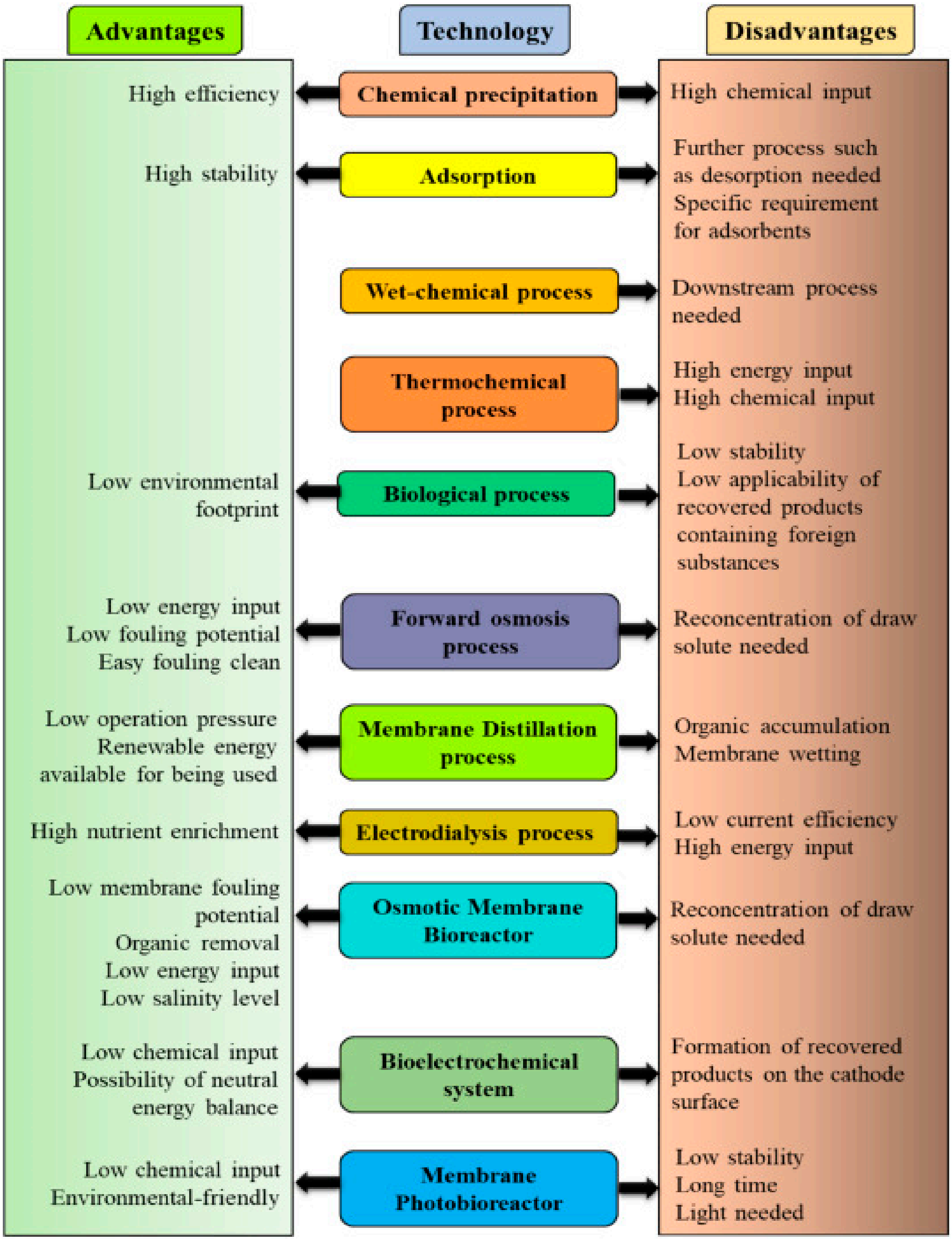

Figure 14. Advantages and disadvantages of different nutrient recovery processes [82].

Chemical treatment methods can efficiently remove a wide range of contaminants, including heavy metals, organic pollutants, and nutrients. Chemical treatments, such as chlorination, can effectively disinfect and kill pathogens. Chemical treatment processes can be adjusted to target specific pollutants, making them versatile. On the other side, the procurement and handling of chemicals can be expensive. Chemical treatments often produce chemical residuals that need disposal, which can be environmentally challenging. Handling and storage of chemicals pose potential health and safety risks to workers. Some chemical treatments can introduce harmful byproducts or affect aquatic ecosystems. In addition, advanced chemical treatment processes can be complex to design and operate.

In practice, wastewater treatment units must combine both conventional and chemical methods to address a broad spectrum of contaminants effectively while considering cost and environmental impact. The choice of method depends on the specific wastewater composition and treatment goals [82].

2.4.1. Environmental Hazards of Industrial Wastewater

Industrial wastewater discharge into water bodies may result in severe water pollution and negatively impact humans and the ecosystem. Several contaminants are usually present in food-processing wastewater, including organic matter, hydrocarbons, suspended solids, inorganic dissolved salts, heavy metals, surfactants, and detergents. Contaminated water is unsuitable for drinking and irrigation and adversely affects humans, animals, plants, and aquatic life.

2.4.2. Water Quality

Water quality is the main parameter for developing wastewater management systems. Wastewater treatment scenarios, efficiency, and techniques are designed to address the characteristics of wastewater and water consumed by each unit. The water quality and characteristics are essential to using water pinch or optimization techniques. In wastewater management systems, treated wastewater streams are referred to as "sources" of water, while units in which water is used are commonly referred to as "sinks". The minimum acceptable threshold of the water used in any sink process is essential to design a treatment method.

The operating conditions such as pressure, temperature, device materials, and porosity determine the minimum acceptable threshold of water required for each sink process [83,84]. Understanding the production process limitations is vital to determine acceptable water quality. As the wastewater characterizations such as contaminants (e.g., TSS, BOD_5, COD) grow, applying water management strategies becomes more demanding and costly. Treatment methods that address specific contaminants are more favorable to use than other nonspecific wastewater treatment methods, considering their design and practice. However, applying such processes in food-processing wastewater treatment is problematic since treatment methods/processes are usually sensitive to different contaminants, and multiple-contaminant approaches are then suggested [94,108].

2.5. Development and Integrated Management

Treatment of food-processing wastewater will help recycle and reuse water, recover resources, and protect the environment. Industrial wastewater, in general, is divided into gray, white, and black water according to the wastewater characteristics and reuse potential. Graywater treatment is simple and requires solids removal before reusing [83]. White water can be reused for industrial applications without any treatment since the quality of white water is quite similar to fresh drinking water.

Graywater contains raw materials and products, increasing the potential for recovering resources and reusing water. Physical treatment methods are usually preferred for graywater treatment, as the organic wastewater loadings increase, including COD, BOD_5, and other nutrients. Further complicated treatment processes are needed, and such wastewater is no longer considered graywater. Membrane-based techniques have shown efficient treatment of graywater produced from food processing units compared to standard physical methods considering water, energy, and land requirements [84].

2.5.1. Industrial Wastewater Treatment Levels

Industrial wastewater treatment is categorized into the following levels in Figure 15. The raw wastewater is treated first using preliminary and primary treatment methods to remove coarse materials and suspended particles. Then, the refined wastewater is treated using secondary/biological treatment methods [109].

