



Review

Food processing wastewater purification by microalgae cultivation associated with high value-added compounds production – A review☆

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ABSTRACT

Microalgae have been considered as an efficient microorganism for wastewater treatment with simultaneously bioenergy and high value-added compounds production. However, the high energy cost associated with complicated biorefinery (e.g. microalgae cultivation, harvesting, drying, extraction, conversion, and purification) is a critical challenge that inhibits its large-scale application. Among different nutrition (e.g. carbon, nitrogen and phosphorous) sources, food processing wastewater is a relative safe and suitable one for microalgae cultivation due to its high organic content and low toxicity. In this review, the characteristic of different food wastewater is summarized and compared. The potential routes of value-added products (i.e. biofuel, pigment, polysaccharide, and amino acid) production along with wastewater purification are introduced. The existing challenges (e.g. biorefinery cost, efficiency and mechanism) of microalgal-based wastewater treatment are also discussed. The prospective of microalgae-based food processing wastewater treatment strategies (such as microalgae-bacteria consortium, poly-generation of bioenergy and value-added products) is forecasted. It can be observed that food wastewater treatment by microalgae could be a promising strategy to commercially realize waste source reduce, conversion and reutilization.

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1. Introduction

Food production chain requires water at different stages including irrigation, processing, cooling, heating, and cleaning. Approximately one-third of global food is lost or wasted along the food supply chain to human consumption [1]. It is estimated that more than 97% of food waste in the United States is disposed, which causes additional environmental problems [2]. Food and Agriculture Organization (FAO) indicated that from 2000 to 2050, global meat and milk production would increase by 102% and 82%, respectively [3]. Meat-based diet has a larger water footprint (36% larger) than vegetable [4]. For example, approximately 29, 31, and 112 L of water are required to produce 1 g of animal

protein from egg, milk, and meat, respectively; while producing 1 g of cereal protein, around 21 L of water are used [5]. In 2014, beer production in the world's top ten countries reached 119 million kl, and an average of 4.5 L of water was consumed for each liter of beer produced [6,7]. Along with the huge amount of pure water demand, wastewater emission and treatment of agricultural commodities should also be focused.

Food processing is vital for the food supply chain, and its water footprint is of great consideration, not only because of the substantial water utility (as shown in Fig. 1) in the manufacturing, but also for the significant volumes of wastewater [9]. Unlike municipal and industrial wastewater, food processing wastewater includes amounts of organic matter that could be a potential nutrition resource for microorganism [10]. Meanwhile, the nontoxicity (without or trace organic contaminants and heavy metal) is also the advantage of food processing wastewater compared with chemical or municipal wastewater [11].

Normally, nutrition (organic compounds, nitrogen, phosphorus, etc.) removal from food processing wastewater can be carried out by chemical or physical techniques [12]. However, the bottlenecks of these methods, such as the use of large amounts of strong acids, high operating costs and risk of secondary pollution, would adversely reduce the

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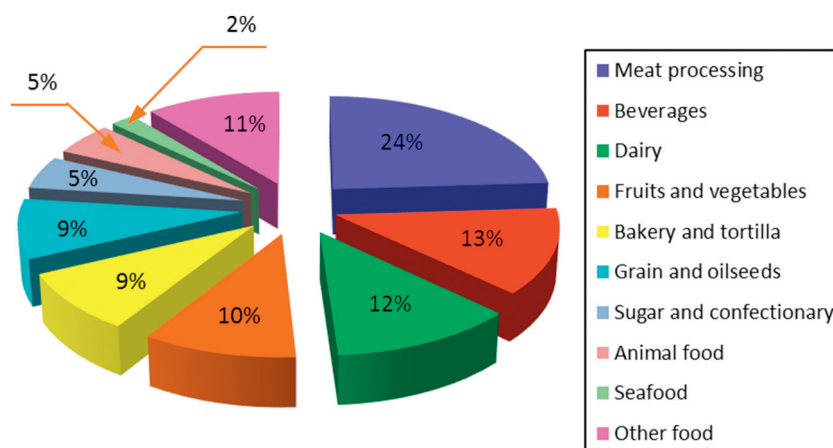


Fig. 1. Proportion of freshwater consumption in the dominant food industries [8].

efficiency during commercial application [13]. To overcome the existing challenges, there is a growing interest in the development of more efficient and environmental friendly strategies for food processing wastewater treatment.

Recently, biological wastewater treatment *via* microorganisms has attracted attention because of its advantages such as being environmentally friendly, easy operation in basic bioreactor, value-added ingredients co-production potential, efficient wastewaters purification, *etc.* [14]. During metabolism process, nutrition in wastewater could be used as carbon, nitrogen, and phosphorous source for microorganism. Bacteria (*e.g.* anaerobic and aerobic) and microalgae cultivation are two typical biological technologies that have been researched for wastewater purification. However, anaerobic treatments are unable to remove biological nitrogen and phosphorus, and require frequent adjustments for alkalinity [15]. Aerobic treatments suffer from high investment and energy cost to meet COD biotransformation, nitrogen and phosphorus removal, sludge thickening, and other requirement [16]. Meanwhile, aerobic process also generates CO₂ and sludge, which is negative for the mitigation of greenhouse gas emission. By contrast, the main nutritional requirement for microalgal growth includes carbon (C), nitrogen (N), phosphorous (P), and micronutrients such as iron (Fe), magnesium (Mg), and calcium (Ca), which are present in wastewater [17]. Microalgae can simultaneously remove biological carbon, nitrogen and phosphorus, and achieve wastewater purification. Recent research also demonstrated that microalgae have the metabolic potential to effectively reduce high concentration of nutrients such as carbon (C), phosphorus (P), and nitrogen (N) present in different food processing wastewater [18]. Along with the purification of wastewater quality, several potential value-added products (*e.g.* biofuel, functional pigment, amino acid, and polysaccharide) could be also generated [19]. What's more, microalgae could simultaneously remove organic carbon from wastewater and inorganic carbon from flue gas under the mixotrophic cultivation mode, which has the advantage of integration of bioenergy production and carbon capture and storage (namely, BECCS) [20,21].

