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Microbial Biotransformation and Biomineralization of Organic-Rich Waste

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Abstract

Purpose of Review Improper discharge of industrial effluents would lead to direct contamination of our water, air, and soil systems. Without proper treatment, both these inorganic and organic-matter-containing waste would pose harmful effects towards aquatic organisms, overall water quality, reduction in soil health, and increase in greenhouse gasses from anaerobic microbial degradation activities.

Recent Findings Current treatment technologies involve the use of combined chemical, biological, and physical approaches, which has been proven very effective. Another useful alternative is to utilize the high organic content present in the waste as substrate for the metabolism of microbes as catalyst in industrial processes including water treatment as well as production of useful microbial secondary metabolites such as pigments.

Summary This review highlights some example for the microbial biotransformation and biomineralization of organic-rich industrial discharges. This is important based on its potential to be applied as useful alternative techniques to dispose huge volumes of industrial waste as well as reducing high cost of sustaining biological-based industrial processes that would require substantial investment notably for the microbial growth medium. Nevertheless, clear insight into the engineering aspects of such processes and sufficient knowledge on its feasibility to function properly at pilot-scale level are of paramount importance prior to any commercialization attempts.

Keywords Biodegradation · Organic waste · High strength · Organic nitrogen · Food waste

Introduction

Generally, industrial waste can be divided into two broad types, namely, organic and inorganic. Organic industrial waste is mostly generated from agricultural activities which contain high concentration of organic substances such as various classes of hydrocarbons, oils, lipid, grease, organic chemicals, and others that contributed directly to the biological oxygen demand (BOD) parameter while inorganic industrial waste (mostly toxic) is generated by industries such as metal-processing, textile manufacturing, and printing that contain major compounds such as acids, bases, phenols, cyanide, and heavy metals which can be represented as chemical oxygen demand (COD). For agricultural activities, the productivity is highly dependent on various factors such as soil health, natural gasses, water irrigation, and pollination insects. However, without proper management, intensive agricultural practice would lead to long-term deterioration of environmental quality notably from large

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emission of greenhouse gasses (natural decomposition of animal's manure and excess field-application of fertilizer), huge land clearing activities that would normally include burning of biomass as well as land and water pollution, i.e., uncontrolled application of non-biodegradable chemicals such as pesticides [1, 2].

One example is pineapple plantation activities. Overall pineapple production throughout the world in the year 2019 amounted to around 28.18 million metric tons [3]. A massive increase in pineapple production, particularly canning, has resulted in a huge amount of waste due to the removal of unwanted parts for human consumption and poor fruit handling [1, 2]. The cannery sector normally delivers solid pineapple waste to farmers for use as animal feed or fertilizer [4]. On the other hand, liquid pineapple waste (LPW) is discharged into the nearby river without being treated. Pineapple waste has a high moisture level (over 80%), carbohydrates (50–80%), vitamin C, and beta carotene content [5]. High-value components such as cellulose, lignin, protein (bromelain), and simple sugars are present in various parts and forms of pineapple waste [4]. The use of LPW, for example, as a growth nutrient, is an excellent indicator of how to employ cheap and readily available industrial waste instead of the much more expensive rich-medium, which may present the single most important factor in making this approach commercially viable.

Another example for organic-rich waste is fruit waste which has become a major problem in terms of disposal and treatment especially in huge urban cities with increasing population but decreasing land availability. Currently, fruit waste management through landfilling or incineration is often limited by emission of methane and carbon dioxide gasses during landfilling and incineration and simultaneously generates pollutants and other toxic substances. Food wastes were mainly produced by households, food manufacturing industries, and food service sectors [6]. The residues produced from grain processing (maize, barley, wheat, triticale, sorghum, rye, and oats) and sugar industries (cane and beet) are mostly used for bioethanol production, whereas oilseed wastes (rapeseed, jatropha, canola, palm oil, soybeans, castor, and neem) are used for production of biodiesel.