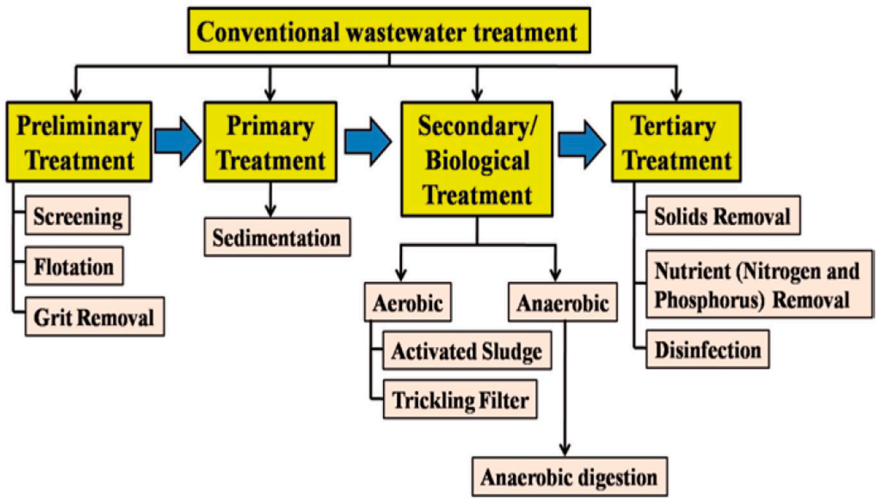

Figure 15. Treatment of industrial wastewater [109].

2.5.2. Operations of Wastewater Treatment Processes

The treatment processes consist of several unit operations Figure 16.

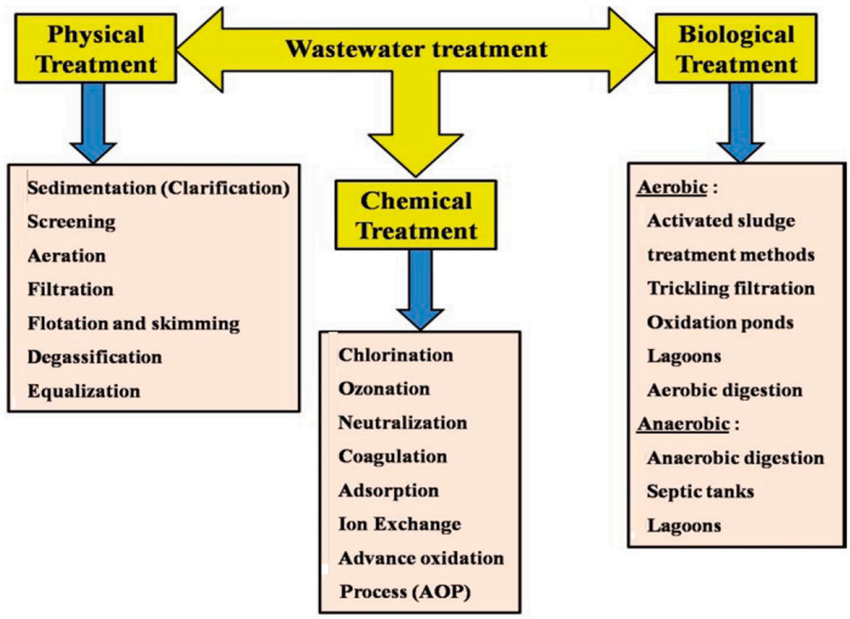

Figure 16. Wastewater treatment operations [109].

2.5.3. Membrane Separation Techniques

Membrane separation techniques can separate valuable chemicals and raw materials with high efficiency and minimum energy requirement [110–113]. Due to the expected membrane fouling and the high concentration of suspended solids in food processing effluent, membrane fabrication, and regeneration were modified significantly to reduce the fouling effect. New research trends are directed toward manufacturing specific contaminants membranes, which can be used to remove specific contaminants at high efficiency. For example, several selective nanocomposite membranes were developed to remove heavy metals, ions, and pathogens.

Reducing the concentration of contaminants is essential to minimize the harmful effect on the environment. Several harmful compounds are released into the environment if food waste is not adequately treated, including organic solvents, phenolic compounds, sweeteners, artificial dyes, and food preservatives. The maximum permissible amount

(MPA) of COD and BOD_5 discharge is 120 and 40 mg·L^{-1}, respectively. Usually, COD and BOD5 levels in food-processing waste could reach around 20 times the allowable MPA. Biological treatment methods must be used to reduce the high levels of COD and BOD_5 discharged from the food industry.

TDS and TSS negatively impact unit operations, leading to membrane fouling, erosion, and environmental impacts. TDS and TSS are used, and non-soluble suspended matter is present to index the soluble and non-soluble suspended matter in the wastewater. TSS affects the membrane processes commonly used in the food industry and increases the membrane fouling rate [113]. COD, and insoluble chemicals such as pesticides from the TSS in food processing industries. Several treatment strategies and conventional treatment methods are necessary to reduce TDS and TSS. Several water management strategies rely on minimizing physical and organic contaminants from the source, such as separation-from-origin and preventing wastewater mixing.

Membrane treatment technology is one of the promising technologies for treating wastewater from food industries. However, membrane operation suffers from unavoidable fouling problems and high operating and initial costs. To use membrane technology effectively for wastewater treatment, the two significant challenges must be addressed. Fouling is the primary reason for the considerable delay in implementing membrane separation processes since it leads to high operating and maintenance expenses and lower separation efficiency, leading to a higher restoration frequency of membranes. Fouling occurs due to continued solids deposition on the membrane surface or the subsequent blocking of the membrane pores.

Nitrogen- and phosphorus-containing nutrients are the third challenging group of contaminants in food-processing wastewater treatment. N and P compounds originate from protein compounds and agricultural fertilizers such as $N\text{-}NH_3$, $N\text{-}NO_3$, and PO_4 [104]. Controlling nitrogen and phosphorous content in the wastewater is important to maintain the biological treatment methods in good operating conditions. Higher levels of nitrogen may increase the chances of algal bloom. Harmful algal blooms (HABs) are the sudden and unrestrained wild species growth of algae. This type of algae is destructive to the ecosystem, releases toxic substances, and decreases dissolved oxygen, and increases fish and aquatic animal mortality [82]. Some forms of nitrate and nitrite may lead to a negative impact on human health. The MPA in the discharged wastewater of TN and TP is 40 mg/L. Several algal methods have been developed recently for treating meat, dairy, and edible oil processing units' effluents. The cultivated algae are used later for producing biofuels. The algae processes are still under development, and further research is needed. Figure 17 illustrates the ladder of growing value proposition for water reuse as the water quality/the value chain investment increases.