To estimate the techno-economic feasibility of food wastewater purification *via* microalgae with simultaneously value-added ingredients production, the state-of-art food wastewater emission and microalgal treatment is summarized in the work. Especially, the advantage and challenge of microalgae cultivation method for potential value-added compound production from food processing wastewater are discussed. In detail, the characteristics (*i.e.* COD, total nitrogen, total phosphorus, and metal) of different food processing wastewater (such as soybean processing, dairy, beverage, meat processing, oil mill, and starch processing) are summarized. The potential routes for converting nutrient in food wastewater into value-added products (*e.g.* biofuels, pigment, polysaccharide, and amino acid) are discussed. Meanwhile, the challenge and prospective of microalgae cultivation by food wastewater are also reviewed.

2. Characteristics of Wastewater in Food Industry

2.1. Food processing wastewater sources

Food processing wastewater has unique characteristics compared with other wastewater sources, including high biochemical oxygen demand (BOD), chemical oxygen demand (COD), dissolved and suspended solids (TDS and TSS), fats, oil, and grease (FOG), and strong odor [22,23]. Generally, it contains low amounts of toxic pollutants (*e.g.* heavy metal, antibiotics, *etc.*), which indicates that there is a higher potential to produce microalgal value-added ingredients (*e.g.*, protein, polysaccharides, pigment, and vitamin) from food wastewater than that from industrial one. In addition, the characteristic difference of food wastewater might have a significant influence on the microalgae growth and value-added ingredients species. For example, if microalgae are deprived of nitrogen, the synthesis of biomolecules rich in nitrogen (such as proteins and chlorophylls) would be inhibited, and biomolecules rich in carbon (such as carbohydrates and/or lipids) are accumulated [24]. Therefore, the overview of different food industry wastewater (such as soybean processing, dairy, starch processing, beverage, meat processing, and oil mill) is presented in Fig. 2, and their characteristics are summarized in Table 1.

2.1.1. Soybean processing wastewater

Bean curd is a common diet ingredient in Asian countries. Processing per ton soybean usually generates about 7 to 10 tons of wastewater with a chemical oxygen demand (COD) of 10 to 20 g·L⁻¹ [16,42]. Generally, soybean processing wastewater contains monosaccharide, oligosaccharides, vitamins, organic acids, amino acids, lipids, whey protein, isoflavone, saponin, P, Ca, Fe, and other nutrients [43,44].

2.1.2. Dairy wastewater

Dairy industry can also generate significant quantities of wastewater. Usually, approximately 0.2 to 10 L of wastewater is discharged to produce per liter of processed milk [45]. Dairy wastewater may be generated by milk equipment and containers washing, quality control, laboratory analyses, and processes of whey, cheese, and ice-cream production [28]. Dairy wastewater is generally characterized by its high chemical oxygen demand (COD), biological oxygen demand (BOD), and volatile solids [46]. Major constituents of dairy wastewater are lactose, soluble proteins, lipids, mineral salts, and detergents [29,30].

2.1.3. Starch processing wastewater

Starch processing wastewater is a typical food processing wastewater that contains abundant organics and nutrients [47]. For example, as the fifth most important staple crop in the world, cassava processing can generate at least 600 L of wastewater to treat per ton of raw root (which

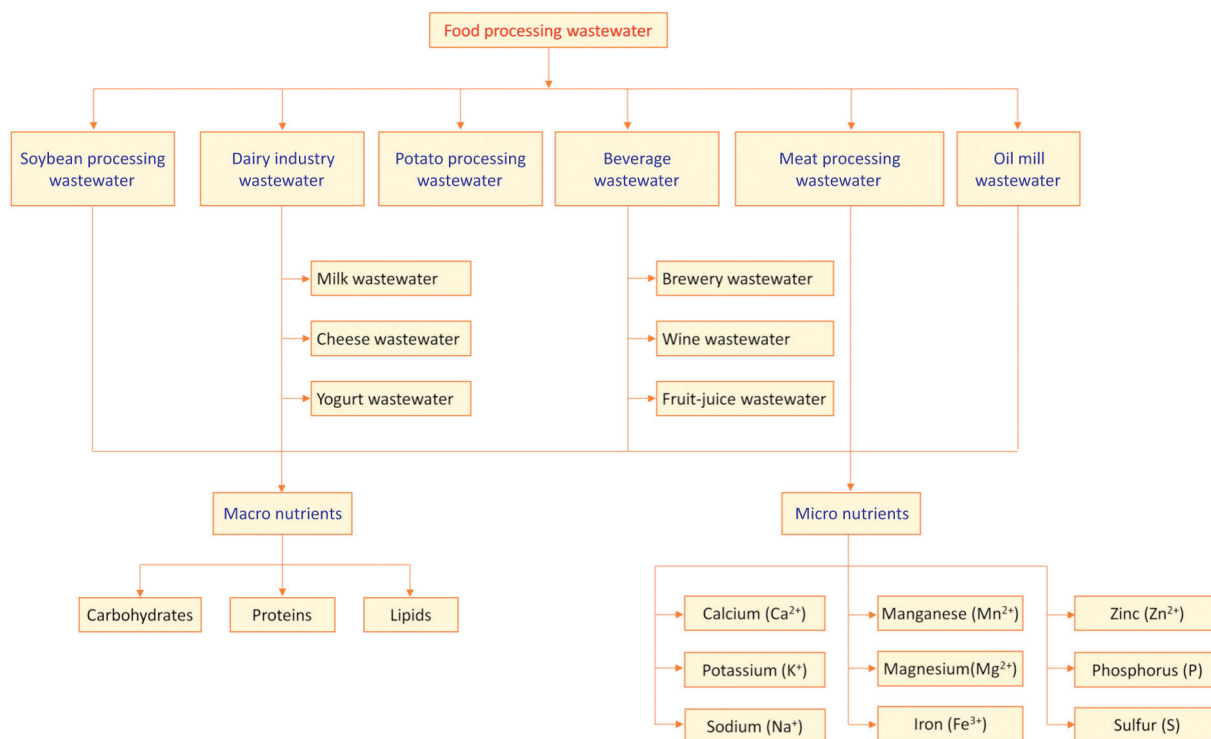


Fig. 2. The characteristic overview of wastewater in food processing industry.

yield is about 285 million tons per year) [31]. Cassava wastewater is a carbohydrate-rich starch waste with high COD, BOD, total solids, and low ammonium–nitrogen concentrations, which is abundant in natural cyanoglycosides [32,48].