Some of the currently available systems to treat organic-rich industrial waste include suspended biomass, fixed biomass, combined system, and lagoons which can be operated both in aerobic or anaerobic modes. For aerobic system, examples of processes are conventional activated sludge (CAS), step-feed activated sludge (SFAS), contact stabilization activated sludge (CSAS), completely mixed activated sludge (CMAS), selector activated sludge (SAS), modified Ludzack-Ettinger process (MLE), and enhanced modified Ludzack-Ettinger process (eMLE). Of these, the moving bed biofilm reactor (MBBR) technology offers a flexible, simple, reliable, and cost-effective bioprocess that uses thousands of polyethylene biofilm carriers operating in mixed motion within an aerated wastewater treatment basin [7]. Each biocarrier provides a protected surface area to support the growth of bacteria; the high-density bacteria population, in turn, helps achieve high-rate biodegradation within the system, thus supporting BOD reduction, nitrification, and total nitrogen removal. Apart from MBBR, there is also the integrated fixed-film activated sludge (IFAS) system which integrates biofilm carrier technology within conventional activated sludge [8]. IFAS technology is the first process specifically designed for ideal operation in municipal wastewater treatment/activated sludge processes. Another example is the Bardenpho process [9], a system used in municipal wastewater treatment specifically for nitrogen removal. Depending on the load of the wastewater stream, it can be employed either as a four-stage system (anoxic basin, aerobic basin, second anoxic basin, and a small reaeration aerobic basin) or five-stage system (anaerobic, anoxic, aerobic, anoxic, aerobic).

To date, there are some reports available on the biotransformation or bioutilization of organic-rich industrial discharges into useful products that can be used in various applications. Nevertheless, most of these reports tend to highlight individual utilization of organic-rich effluent for a rather specific application. In view of this, it is the aim of the present review to highlight a more diverse biological-based utilization of organic-rich industrial discharges. In some of the sections, personal experience of the authors in working with real organic-rich industrial charges was also included to enhance the understanding of readers on subject matters discussed.

Health Effects of Pollutants in Organic-Rich Waste

Organic waste or biodegradable waste can be generated from various industrial sectors, commercial activities, or household discharges. Organic-rich wastes, i.e., containing high concentration of organic compounds, are mostly generated from industrial activities. One example for industrial activities that generated high volumes of organic-rich waste is the agricultural sector. Most of the pollutants associated with agricultural activities can be traced from the long-term applications, and sometimes excessive usage, of fertilizers, pesticides, and biosolids or manure [10].

Pesticides can be grouped into several types according to its targeted use, namely, bactericide, herbicide, fungicide, insecticide, molluscicides, nematicide, and veterinary [11]. For cropping activities, insecticides and herbicides were used because the main problem that decrease crop's yield comes from insects and the weed itself [11]. Example for active compound found in insecticide includes organochlorine (OCL), organophosphate, and carbamates while herbicide contains paraquats [12]. OCL, for instance, have been further classified according to their chemical name, toxicity, and their persistence in the environment where from the 20 types of OCL listed, 12 were regarded as highly persistent with long half-life of up to 10–15 years [13]. These include dichlorodiphenyltrichloroethane (DDT), 1,1-dichloro-2,2 bis (p-chlorophenyl) ethane (DDD), dichlorodiphenyldichloroethane (DDE), dieldrin, methoxychlor, chlordane, heptachlor, lindane, isodrin, isobenzan, benzene hexachloride, and mirex. OCL have been reported to result in various human's metabolic syndrome, malnutrition, inflammation, hypertension, and cardiovascular disorders [14, 15]. Primary route for contact between OCL and human is either direct absorption (pre and during applications) or through ingestion of poorly washed food produce [13, 15]. Xu et al. identified endosulfan, as one of the major components in pesticides that may also contribute to cardiovascular diseases [16].