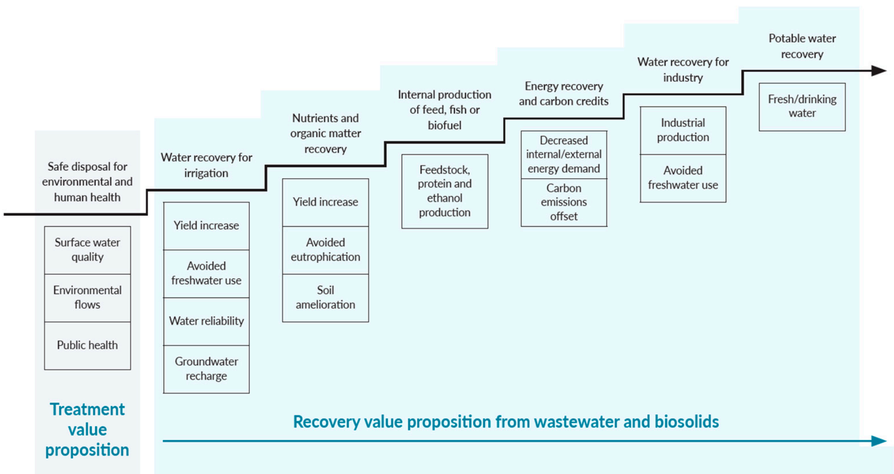

Figure 17. Ladder of increasing value propositions for reuse with increasing investments in water quality or the value chain [82].

3. New Integrated Methods and Technologies

3.1. Microbial Fuel Cells

Microbial fuel cells (MFC) can be used to recover valuable chemicals and energy by treating food industry wastewater. A direct product of MFC is clean electricity. MFC was used successfully to treat dairy industry wastewater for more than 75 days [114]. A 95% removal efficiency of BOD_5 was achieved, resulting in a power density of 27 $W.m^3$ [115,116]. MFC was used for treating the effluent of the vegetable oil industry using 20 samples for 72 h. The results indicated that MFC could play an influential role in treating effluent. MFC is improved with time and temperature at COD removal efficiency of 80%. MFC uses microorganisms to generate electricity, which affects the MFC performance; a plant-based rhizosphere microbial community can be employed to avoid such issues.

3.2. Recovery of Proteins and Lipids

Dairy industry wastewater contains high COD and BOD_5 ladings due to lipids, proteins, and hydrocarbons. Na-lignosulphonate can recover valuable chemicals from wastewater and remove the BOD_5. In total, 96 and 46% of the lipids and proteins were recovered at a BOD_5 removal efficiency of 73% at 22 °C [117,118]. Algal photo-reactors represent an efficient method for recovering lipids and proteins and can be used for water-containing toxins, which can be treated using microalgae. Solvent extraction of lipids did not show interesting results in scaling the process to an industrial scale [119]. Lipids can also be produced by treating fish-processing wastewater using microalga cultivation of *Chlorella vulgaris*. This process can be developed further for producing lipids from fish-processing wastewater inside a bio-refinery process [120]. High turbidity could affect microalgae growth, so the TSS should be reduced before the biological treatment [121].

3.3. Recovery of Ammonium and Phosphate

Composting of food-processing waste generates struvite to recover ammonium and phosphate. The process can be combined with food-processing waste and sewage sludge ash. The precipitate consists of mostly struvite with a percentage of ~72%, demonstrating elevated P-bioavailability and heavy-metal traces [122]. *Schizochytrium* sp. is used for treating tofu whey wastewater to produce docosahexaenoic acid. COD, TN, and TP removal were 64.7, 59.3, and 66%, respectively [123]. Several processes were developed to recover ammonium and phosphate separately by using electrodialysis. A monovalent anion-selective membrane can prevent the contamination of phosphorus streams by ammonium or other single-charged anions [124–127].

3.4. Production of Biopolymers

Biopolymers are used in several applications. Biopolymers can be produced from food industry wastewater through extraction or fermentation without requiring pretreatment. Food industry waste, containing high organic content, is a potential feedstock for biopolymer production. *Cupriavidus necator* is used to convert brewery waste stream to produce poly-3-hydroxybutyrate biopolymer. The maximum biopolymer yield and volumetric productivity achieved were 0.28 $g\ g^{-1}$ and 0.022 $g\ L^{-1}\ h^{-1}$, respectively [128]. The process is still not economically viable due to the need for sterilization requirements and pure microbial cultures. The high production cost of biopolymer production procedures compared to traditional plastic production methods hindered the commercialization of the process.

3.5. Production of Xanthan

Biosynthesis of xanthan species while treating challenging winery wastewater is a viable option for recovering valuable resources from wastewater from food processing units. Maximum xanthan production was 23.85 $g\ L^{-1}$. The conversion efficiency of sugar, nitrogen, and phosphorus was 90.8, 71.7, and 83.1%, respectively. This process can be employed for winery wastewater treatment and recovering valuable resources as feedstock for the xanthan production industry [129,130].

3.6. Biogas Production by Anaerobic Digestion

Anaerobic digestion (AD) of municipal solid waste was studied in detail for producing combined heat and power (CHP) [131,132]. AD of food industry wastewater and sewage sludge was conducted using two parallel anaerobic digestion reactors at a scale of 8500 m^3 for each reactor [133,134]. In total, 8300 m^3 d^{-1} of biogas was produced from each reactor; the unit was operated for 12 months. Around 0.048 m^3 d^{-1} of biogas is produced from dairy-processing wastewater treatment using a reactor volume of 0.28 m^3 using microwave and ultrasonic generators. Future work should target the process economics and pretreatment methods needed to improve the quality of feedstock [135,136].

3.7. Heat Recovery

Heat recovery from wastewater streams is not studied in detail. There is a potential to recover a considerable amount of heat from wastewater streams. In general, heat exchangers are employed in the food processing units to eliminate microbial activity and to increase the products' shelf life. In addition, heat exchangers can condition products/streams before filling or drying [137,138]. Recovering the heat by heating up cold streams will minimize process energy demand. The optimum heat recovery process can be developed based on the operating temperature and wastewater volume. Several heat transfer systems have been developed and used in the food industry. Water was preheated to 60 °C in a whey facility by using heat in a stream at 230 °C, achieving 35–55% in energy efficiency. Heat recovery in the food industry can be achieved using gravity film and plate heat recovery methods.

3.8. Mining of Resources from Wastewater

Several valuable compounds are available in wastewater, so wastewater can be used to generate valuable natural resources. Resource reuse is more attractive when the re-source, remake, and rethink concept is applied for creating new added-value products from waste streams. Figure 18 shows the possibilities of resource recovery from wastewater [82].