2.1.4. Brewery & winery wastewater

According to the FAO statistics in 2014, beer production of dominant countries reached 119 million kl, with Brazil contributing over 10% of this amount (14 million kl) [6]. Brewery wastewater can be generated

during washing, filtration, and fermentation with high loads of organic matter (sugars and yeasts) and suspended solids [7]. It is worth noting that water contributes around 95% of beer, and simultaneously an average of 4.5 L of water is consumed for each liter of beer, with the ratio sometimes being as high as 10:1 [49,50].

The winery industry is a sector of great potential worldwide and approximately 2.8 billion wines are produced every year [51]. The winery industry generates approximately 1.3 to 1.5 kg of residues to produce per liter of wine, 75% of which is winery wastewater

Table 1
Characteristic of different food processing wastewater

Sources of food wastewater	Characteristics	References
Soybean processing	• High organic content, consisting of 40%–60% carbohydrate • High COD ($10\text{--}20\text{ g}\cdot\text{L}^{-1}$) and BOD values derived from the high protein content • High ammonia nitrogen content • Major constituents are lactose, soluble proteins, lipids, mineral salts and detergents, etc.	[25–27]
Dairy	• Generally in neutral conditions • COD concentration is usually between 2 and $10\text{ g}\cdot\text{L}^{-1}$ (whey wastewater up to $70\text{ g}\cdot\text{L}^{-1}$) • High concentration of solids with half of its as in volatile form • Nitrogen and phosphorus contents comparatively lower than other industrial sources • High COD (varied from 6 to $56\text{ g}\cdot\text{L}^{-1}$), and rich in starch and free sugars	[28–30]
Starch processing	• High concentrations of several mineral nutrients • High C:N:P ratio (330:30:1 in molar basis) • Low ammonium–nitrogen concentrations	[31–33]
Brewery	• High loads of organic matter (COD varies from 2000 to $32500\text{ mg}\cdot\text{L}^{-1}$) and suspended solids • Total nitrogen from 25 to $450\text{ mg}\cdot\text{L}^{-1}$ (N-NH_4^+ around 5 to $20\text{ mg}\cdot\text{L}^{-1}$) • Total phosphorus varied from 0.5 to $220\text{ mg}\cdot\text{L}^{-1}$ • Acidic pH (usually varied from 3 to 6), and alkalinity varied from 200 to 3000 • High concentrations of soluble organic acids, ethanol, sugars, and alcohols	[7]
Winery	• High molecular weight compounds (e.g., polyphenols, tannins, and lignin) • High colority • Low pH (usually between 3 and 4)	[34,35]
Meat processing	• High organic content due to the presence of blood, tallow and mucosa, etc. • High nitrogen and phosphorous content • High fat content and high concentrations of dry residues, sedimentary and total suspended matter	[36–38]
Oil mill	• Acidic pH and low alkalinity • High electric conductivity • Low nitrogen content • High lipidic and phenolic fractions (e.g. organic long chain fatty acids and tannins)	[39–41]

[52,53]. It can be generated in washing operations during grape harvesting, pressing, and first fermentation phases. Therefore, amount of sugars, ethanol, organic acids, aldehydes, soaps, and other detergents would exist, and thus easily leading to high COD and TOC, color, and low pH [34,54].

2.1.5. Meat processing wastewater

The meat processing industry contributes the largest proportion (about 24%) of the total freshwater consumed by the food and beverage industry [55]. In the last decades, global meat production has been doubled, and the growth trends would continue until 2050 [55,56]. Along with the increase demand of meat products, amount of wastewater would be generated via slaughter, washing, processing, and packing. It has been estimated that the European slaughterhouse industry produces 145 million m³ of wastewater per year [57]. Typical cold meat industry wastewater has a high content of COD, BOD, fats, oils and greases, high content in total nitrogen (TN) and total phosphorus (TP), intense coloration, and high conductivity [58].

2.1.6. Oil mill wastewater

Palm and olive oil are two typical oil mill products. The palm oil industry is mainly active at Southeast Asia region (e.g. Malaysia and Indonesia) [59]. Olive oil is mainly produced in the Europe (e.g. France, Serbia, Macedonia, Cyprus, Turkey, and Mediterranean Basin) [39]. In Malaysia, the palm oil industry is one of the leading agricultural industries, with an average of crude palm oil (CPO) production over 13 million ton·year⁻¹ [60]. Several million cubic meters of freshwater is used in the olive oil mill industry, and eventually discharged in the form of olive mill effluents (OME) [61,62]. During palm oil production, approximately 1.5 m³ of freshwater is required to process 1 ton of fresh palm fruit bunches (FFBs), and simultaneously, 0.75 m³ of palm oil mill effluent will be generated [63]. Palm oil mill effluent (POME) is characterized by complex substrates comprising of amino acids, inorganic nutrients such as sodium, potassium, calcium, magnesium, short fibers, organelles, nitrogenous constituents, free organic acids, and a mixture of carbohydrates ranging from hemicelluloses to simple sugars [64].

2.2. Physicochemical properties

COD, pH, mixed liquor suspended solids (MLSS), total nitrogen, specific nitrogen (NH₄⁺, NO₂⁻, NO₃⁻), total phosphorous, and total surfactants are the critical parameters that influence microalgae growth and value-added ingredients accumulation. The pH of the waste indicates its freshness, and always changes upon storage or hydrolysis [65].

2.3. Nutritional ingredient

Various organics in the wastewater can be utilized as the nutritional ingredient for microorganism metabolism. For the food processing wastewater, substantial carbohydrates (e.g. potato processing wastewater), fatty acids (e.g. oil mill wastewater and meat industry wastewater), and amino acids (e.g. soybean processing wastewater and meat industry wastewater) are the optimal metabolic feedstock for microalgae growth to produce biofuel or value-added products.

2.3.1. Carbon

Typically, microalgae can fix CO₂ (existing as bicarbonate in algae solution) from the atmosphere by photosynthesis. Compared to inorganic carbon, organic carbon can be more efficient carbon source via heterotrophic microalgae cultivation. Generally, the parameters of BOD and COD for wastewater from the food industry are 10 or even 100 times higher than municipal wastewater, which indicates abundant organic carbon can be used as heterotrophic carbon source [10]. The characteristics of typical wastewater in food industry are summarized in Table 2.