DDT is well documented for its toxicity [17, 18]. Due to its lipophilicity, DDT could easily cross the blood–brain barrier and accumulate in the brain, hence expediting chances on the risk of the development of Parkinson disease [19]. Organophosphates that are considered as week carcinogens [20] may also significantly result in the development of non-Hodgkin lymphoma after being exposed to their component, malathion [21]. Exposure to organophosphates via breathing also may lead to increase of oxidative stress, mitochondrial disruption, and upregulation of the executioner caspase, caspase-3 which will cause cellular death [22]. In the meantime, dieldrin (1,2,3,4,10,10-hexachloro-6,7epoxy1,4,4α,5,6,7,8,8α-octahydro-1,4-endo,exo-5,8-dimethanonaphthalene) has been reported to induce toxic effects such as neurotoxicity, reproductive toxicity, carcinogenicity, and immunotoxicity [23]. A study by Sarty et al. shows that when the embryo of a zebra fish was treated with 0.347–3470 µM of dieldrin, it suffers with cardiac edema, tremors, and several skeletal distortions [24]. In addition, an agricultural health study found that the exposure to dieldrin may result in a 5.6-fold increase on the risk of developing lung cancer [25]. A correlation study between toxic OCL pesticides and breast cancer by Eldakroory et al. shows that there was significantly higher concentration of methoxychlor in tumor tissue samples compared to the surrounding normal tissue [26]. In addition, research by Zeng et al. concluded that methoxychlor shows the highest toxicity to *Daphnia magna* where this situation will be a potential risk to the ecological system [27]. Methoxychlor capacity of subtle toxic effects on body's hormonal system may result in endocrine disorderly property with main effects on reproduction [28]. Long-term exposure to carbamate could result in the alteration of mitochondrial function and T cell activity [20] as well as oxidative stress, alteration in immune and hormone responses and tumor formation [29]. Paraquat toxicity has been reported to proceed through intervention of the intracellular electron transfer photosystem notably the reduction of NADP + to NADPH [30]. In addition, long-term exposure to paraquat can lead to lung, liver, kidney, and brain toxicity in human, and also, multiple organ dysfunctions that would lead to acute pulmonary fibrosis, cardiogenic shock, renal and hepatic failure, and death [30]. Huang et al. studied the effect of paraquat on interleukin-6 (IL-6) and tumor necrosis factor-α (TNF-α) in macrophages where it was reported that the presence of 1 mM of paraquat resulted in significant increase in the fluorescence intensity for reactive oxygen species (indicating toxicity) as well as increase in the expression levels of IL 6 and TNF-α [31].

Long-term and uncontrolled applications of fertilizers can result in the increase in the accumulation of heavy metals in the soil. Most common elements found in contaminated soil from long-term application of fertilizers include Cu, Zn, and Cd [32] with Cd being the most toxic followed by Zn and Cu. Apart from synthetic fertilizers, the application of animal manures as natural fertilizers in agricultural activities is also a well-documented source for heavy metal contamination of soil [33•]. Zhen et al. reported the presence of 0.17 $mg \cdot kg^{-1}$ Cd, 228 $mg \cdot kg^{-1}$ Zn, and 43.6 $mg \cdot kg^{-1}$ Cu in agricultural plots, where these values are much higher compared to agricultural plots added with synthetic fertilizers only [33•]. Cd has been reported to interfere with male reproductive systems and semen quality [34] as well as substantial harm to the lungs [35]. Cd has been reported to cause renal damage on children from damaged proximal convoluted tubules due to mitochondrial dysfunction [36]. Apart from Cd, Cu had been associated with gastrointestinal (GI) side effect such as stomach pain, jaundice, anorexia, and vomiting [37•].

Biotransformation/Biomineralization of Organic-Rich Waste in Various Useful Processes

Based on its high organic composition, organic-rich waste has the potential to be further processed into various useful materials and processes such as activated carbon [38], feedstock for biomethanation [39], biohydrogen production [40], as growth medium for large-scale production of fungi [41], bioelectricity generation [42], algal lipid accumulation [43], and bioenergy production [44], as illustrated further in Fig. 1. Some specific examples for the biotransformation and biomineralization of these organic-rich waste are as given in the following sections.

Fig. 1 Some examples for biotransformation and biomineralization of organic-rich waste into various useful materials and processes

Biotransformation of Liquid Pineapple Waste in Cr Detoxification and Pigment Production Processes