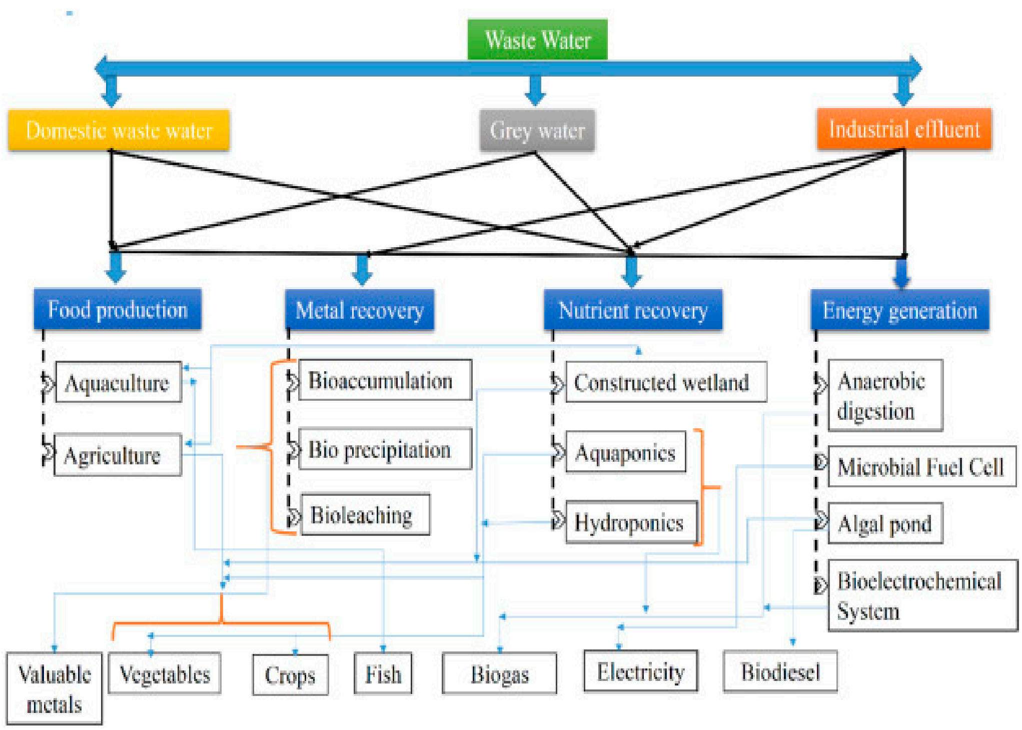

Figure 18. Different aspects of resource recovery from wastewater [82].

Several methods can be used for nutrient recovery from wastewater streams, including chemical, biological, and membrane bioreactors, bio-electrochemical systems, and membrane photo-bioreactors. The recovery using chemical processes includes either adsorption or precipitation steps. The precipitation step is performed using magnesium- and calcium-based compounds to facilitate the precipitation process. The adsorption step is performed using either ion exchange, electrostatic attraction, or surface precipitation. Nutrient recovery using membrane systems is conducted using forward osmosis or electrodialysis. Nutrient recovery within the bio-electrochemical system and photo-bioreactor is performed by employing microbes and algae. An efficient nutrient recovery can be achieved by combining the forward osmosis process and the bio-electrochemical system. The membrane photo-bioreactor can be developed by combining combined photo-bioreactor with a membrane technology [139].

4. Water Management Framework

In the circular economy framework, economic development is directly proportional to resource conservation and environmental sustainability. Adopting the circular economy concept in wastewater management promotes resource recovery as a central element and provides a strategy to improve water supply. Water systems management to harmonize the circular economy concept is based on three principles: (i) design out waste externalities treatment process, (ii) keep resources in use, and (iii) regenerate natural capital [140]. There is a need to address both economic and environmental concerns associated with food-processing effluent. The optimum solution must align with sustainability goals.

Within the context of the circular economy framework, economic growth is closely tied to the conservation of resources and the sustainability of the environment. In the realm of wastewater management, embracing the circular economy concept places a strong emphasis on resource recovery and offers a strategy to enhance the water supply. The management of water systems, in alignment with circular economy principles, revolves around three core principles: (i) eliminating the creation of waste externalities in treatment processes, (ii) maintaining the utilization of resources, and (iii) rejuvenating our natural capital [140].

Consequently, the sustainable reclamation of resources from wastewater holds the potential to generate revenue by creating marketable products, ensuring the safety of water reuse, and upholding water quality standards tailored to specific applications and economic objectives [141]. To effectively integrate circular economy (CE) principles into the wastewater sector, besides technological advancements, various other factors such as financial viability, societal impact, environmental considerations, risk assessment, and energy efficiency must be carefully weighed. Moreover, it necessitates proper environmental education, heightened awareness, and a comprehensive understanding of CE principles to facilitate the adoption of a CE model. Therefore, the adoption of circular and sustainable solutions by companies and wastewater operators can significantly expedite the transition toward a CE model [142].

Food industry waste can be recycled to create a circular economy in agri-food fields. Waste recycling of food industry residues can produce value-added products since the waste contains valuable nutrients and is rich in renewable energy. Several useful products, such as biofuels, bioenergy, and bio-fertilizers, can be generated from food industry waste. In addition, metal compounds and nutrients can be extracted and reused in several applications. A circular economy concept in the food industry will help circulate resources and nutrients in a closed loop, minimizing discharging streams to the environment. Food waste can generate valuable chemicals and nutrients in addition to energy. In comparison, biodegradable materials can be recycled further to produce other biodegradable products, alternatively, as an end-of-life option in lieu of carbon capture for CO_2 sequestration. To explore the opportunities for developing a circular economy in sustainable food waste management, understanding existing food waste situations worldwide is a crucial cornerstone [143].

Figure 19 illustrates the feasible route for recovering value-added products from food wastewater, improving the revenue generated.

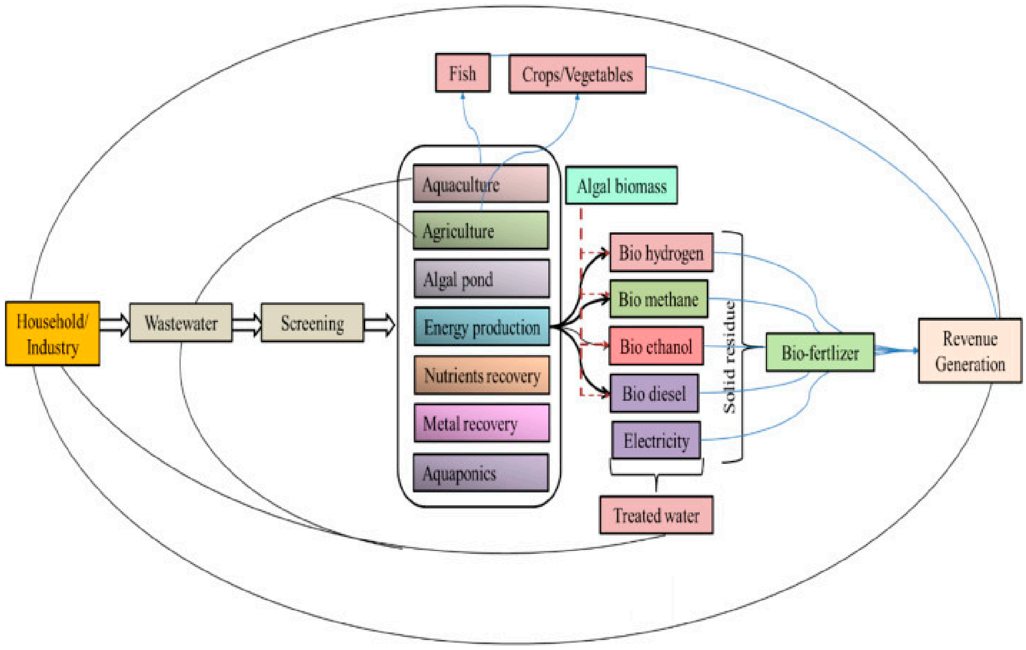

Figure 19. The feasible route for generating value-added products from wastewater [82].