2.3.2. Nitrogen

Protein is an important constituent in food processing wastewater. Nitrogen content varies with the wastewater types and concentration of amino acids. Organic N is originated from inorganic sources, including nitrite (NO₂⁻), nitrate (NO₃⁻), nitric acid (HNO₃), ammonium (NH₄⁺), nitrogen gas (N₂), and ammonia (NH₃) [76]. Algae play a crucial role in transforming inorganic N (including NO₃⁻, NO₂⁻, and NH₄⁺) to its organic formula via assimilation process, which is performed by all eukaryotic microalgae [77].

2.3.3. Phosphorus

Phosphorus is a non-renewable and irreplaceable resource for food production. Along with food processing, phosphorus is discharged as a main pollutant in wastewater that causes eutrophication in natural waters. Every year, approximately 1.3 million tons of phosphorus is discharged in wastewater treatment worldwide [78]. Phosphorous removal from wastewater can be carried out by physical, chemical, biological, or hybrid processes. Currently, the most widely implemented technology is enhanced biological phosphorus-removal (EBPR) processes, because they are the most economic methods to reduce the phosphorus content and avoid anion enrichment of the treated wastewater [12].

2.3.4. Metal ion

Metal ions play an important role in the metabolism of microalgae, as they take part in a variety of biocatalytic reactions, and act as

Table 2
Quality of different food processing wastewater

Source of wastewater	pH	COD/mg·L ⁻¹	TOC/mg·L ⁻¹	T-N/mg·L ⁻¹	NH ₄ ⁺ -N/mg·L ⁻¹	T-P/mg·L ⁻¹	References
Soybean processing	6.1	13215	–	267.1	52.1	56.3	[16,66]
Dairy	7.8	2000–6000	120	300–400	300	20–70	[28,67]
Brewery	3–11	2000–32500	–	25–450	5–21.6	0.5–216	[7,68]
Potato processing	4.5	37000	–	620	190	560	[66]
Winery	2.5–12.9	320–49105	41–7363	10–415	–	2–280	[53]
Slaughterhouse	4.9–8.1	500–15900	70–1200	50–841	–	25–200	[11,69]
Olives oil mill	3.5–6.6	800–135000	7884–8759	50–300	–	107.7–120.2	[39,70]

Source of wastewater	Na/mg·L ⁻¹	Cu/mg·L ⁻¹	Zn/mg·L ⁻¹	Mg/mg·L ⁻¹	Mn/mg·L ⁻¹	Co/mg·L ⁻¹	Fe/mg·L ⁻¹	Ca/mg·L ⁻¹	SS/mg·L ⁻¹	References
Soybean processing	1387	0.55	6.91	173.5	0.21	–	5.16	51.47	1125	[16]
Dairy	345.65	0.3	0.3	28.45	1.25	0.65	1.10	38.10	2.8 ± 0.02	[67]
Brewery	–	0.03	0.17	30.55	0.34	<0.0001	0.08	16.12	540	[71]
Starch processing	226.17	–	1.24	49.12	0.13	–	0.94	126.36	3800	[72]
Winery	424.7	–	–	24.9	–	–	–	20.9	–	[73]
Meat processing	136.3	0.79	0.14	7.96	0.03	<0.01	0.21	22.58	–	[74]
Olives oil mill	5.9	–	–	12.2	0.13	–	0.45–20	5.46	8000–18000	[75]

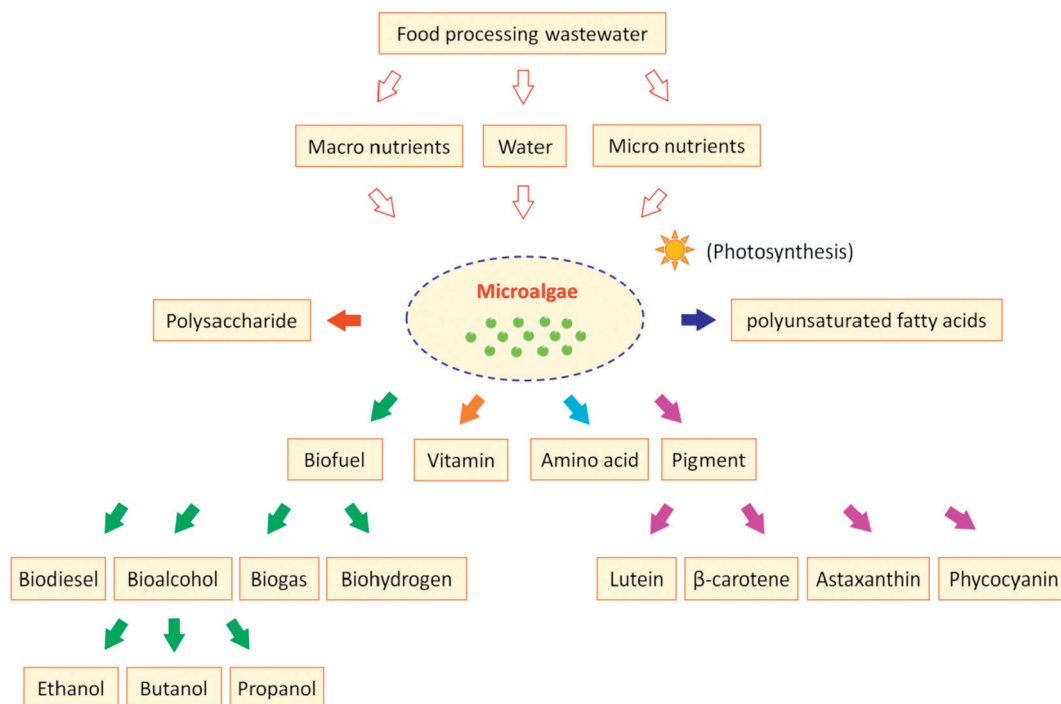


Fig. 3. Food processing wastewater utilization towards value-added products via microalgae cultivation.

cofactors for enzymes responsible for growth and product formation [65]. They also maintain osmotic pressure of the cells in the production medium. Both metal limitation and overload may cause algae cell death [79].