4.1. Resource Recovery

Food-processing effluent contains valuable materials, including proteins and lipids, alongside low concentrations of heavy metals and toxicants. This emphasizes the importance of developing integrated management systems to recover these resources, improving the economic value of the process.

The resource recovery (4R concept) was developed based on the following four steps: REDUCE, REUSE, RECYCLE, and RECOVER. Around 20–30% of food is wasted during the pre-harvest step in developing countries due to several supply chain constraints. This ratio may reach up to 72% in some cases. It is crucial to develop technologies capable of recycling and repurposing food industry waste. Packing and containers made of plastic can be reused and recycled [144]. Considering economic and operating boundaries, waste cooking and palm shells can be converted into biodiesel [114]. Corncob is another food waste that can produce biofuels through pyrolysis. The produced fuel can be employed as a biofuel in addition to producing other valuable chemicals [145]. Three principles govern the circular economy: protecting and enhancing regular capital; the reorganization of resources by remanufacturing, restoring, and reusing materials inside their technical and biological cycles; and, finally, the utilization of food manufacturing byproducts and nutrients [146]. Implementing the circular economy instead of conventional WWT methods ensures valuable RR, including water and raw materials. In addition, the circular economy will reduce GHG emissions from food industrial activities [111].

4.2. (4R) Scheme

The 4R scheme can manifest in various forms: in-process reusing of IWW (industrial waste works) with/without treatment; IWW recycling, related to the water recovery for drinking by substituting or improving the existing treatment plant; resource recovery from wastewater generated during food processing, including inorganic nutrients such as nitrogen and phosphorus, organic fertilizers, biopolymers, energy, biogas, heavy metals, and salts [147]. These scheme strategies in IWW are designed to close industrial water cycles and obtain invaluable components that require a combination of wastewater treatment methods, as shown in Figure 20. However, wastewater comprises several contaminants, particular pollutants, elevated organic matter contents, and nonbiodegradable components, which make this task tedious [148].

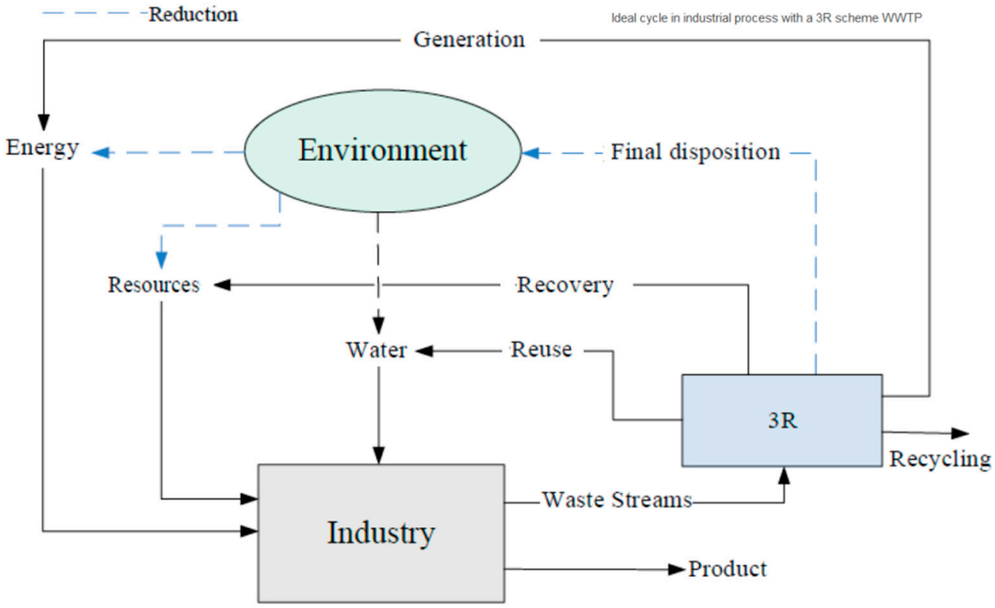

Figure 20. 4R scheme [148].

5. Case Studies

5.1. Slaughterhouse Wastewater Management and Resource Recovery

Actual samples of municipal wastewater (SWW) were collected from licensed MPPs (Municipal Pollution Plants) in Ontario, Canada. These samples had average concentrations of 1950 mg/L for COD (Chemical Oxygen Demand), 1400 mg/L for BOD_5 (Biochemical Oxygen Demand), 850 mg/L for TOC (Total Organic Carbon), 750 mg/L for TSS (Total Suspended Solids), 200 mg/L for TN (Total Nitrogen), and 40 mg/L for TP (Total Phosphorus). Additionally, anaerobic and aerobic sludge inocula were obtained from the Ash-bridges Bay Municipal Wastewater Treatment Plant in Toronto, Canada. The concentrations of these inocula were 40,000 mg/L and 3000 mg/L, respectively. These inocula underwent a 60-day acclimatization process. The combined ABR-AS-UV/H_2O_2 system used in the study included a 36-L Anaerobic Baffled Reactor (ABR) with five equal-volume chambers and individual biogas collection, a 12.65-L aerobic Activated Sludge (AS) reactor with controlled airflow to maintain dissolved oxygen (DO) concentrations at 2 mg/L, and a 1.35-L UV-C photoreactor with recycle. The UV photoreactor had an output power of 6 W and ensured uniform light distribution [149].

The meat processing industry is faced with the imperative of integrating waste minimization and resource recovery into its strategies for managing wastewater (SWW). This entails recognizing the portion of waste and byproducts within the industry that can be potentially recovered for direct reuse, including valuable nutrients and methane as a biofuel source. Figure 21 provides a schematic representation of the ideal operational flow within a meat processing plant and its supply chain, encompassing activities from animal farming and raw material acquisition to final product creation, waste disposal, and the reclamation of recoverable resources. In light of escalating environmental concerns and the call for sustainable practices, meat processing plants should prioritize cleaner production methods. This involves classifying and reducing waste generation at its source, with an emphasis on on-site treatment as the preferred approach for both water reuse and harnessing potential energy resources. Consequently, careful consideration must be given to adequately treating SWW effluents to align with these objectives.

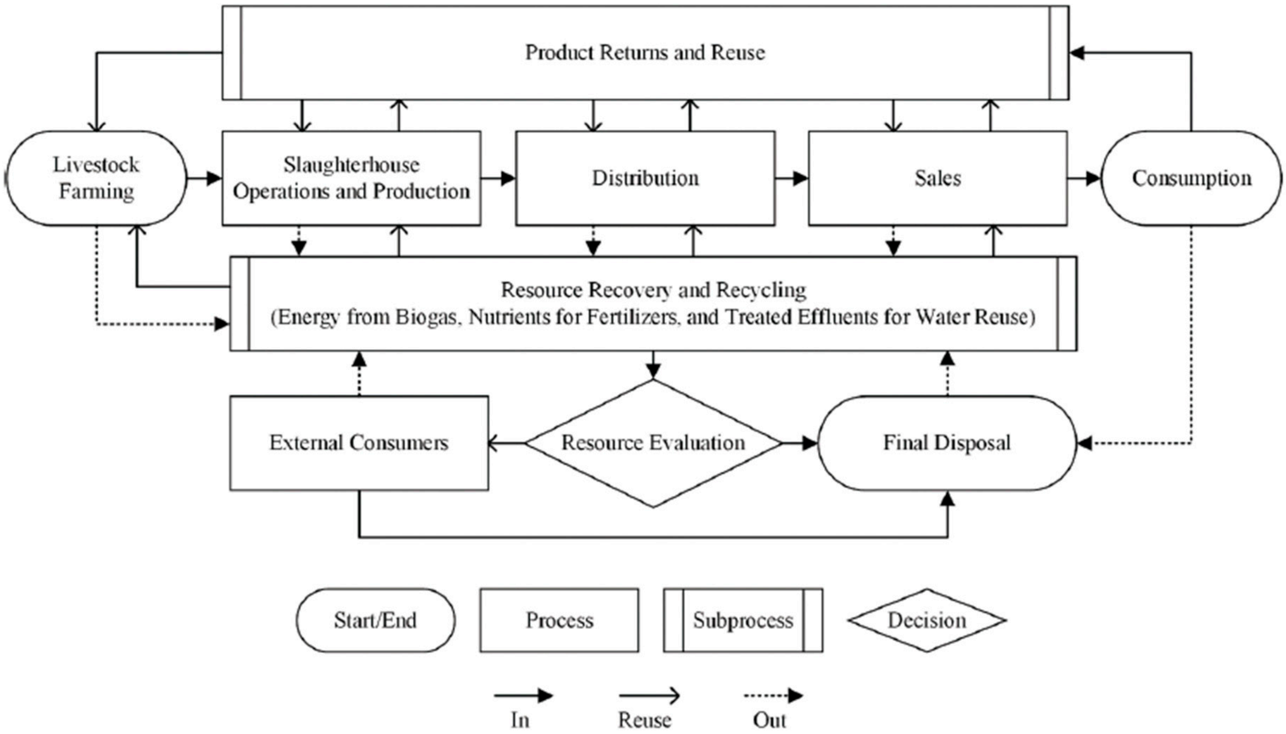

Figure 21. Presents a schematic illustration of the ideal operation of a meat processing plant and supply chain.

5.2. Recycling and Reuse of Fish Processing [150,151]

The wastewater management concept aims to develop a management cycle or system to control the wastewater flow from several units and through the flowing streams. Disposal of untreated or poorly treated wastewater has severe consequences for health and the environment. The wastewater management cycle usually contains four essential interconnected steps/stages:

1. The reduction or mitigation of pollution at its source, considering both the pollution load and the volume of wastewater generated. This involves prohibiting or regulating the use of certain pollutants to prevent or restrict their entry into wastewater streams through various means, including regulatory and technical measures. Additionally, this step encompasses initiatives to minimize the quantity of generated wastewater, such as demand management and enhancing water use efficiency.
2. The elimination of pollutants from wastewater streams: Implement processes that can treat and eliminate wastewater contaminants, environmental consequences, or negative effects, generating a safe-to-use/discharge treated water stream without any environmental consequences or negative effects. The optimum treatment process is chosen based on the concentration and nature of contaminants and the end use of the treated water.
3. Wastewater reuse: Reusing treated/untreated wastewater can be done only in a monitored process to ensure safe use. Usually, treated water is used for irrigation, while with existing advanced treatment technologies, adequately treated water can be utilized in several applications after.
4. The valuable resources recovery: Wastewater contains several valuable compounds and nutrients that can be separated from wastewater either directly, such as heat and organic matter, or using extraction methods such as biofuels, in addition to nitrogen and phosphorus, which can be used for producing fertilizer. Impact of wastewater discharged to the environment as shown in Table 28.

Table 28. Impact of wastewater discharged to the environment.

Impacts on	Examples of Impacts
Health	• Increased burden of disease due to reduced drinking water quality • Increased burden of disease due to reduced bathing water quality • Increased burden of disease due to unsafe food (contaminated fish, vegetables and other produce irrigated) • Increased risk of disease when working or playing in wastewater-irrigated area
Environment	• Decreased biodiversity • Degraded aquatic ecosystems (e.g., eutrophication and dead zones) • Foul odors • Diminished recreational opportunities • Increased greenhouse gas emissions • Increased water temperature • Bioaccumulation of toxins
Economy	• Reduced industrial productivity • Reduced agricultural productivity • Reduced market value of harvested crops, it unsafe wastewater is being used tor irrigation • Reduced opportunities tor water-based recreational activities (reduced number of tourists, or reduced willingness to pay for recreational services) • Reduced fish and shellfish catches, or reduced market value of fish and shellfish • Increased financial burden on healthcare • Increased barriers to international trade (exports) • Higher costs of water treatment (for human supply and other uses) • Reduced prices of properties near contaminated water bodies

Another crucial function of the wastewater management cycle is to alleviate adverse effects on human health, the economy, and the environment. When we consider the numerous advantages of enhanced wastewater management, many of these processes can be deemed cost-effective, thereby enhancing the overall value throughout the wastewater management cycle. This, in turn, supports the continued development of water supply and sanitation systems. Building on the premise that it is feasible to align water quality requirements with specific water use locations, the implementation of multiple-use systems with cascading reuse of water, moving from higher to lower water quality levels, can render water reuse more economically viable compared to establishing extensive water treatment facilities at each point of water extraction within a river basin. E.g., Potential recycling and reuse of effluents in the fish-processing industry as shown in Figure 22.

Recent market studies indicate a favorable trajectory in investments for water and wastewater treatment in developing countries. Globally, utilities' annual capital expenditures for water infrastructure and wastewater infrastructure have been approximated at USD 100 billion and USD 104 billion, respectively.

The increasing demand for water resources underscores the necessity for a more efficient utilization of wastewater. Factors such as population growth, urbanization, shifting consumption patterns, climate change, biodiversity loss, economic expansion, and industrialization collectively influence water resources and wastewater streams, subsequently impacting atmospheric, terrestrial, and aquatic pollution. A more effective approach to wastewater management holds the potential to alleviate the consequences of some of these pressures. Regarding resource sustainability (as depicted in Figure 23), effective wastewater management mandates supportive policies: the implementation of policies that proactively reduce pollution at the source; tailored technologies: the utilization of customized technologies that facilitate treatment tailored to specific purposes, optimizing resource utilization; and resource recovery consideration: the acknowledgment of the advantages associated with resource recovery. By addressing these aspects, sustainable wastewater management can play a pivotal role in mitigating the impact of various environmental and societal challenges.