3. Potential Value-added Products from Food Wastewater via Microalgae Cultivation

The treatment of food processing wastewater is significant for environmental protection. Nowadays, most of food wastewater treatment plants (FWWTPs) adopts anaerobic digestion via sludge treatment. However, the low organic loading and biogas (methane) yields are the main challenges due to the low biodegradability of wastewater sludge [80], which lead to energy-intensive of current FWTPs. Process optimization and poly-generation of value-added products along with

food wastewater purification has been recognized as a promising alternative. By reusing macro and micro nutrients in food wastewater, microalgae could be considered as a suitable media to co-product biofuel (e.g. biodiesel, bioalcohol, biogas, and biohydrogen), polysaccharide, pigment (e.g. lutein, astaxanthin, and phycocyanin), amino acid, vitamin, polyunsaturated fatty acids, etc., as shown in Fig. 3.

3.1. Biofuel production

Biofuel has been considered as a green and renewable alternative for fossil fuels. As the third generation, biofuel derived from algae biomass has the advantages of high growth rate and without competition of environment and ecosystem. Meanwhile, cultivation of microalgae can be carried out at the extreme condition (e.g. flue gas or wastewater). Therefore, pollutant purification of food industry effluent could be

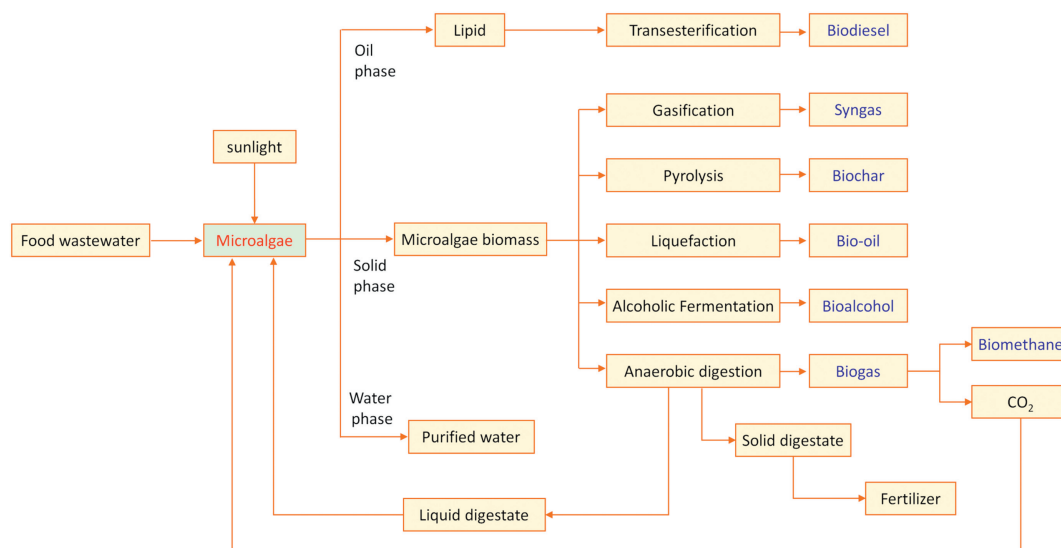


Fig. 4. The potential pathways of microalgal biofuel production via food processing wastewater.

simultaneously realized along with various biofuel production, as illustrated in Fig. 4. Different biofuel can be obtained from the harvested microalgae biomass via biochemical (e.g. transesterification, photobiological H_2 production, anaerobic digestion, and fermentation) or thermochemical (e.g. hydrolysis, gasification, pyrolysis, and liquefaction) technologies [81].

3.1.1. Biodiesel

Lipid, consisted of free fat acid and triglycerides, can be extracted from microalgal cell and used as a promising feedstock for biodiesel production via dry or wet routes [82,83]. For the dry route, the harvested microalgae biomass is dried before transesterification, since water would adversely affect the reaction performance. Drying of algae generally leads to a high algal biodiesel production cost, which contributes around 80% to 90% of the total cost [84,85]. For the wet route, the triglycerides in the wet microalgae biomass is firstly converted into free fat acid by hydrolysis. Then, the esterification reaction is carried out at high water content. The main advantage of wet route is that the energy-intensive drying process is avoided [86,87].

3.1.2. Bioalcohol

Unlike terrestrial crops, microalgae cell wall is sufficient (70% to 72%) in starch, sugar, hemicellulose and cellulose, which can be fermented in anaerobic digester to produce bioalcohol (e.g. ethanol, propanol and butanol) [88,89]. Meanwhile, the starch content of microalgae could be improved (up to 60% in dry mass) by controlling the nitrogen or iron concentration during cultivation [90–92]. However, most of carbohydrates are existed in the microalgae cell wall. Thus, suitable pretreatment (e.g. acidic/alkaline catalysis, enzymolysis, ultrasound, and mechanical disruption) is necessary to release the carbohydrates before they can be utilized as feedstock for fermentation [93].

3.1.3. Biogas

Anaerobic digestion of microalgae biomass, generated from wet microalgae concentration, cell disruption and lipid extraction, is a key panel route to produce gas phase biofuel integrated with biodiesel production [94]. Food wastewater, with its high biodegradability, has been proved to be a desirable carbon source for methane fermentation [95]. Anaerobic digestion can operate in both mesophilic (35 °C) and thermophilic (55 °C) conditions [96]. Constant mesophilic temperature for anaerobic digestion of *Ulva* sp. could achieve 180 ml·g⁻¹ VS of methane yield, but with slower breakdown of organic compounds [97].

3.1.4. Biohydrogen

Hydrogen is regarded as a clean energy carrier because of its advantages of high energy density and being environmentally friendly [98]. Biohydrogen could be generated via photobiological and fermentative ways from algae biomass or biodiesel by-products (e.g. glycerol) [99, 100]. *Scenedesmus obliquus* and *Chlamydomonas reinhardtii* are the most common microalgae for biohydrogen production [101]. Hydrogenase is the main enzyme to catalyze these reactions. Photobiological reaction involves oxidation of ferredoxin by hydrogenase enzyme in electron transfer chain, which liberates hydrogen. In dark fermentation, hydrolysis and acidogenesis are carried out by hydrogen producing bacteria such as *Clostridium* sp., *Enterobacter* sp., *Lactobacillus* sp., *Bacillus* sp., *Klebsiella* sp., *Citrobacter* sp. [102,103]. Conversion crude glycerol into biohydrogen via glycerol fermentation is a low capital and operation cost way, and it can help decrease biodiesel production cost and facilitate the techno-economic feasibility of microalgae biofuel.

3.2. Pigment

Pigments are important nutraceuticals known for their potent antioxidant activities and have been extensively used as health supplements [104]. Microalgae cultivation is a promising alternative route

for natural pigment production, and food wastewater is a potential nutrient source for the growth of algae due to its non-toxic characteristic. To extract pigment from harvested microalgae, supercritical CO_2 or the mixture of CO_2 and ethanol as media could be an uncontaminated and undamaged approach [105].

3.2.1. Lutein

Lutein is a xanthophyll pigment known for its antioxidant activities and its protective role against eye damage [106]. Lutein is also identified as the primary ingredient in microalgal extractions that protect the eye from harmful glycosylation of retina in diabetic individuals, implicating its protective role against diabetic retinopathy [107]. Lutein is used as a food additive (E161b in the European Union) and also as a feed additive to deepen the color of egg yolks and brighten the feather of poultry [108]. The global lutein market was estimated as 135 million USD in 2015 and will continue to rise until 2024 with a growth rate of 5.3% [109]. Although lutein can be commercially extracted from marigold flower petals, it highly depends on seasonal variation. Microalgae can be the potential source of lutein, as many algal species like *Muriellopsis*, *Scenedesmus*, *Dunaliella*, and *Chlorella* can produce lutein at high cellular content from 4 to 7.5 mg·g⁻¹ dry weight of algal biomass [104,110]. Heterotrophic cultures and glucose as carbon source have been proved are the beneficial condition for lutein production via microalgae [111, 112]. Therefore, the starch processing wastewater with high carbohydrate content can be an optimal low-cost feedstock for microalgal lutein production.

3.2.2. Astaxanthin

Astaxanthin has been approved as feed additive and nutritional supplement by the United States Food and Drug Administration (FDA) in 1987 and 1999, respectively [113]. It has the specialty of promoting growth and survival of larvae in aquaculture, improved reproductive performance and egg quality of aquatic animals due to the potent antioxidant activity (500 times higher than α -tocopherol) [114,115]. Currently, commercial astaxanthin is mainly synthesized by petrochemical derivatives (>95%), but the antioxidant capacity is lower than natural astaxanthin derived from microorganism (i.e. yeast, bacteria and algae) [114,116,117]. Heterotrophic cultivation of microalgae for astaxanthin production has been proven to be an economically feasible option for commercially viable astaxanthin [104]. Meanwhile, microalgae can utilize the carbohydrate in the food processing wastewater (e.g. starch industry) as carbon sources, which might facilitate the economic feasibility of microalgal natural astaxanthin production.

3.2.3. Phycocyanin

Phycocyanin derived from *Arthrospira platensis* has been used as a natural pigment in chewing gums, candies, jellies, and dairy products [118]. Furthermore, phycocyanin can be used in clinical, immunological, and diagnostic assays due to its anti-oxidative, anti-inflammatory, anti-carcinogenic, neuro-protective, and hepatic protective effects [119,120]. It should be noted that cultivation of microalgae and extraction of intracellular phycocyanin are the dominant challenges in large-scale production [104]. Meanwhile, microalgae can utilize the organic compounds in the food processing wastewater as nutrients. Heterotrophic cultivation is the suitable mode for natural phycocyanin production via microalgae. Macromolecular components from food processing wastewater can be a promising carbon, nitrogen, and phosphorus source for microalgae growth.

3.2.4. Chlorophyll

Chlorophyll, as one of the main pigment of microalgae, is fat soluble. It can be commonly extracted via organic solvents such as acetone, ethanol and methanol [121,122]. Chlorophyll is usually transformed to sodium copper chlorophyll, which is widely used in the area of food additives, colorants, etc. [123]. However, chlorophyll is sensitive to heat, light, acids, and alkali, being chemically unstable [124]. Therefore,

selection of suitable extraction approach is crucial for efficient chlorophyll production with a high yield.

3.3. Polysaccharide

The polysaccharides generated *via* microalgae cultivation, such as agar, alginate, and carrageenans, have been known as potent gelling and thickening properties, and can be reused in various industries [17]. In addition, sulfated polysaccharides extracted from cyanobacteria, rhodophyta, and chlorophyta can be reused in the field of functional food and medicine for body regulation and healthcare due to their anti-oxidation and anti-inflammatory [121,125,126]. Food processing wastewater, as green and cheap nutrient source, used for microalgae cultivation and botanical polysaccharide production have been widely investigated as a novel therapeutic agent and adjuvant due to their non-toxicity with few side effects [126]. It should be pointed out that most polysaccharides of microalgae are located in the cell wall. Thus, it is difficult to extract microalgal polysaccharides compared with lipid. Until now, the relationship between the structure and the immunomodulatory activity of microalgae polysaccharides is unclear, and further efforts are necessary.

3.4. Protein

Currently, most of microalgae cultivation processes are focused on biofuel production. For food processing wastewater, the protein and polysaccharides co-production is also feasible due to its high value molecules contents and non-toxicity. Meanwhile, the content and amino acid profile of microalgae protein is also abundant, which is suitable for functional food, health care products and animal feed additive [127,128]. Similar to polysaccharides, the major challenge for protein extraction is the low intracellular components availabilities due to the rigid cell wall of microalgae [129]. To overcome the drawback, cell lysis is necessary to achieve a high extraction efficiency of the protein fraction. The common cell lysis techniques include mechanical action (high pressure homogenizers, bead mills), ultrasounds, enzymatic or chemical treatments, thermal or osmotic shocks (repeated freezing/thawing) [129,130]. Recently, ionic liquid, low-temperature high pressure and Pulsed Electric Field (PEF) cell breakage have been paid more and more attention as promising technologies for mild cell disintegration [127,129,132].

3.5. Other value-added ingredient

Vitamin (e.g. VB₁₂ and riboflavin) and polyunsaturated fatty acids (PUFA) (e.g. EPA and DHA) can also be extracted from cultivated microalgae [133]. The production of VB₁₂ from microalgae is dependent on nitrogen (N) availability, and the low-N condition would be more favorable to the accumulation of VB₁₂ compared to the N-replete condition [134]. PUFAs are significant for human and animal health and nutrition, such as in the prevention of various cardiac disorders [135].