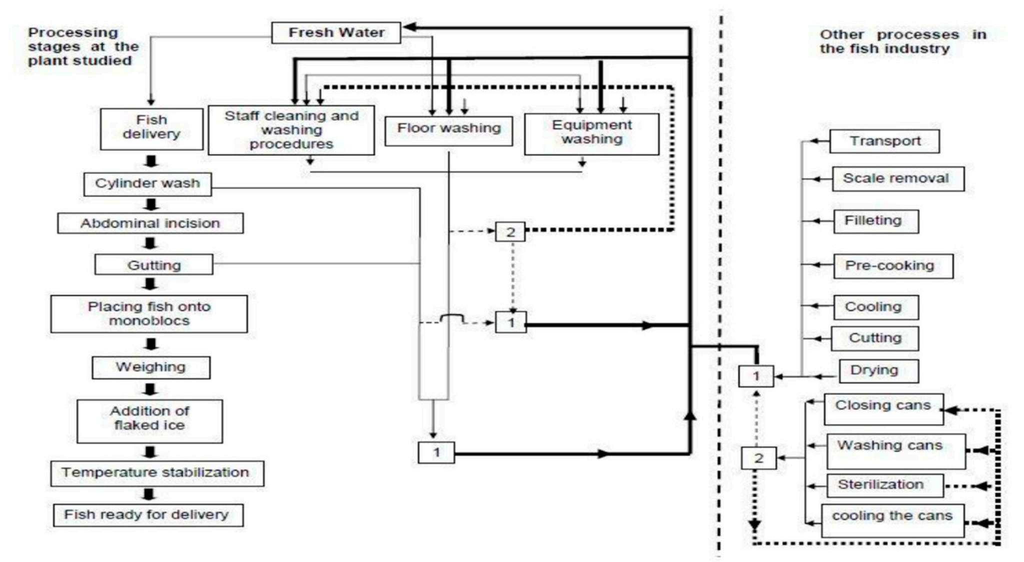

Figure 22. Potential recycling and reuse of effluents in the fish-processing industry [149].

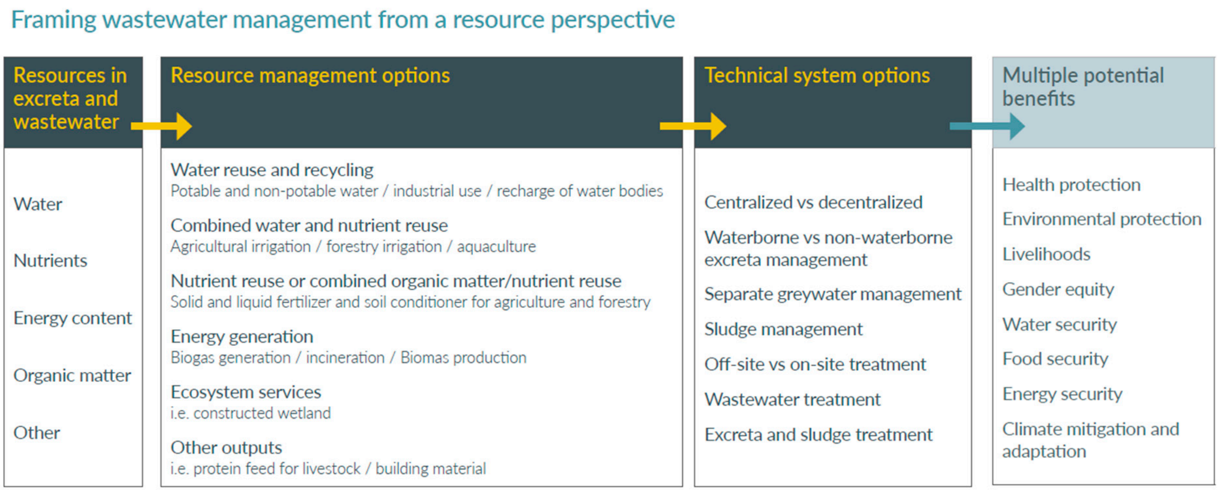

Figure 23. Resource perspective.

Taking a Best Available Technology (BAT) standpoint, adopting an approach that minimizes water, energy, and chemical usage while optimizing waste recovery is highly advantageous. Given the substantial demand for fish proteins in the fish industry and animal production, this approach can significantly enhance profit margins. In the case of filleting oily fish, the standard production process typically involves:

For a unit of 25,000 tons/year of herring (oily fish) to fillet:

Water:

Water consumption	5–8 m^3/ton fish processed
COD discharge	85 kg/ton fish processed
Tot-N discharge	2.5 kg N/ton fish processed
PO_4-P discharge	0.1–0.3 kg P/ton fish processed

Energy:

Filleting	2–5 kWh/ton fish processed
Freezing	50–70 kWh/ton fish processed
Chemicals Antioxidants	100 kg/ton fish processes
Solid waste	50% of processing amount

Recovered byproducts (as depicted in Figure 24).

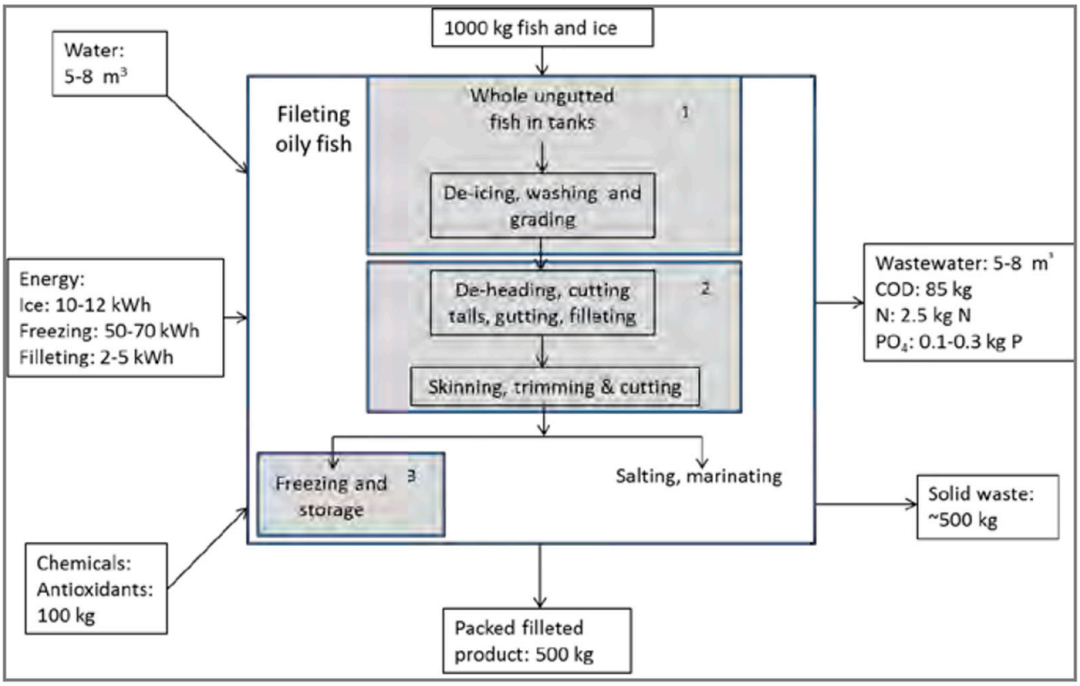

Figure 24. Normal inputs/outputs from the filleting of oily fish [152].

Additionally, fish-processing plants improve economics significantly by recovering valuable materials such as protein, fat, and oil. Several BAT units around the world do not produce any waste, supporting the development of better waste treatment systems.

The fish-processing industry actively adopts waste recovery, reuse, and water-saving solutions. Local conditions, where there are no vulnerable recipients for nutrients or organic loading, have led the industry to adopt water treatment technologies that are not overly complex. However, the growing market for higher-value byproducts is likely to push Best Available Technology (BAT) solutions into a new era, where novel technologies will be employed to recover proteins and fat from the industry's operations.

Furthermore, in the future, we may witness increasing interest in nutrient recovery, particularly phosphorus and nitrogen. Fish proteins are a valuable resource, and the reutilization of byproducts is not only economically advantageous but is also expected to drive BAT practices within this industry toward exciting new developments.