4. Challenges

4.1. Techno-economic feasibility of biofuel and value-added compound production

4.1.1. Complex upstream and downstream microalgal bioenergy process

Although integrating food wastewater purification with microalgae cultivation has presented a promising potential in biofuel and value-added products generation, the complex biorefinery routes, including strains cultivation, biomass harvesting, cell disruption, compound extraction, fractionation, and purification (aiming to separate and recover the desired molecules, e.g., lipids, carbohydrates, protein, and pigments), usually lead to the high production cost [136]. Especially, the high energy consumption associated with drying and biorefinery is the dominant challenges [92]. To compete with fossil fuels, high efficient cultivation of microalgae at large scale is significant. Furthermore,

energy-efficient methods for harvesting, lipid extraction and biorefinery are also necessary for cost-effective production of biofuel as sustainable alternative to fossil fuel [137].

4.1.2. Yield and extraction of value-added compounds

Integration of biofuel production with conversion microalgae biomass into value-added products (i.e. pigment, protein, and polysaccharide) could also improve the techno-economic feasibility of food wastewater treatment *via* microalgae. However, some of the value-added ingredients (e.g. polysaccharides) are the structural components in cell walls, which increases the difficulty of extraction [138]. The yield of value-added compounds is usually low because of the lower biomass production after stress treatments, and the number of steps depended on the specific requirement to purity [133,136]. Thus, cost-effective extraction techniques with high yield of different value-added ingredients are necessary to be developed. Solvent extraction has been widely researched as the most conventional approach, and the selection of appropriate solvent should follow the rules of high product yield and be environmentally friendly. Emerging technologies, such as ultrafiltration and microfiltration, have been investigated for the extraction of microalgae products in recent year [133]. Although there are different extraction approaches, it should be ensured that the extracted ingredients must be safe enough to be functional food, drug, or animal feed to realize their additional value. Doubtlessly, more efforts are necessary to enhance the production efficiency and purity of value-added compounds from microalgae.

4.2. Mechanism of converting pollutants in food wastewater into value-added production *via* microalgae

The organic and inorganic pollutants (i.e. carbon, nitrogen, and phosphorus) from food wastewater could be converted into useful macromolecule (i.e. starch, lipid, pigments, proteins) by microalgae in different metabolism pathways (e.g. Calvin cycle, TCA cycle, oxidative phosphorylation, glycolysis, ferredoxin and ferredoxin-NADP⁺ reductase) [136,139]. The reactions that occurred in the microalgal wastewater purification systems are complex, and the knowledge of bioremediation and biosynthesis mechanism is still scarce compared to that of conventional bacteria wastewater treatment processes. In order to intensify the nutrient removal efficiency from food processing wastewater *via* microalgae, it is significant to further understand the mechanisms involved in carbon, nitrogen, and phosphorus conversion routes.

5. Perspective

5.1. Intensification of microalgal-based food wastewater treatment process

5.1.1. Microalgae–bacteria consortium

Microalgae–bacteria consortium presents the beneficial interactions between photo-autotrophic algae and heterotrophic bacteria concerning the exchange of oxygen and carbon dioxide, and then facilitates the efficiency of the food processing wastewater treatment [140]. Bioelectrochemical system (BES) has been regarded as an efficient and environmentally friendly approach for food processing wastewater treatment with simultaneous bioenergy generation in the form of methane and biohydrogen [141]. However, the most critical bottleneck of BESs is its economic feasibility. As an advanced MFC concept, photosynthetic microalgae microbial fuel cell (PMMFC) utilizes microalgae (e.g. *Chlorella vulgaris*) in the cathode compartment with a bacterial consortium as the anode [142]. The potential configuration arrangement of PMMFC is presented in Fig. 5. Two-chambered and single-chambered MFCs are two major types. The former is more traditional, consisting of anode and cathode compartments separated by a membrane. To overcome the weaknesses of two chambered MFC such as low power output, large volume and high costs for aeration, simpler and more

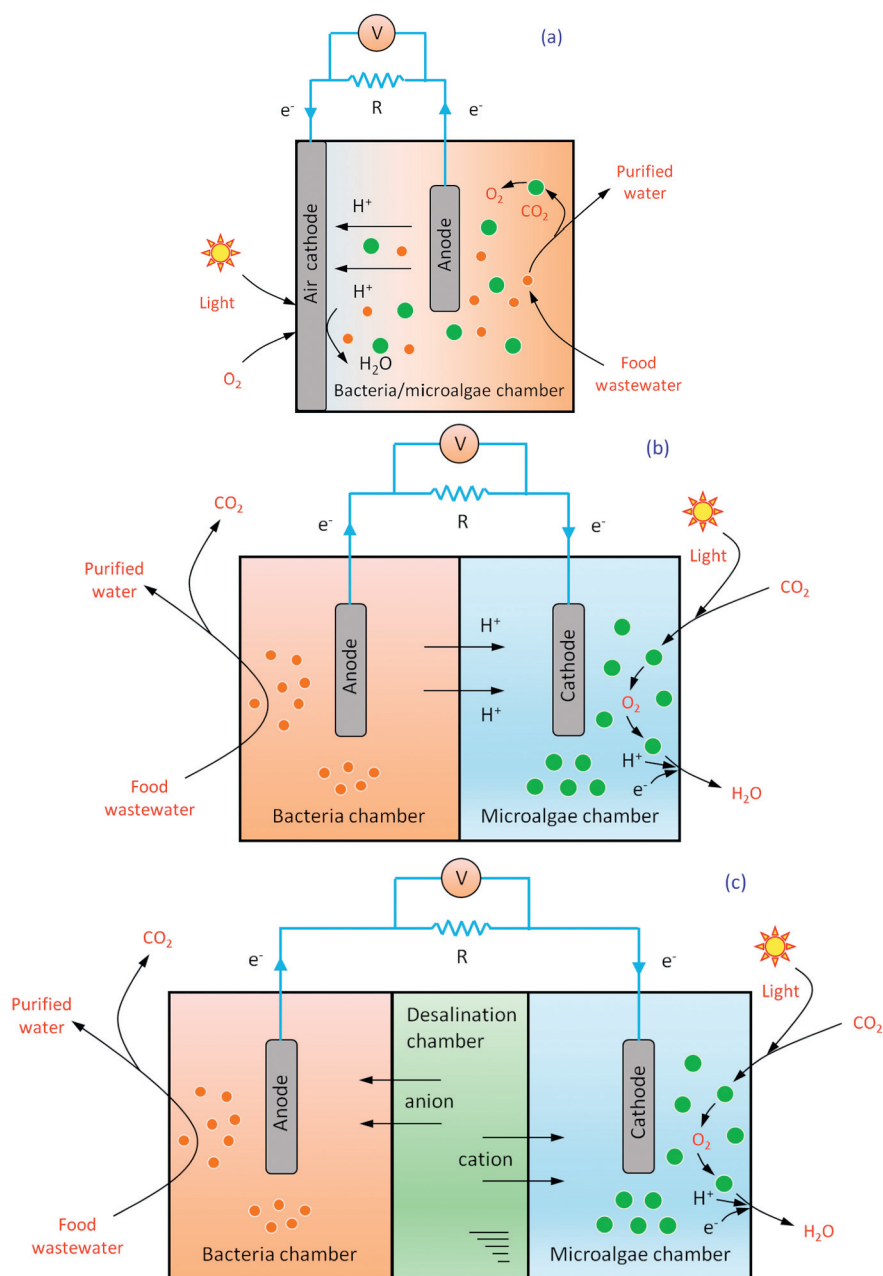


Fig. 5. The schematic of potential configuration for photosynthetic microalgae microbial fuel cell (PMMFC) [143,144]. (a) single-chamber, (b) dual-chamber, and (c) three-chamber.

efficient MFCs are developed by omitting the cathode compartment, *i.e.* single-chambered MFCs (air-cathode MFCs), *via* placing the cathode electrode onto the membrane and exposing the air directly [145,146]. The existing application of microalgae microbial fuel cell (PMMFC) technology in different food processing wastewater is summarized in Table 3. The advantage of PMMFC is that value-added microalgae biomass can be gathered in MFC cathodes with efficient chemical oxygen demand (COD) and nutrient removal in wastewater, and which would steadily increase the economic feasibility of the bioelectrochemical systems [157].

5.1.2. Cultivation mode optimization

Generally, there are three metabolic pathways in microalgae cultivation, namely photoautotrophic (growth by the photosynthetic fixation inorganic carbon through the Calvin–Benson cycle), heterotrophic (growth by the assimilation of organic carbon in the absence of light), and mixotrophic (growth in either metabolic condition) [158].

Compared with photoautotrophic or heterotrophic mode, combination of organic carbon assimilation and simultaneous CO_2 fixation in the mixotrophic mode would be an efficient alternative to enhance growth rates and biomass accumulation [159]. However, the mechanism of photosynthetic pathway (CO_2) and substrate metabolic pathway (organic carbon) concurrent operation is still unclear [160]. Further efforts should be paid on the interaction of each other.

5.1.3. Co-generation of high value-added compounds associated with bio-fuel production

At present, biofuel is one of the most common products for microalgal-based food processing wastewater treatment. However, the production cost of microalgal biofuel is too high compared with diesel because of its complicated process (including cultivation, harvesting, dewatering, drying, extraction, transesterification, and purification). To overcome the high production cost of microalgae biofuel, poly-generation of different value-added produces would be a promising

Table 3

Application of microalgae microbial fuel cell (PMMFC) technology in different food processing wastewater [32]

Source of wastewater	MFC mode	Coulombic efficiency (CE)/ %	COD removal rate/%	Maximum power density (P_{dmax})/ $\text{m} \cdot \text{W} \cdot \text{m}^{-2}$	References
Soybean processing	Single-chamber	33.6	96.4	746	[147]
Cheese whey	Two-chamber	11.3	94	46	[148]
Yoghurt	Two-chamber	4.7	–	54	[149]
Starch processing	Single-chamber	8	98	239.4	[145]
Cereal	Two-chamber	–	95	81	[150]
Brewery	Single-chamber	10	87	205	[152]
Winery	Two-chamber	2	17	105	[152]
Chocolate manufacturing	Two-chamber	–	75	1.5	[153]
Palm oil mill	Two-chamber	0.8	45	45	[154]
Dairy	Two-chamber	37.16	90.46	621.13	[155]
Slaughterhouse	Two-chamber	64	93	578	[156]

alternative [133]. High value-added ingredients such as PUFAs, antioxidants, colorants, proteins, and other compounds can be used to offset the high production cost of microalgal biofuels. These products can be oriented accumulated depending on the microalgal strain [92].

5.2. Gene engineering innovation for efficient microalgae cultivation

Gene engineering is an important tool for the improvement of specific biosynthesis pathways, which can facilitate to understanding the microalgal metabolic and cellular processes [161]. The availability of some advance genetic modification tools makes it possible to engineer microalgae for the efficient production of relevant biofuels and bioproducts [162]. To date, more than 20 microalgae and cyanobacteria species have been sequenced, including species of interest for biofuel, such as *Nannochloropsis gaditana*, *Chlorella vulgaris*, and *Botryococcus braunii* [163]. However, the studies on the metabolism of microalgae cultivated in food processing wastewater are limited. Conventional genetic engineering strategies to enhance specific metabolites rely on modifying individual genes that encode components of a metabolic pathway, but have had mixed success. In some cases, the accumulation or composition of the targeted metabolite can remain largely unchanged. An alternative strategy is transcriptional engineering (TE), which aims to modify multiple components of a metabolic pathway simultaneously, such as by engineering regulators including transcription factors (TFs) [164].

6. Conclusions

Food processing wastewater is rich in nutrient (*i.e.* organic compounds, nitrogen, phosphorus, and metal iron) with trace toxic pollutants (*e.g.* heavy metal, antibiotics). Therefore, it could be a suitable feedstock source for microalgae cultivation to produce high value-added compounds. In this work, the characteristic of dominant food processing wastewater was investigated, and the potential value-added products (*e.g.*, biofuel, protein, pigment, polysaccharides, vitamin, and polyunsaturated fatty acids) could be extracted from treated food processing wastewater. It could be observed that the nutrient composition of different wastewater sources (even for the same source but different processing technologies or units) was also different. Thus, selection of suitable algae species would be critical for efficient purification with maximum ploy-generation of value-added ingredients. Although food processing wastewater could be a potential nutrient source for high value-added compounds production, the techno-economic feasibility should be further enhanced by algae species training, upstream (algae cultivation and harvesting) and downstream (value-added products extraction and purification) biorefinery process optimization. In addition, gene engineering innovation would be also significant for understanding metabolic mechanism of microalgae cell and enhancing wastewater purification efficiency and value-added ingredients productivity.

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