It is worth emphasizing that an effective implementation of BAT should serve as a pivotal tool in stimulating the advancement of a diverse and cutting-edge market for water and energy-efficient technologies and products. As a result, both governments and enterprises are evolving in their approach to managing processing activities, recognizing the importance of these sustainability initiatives.

6. Conclusions

The depletion of natural resources is a pressing global concern. A shift from a linear economic model to a circular one is imperative to address this challenge. In this context, wastewater emerges as a promising and regenerative source for sustainable water and resource recovery. However, there is a significant lack of awareness and understanding regarding the potential of wastewater treatment. It is crucial to acknowledge that wastewater facilities have the capacity to function as closed-loop wastewater bio-refineries. They can recover valuable resources such as chemicals, nutrients, bioplastics, enzymes, metals, and water, all of which serve as useful inputs for various industries and agriculture. This approach aligns with society's increasing demand for water, resources, food, and energy, as it promotes the recycling and reuse of treated wastewater. Resource recovery fosters socioeconomic growth and mitigates environmental challenges stemming from waste generation. Therefore, embracing a circular economy approach in wastewater management holds the promise of addressing multiple societal and environmental needs.

Wastewater represents a valuable secondary resource that can yield more than just energy generation; it also offers an opportunity for extracting metals. Moreover, wastewater can be repurposed as a fertilizer, thereby diminishing the global environmental impact associated with the industrial production of such substances. Although water reuse carries numerous benefits, there remains a notable gap in its promotion and implementation. Effective water reuse necessitates a holistic approach founded on scientifically sound solutions, a robust legislative framework, stringent regulatory measures, and an enabling institutional environment. Industrial symbiosis presents a sustainable approach for managing the wastewater generated, fostering resource synergy. In this context, the concept of a circular economy emerges as the most promising strategy for handling wastewater. It leverages advanced integrated technologies, diverging from traditional treatment methods while concurrently advancing toward self-sustainability, carbon neutrality, and the attainment of Sustainable Development Goals (SDGs) for a more prosperous world.

One of the primary objectives of the 2030 Sustainable Development Goals for Water is to significantly reduce pollution, eliminate the practice of dumping waste, minimize the release of hazardous chemicals, cut global untreated wastewater in half, and promote greater recycling and safe reuse of water. This marks a substantial shift in the approach to wastewater management, moving away from a focus solely on "treatment and disposal". This evolved perspective on wastewater management not only addresses critical concerns related to public health and the environment but also plays a pivotal role in ensuring food and energy security while mitigating the impacts of climate change. Embracing this new concept offers a multitude of benefits. Wastewater emerges as a plentiful source of valuable and sustainable resources within the framework of a circular economy, effectively harmonizing economic growth with the preservation of natural resources.

This is a state-of-the-art review of the capacity of global production, water demand, and wastewater generated by food processing industries worldwide. The primary approach is implementing sustainable food production in the food processing industries. Recent trends in process integration and water management highlight water reuse and recycling by using wastewater as a nonconventional water source. Nevertheless, implementing wastewater management systems requires collecting technical information about food processing industries. Water consumption, wastewater generation, and feasible wastewater treatment methods were reviewed initially.

The food processing industries use large amounts of water, which may negatively impact the environment and require several treatment methods before discharging the wastewater. To diminish the negative impacts, an integrated approach should be implemented, considering higher process productivity, water, and environmental protection to reduce water demand and generation of wastewater. A detailed systematic review was presented for sustainable wastewater management strategies by reusing and recovering the water and valuable resources. The ultimate goal of sustainable operation in food processing industries is increasing productivity, reducing operating costs, and eliminating environmental consequences. This article investigated the recovery of valuable resources to foster socioeconomic growth and to mitigate environmental challenges stemming from waste generation, enabling a circular economy approach in wastewater management.

Due to the limited availability of natural resources, including water, wastewater represents a great opportunity to recover valuable nutrients and resources. As a result of extended suburbanization and utilization of limited natural resources, better resource management tools and measures should be implemented. Several valuable chemicals and nutrients are present in wastewater generated from food industries, including organic materials, metals, nutrients, and chemicals. The management of such valuable resources can be achieved by implementing a transformation model for value-added materials recovery. The circular economy through a "closed-loop" process by reusing and recovering materials and energy was discussed in detail by identifying the emerging technologies available for treating food industry wastewater to recover resources. Biological treatment methods for food industry wastewater can treat the effluent and recover resources such as lipids and proteins, approaching the circular economy concept.

Technologies used for conventional wastewater treatment and advanced treatment technologies, including anammox technology, algal treatment, and microbial fuel cells, have been reviewed. In addition, recovering the energy contained in the wastewater streams in the form of biogas and biofuels was discussed as a tool for generating clean energy from wastewater streams. New trends in wastewater treatment and recovery processes, such as other single-cell proteins, biopolymers, and metals, were deliberated. The state-of-the-art highlighted the use of wastewater after adequate treatment in agriculture, fisheries, aquaponics, and algal cultivation. A critical assessment of adopting the circular economy in the food industry was discussed. Resource recovery from food industry wastewater through the integration of wastewater management systems will ensure efficient utilization of resources.

However, research is needed to develop more robust treatment systems that can handle the variation of food industry loadings and composition. In addition, it improves the performance of innovative treatment technologies such as pyrolysis reactors and microbial fuel cells. In future work, it is recommended to develop more robust technologies to valorize the wastewater resources. This review suggests that for future research directions, the development of more robust treatment systems, particularly pyrolysis reactors and microbial fuel cells, should be explored to effectively address variations in food industry loadings and composition. These systems can play a significant role in managing the wastewater generated by the food industry.

Funding: This research received no external funding.

Institutional Review Board Statement: Not applicable.

Data Availability Statement: No new data were created or analyzed in this study. Data sharing is not applicable to this article.

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

Abbreviations

AD	Anaerobic digestion
BAT	Best available technologies
BOD_5	Biological oxygen demand
CHP	Combined heat and power
COD	Chemical oxygen demand
HAB	Harmful algal blooms
IWW	Industrial Waste works
MFC	Microbial fuel cell
MPA	Maximum permissible amount
O&G	Oil and grease
SBR	Sequence Batch Reactor
SGD	Sustainable development goals
TN	Total nitrogen
TP	Total phosphorus
TS	Total solids

TDS	Total dissolved solids
TSS	Total suspended solids
UASB	Up-flow anaerobic sludge blankets
WWTPs	Wastewater treatment plants
UF	Ultrafiltration
RO	Reverse Osmosis
NF	Nanofiltration
RFBB	Ring Fixed Bed Bioreactor
EC	Electro-coagulation
HCPB	Hollow-centered packed bed
MBR	Membrane bioreactor
FPWs	Food process wastewater
IM	Integrated Management
CE	Circular Economy
VA	Value Added
RR	Resource Recovery
4R	Reduce, Reuse, Recycle, And Recover
SWW	Slaughterhouse wastewater
SC	Supply chain
WHO	World Health Organization
UNICEF	United Nations International Children's Emergency Fund
UNEP	United Nations Environment Program
WWW	Worldwide Water

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