Large-scale remediation is a cost-effective and agreeable method for the treatment of heavily Cr-contaminated soil and recovering metals [45]. One example is the ChromeBac™ system as reported by Ahmad et al. for the biological treatment of Cr-containing wastewaters in a 200-L bioreactor [46]. This system involves the use of LPW as a low-cost growth medium to remove Cr(VI) from electroplating wastewater. ChromeBac™ system was developed in a pilot-scale bioreactor utilizing *Acinetobacter haemolyticus* EF369508 (*A. haemolyticus*) as the main Cr(VI)-reducing microorganisms with rubberwood sawdust as packing material followed by flocculation/coagulation and filtration treatment. Raw Cr(VI) wastewater was mixed with LPW (LPW) as a nutrient for the growth of *A. haemolyticus*. With an outflow concentration of less than 0.02 mg Cr(VI) L^{-1}, complete reduction to Cr(III) was achieved. Ishak et al. evaluated a combined treatment of the ChromeBac™ system and chromate reductase beads to increase Cr(VI) reduction in wastewater using immobilized chromate reductase alginate beads [47]. The bioreactor was supplied with a mixture of 10% (v/v) LPW and neutralized Cr(VI) solutions (30–60 mg L^{-1}) at a rate of 0.11 m^3 h^{-1}. Approximately 90% of the original Cr(VI) was decreased after 24 h of contact inside the bioreactor. Cr(VI) residuals were reduced to between 1.0 and 1.5 mg L^{-1} using immobilized chromate reductase alginate beads packed in a 10-L flow-through column. The ability of glucose to act as the most effective electron donor to increase chromate reductase activity from the crude cell-free extract was also demonstrated in this work, with a maximum specific activity of 9.1 pmol min^{-1} mg^{-1} protein (a decrease of 23% Cr(VI)). This finding supported the statement from Zakaria et al. that LPW with a high glucose/sucrose content is the best carbon source for *A. haemolyticus* growth in the presence of Cr(VI) [48].

Pineapple waste proves to be a valuable substrate with considerable promise if the appropriate measures and technology are used to convert its various components [49]. Rosli and Ahmad reported the potential of *Acinetobacter* sp. and *Cellulosimicrobium* sp. grown in pineapple waste for reducing COD in textile wastewater [50]. The pineapple waste was neutralized prior to use due to the presence of acetic acid and lactic acid, resulting in a decrease in the pH value. Reduction of COD from textile wastewater by *Acinetobacter* sp. and *Cellulosimicrobium* sp. was more than 50% after 5 days of the treatment process. This study suggests that pineapple waste provides nutrients for the growth and resilience of cultures. Nduka et al. found that bio-stimulation of organic wastes such as pineapple, banana, and watermelon waste with indigenous bacteria effectively reduced cyanide levels [51]. The treatment was successful in removing around 98% of cyanide from soil samples contaminated with cassava plant wastewater. Numerous biological parameter studies indicated that the soil's original high levels of cyanide considerably decreased during the bioremediation process. In another study, the potential of using *Aspergillus niger* (*A. niger*) fermented LPW as a source of citric acid for the removal of chromium (Cr), copper (Cu), lead (Pb), nickel (Ni), zinc (Zn) as well as some pathogens from anaerobically digested sewage sludge, was successfully demonstrated [52]. The concentration of the carbon source is critical in *A. niger* citric acid fermentation. The maximum rate of citric acid formation was achieved at 14–22% of sugar in the medium.

Another reported application of LPW is for the production of microbial secondary metabolites such as pigments. Aruldass et al. investigated the possibility of using LPW as an alternative growth medium for *Chromobacterium violaceum* (*C. violaceum*) UTM5 in violet pigment production [53•]. A high violet pigment yield of 5790 ± 10 mg L^{-1} was obtained from the cultivation of *C. violaceum* UTM5 in LPW with the addition of L-tryptophan as supplementation to enhance the pigment yield (Fig. 2). L-tryptophan acted as a precursor and formed basic structure of violacein. It was found that all the carbon, nitrogen, and hydrogen atoms of violacein were derived from two molecules of L-tryptophan and the oxygen atoms are from oxygenation of indole rings of intermediate violacein compound [53•]. Venil et al. have also extracted violet pigment for application in textile dyeing using the same bacteria culture in LPW [54]. *C. violaceum* UTM5 was cultivated in a controlled environment with LPW and the highest pigment yield was 5800 ± 10 mg L^{-1}. The use of LPW, a highly nutritious medium, would create a "shift-up" condition in which *C. violaceum* UTM5 cells would be anticipated to construct additional ribosomes, increasing their capacity for protein synthesis, followed by an increase in protein and DNA synthesis, as well as reproductive rate [55]. In a similar study on the use of pineapple waste as a growth medium to produce a violet pigment, Yatim et al. successfully synthesized the violet pigment on the nanoscale through an encapsulation technique using chitosan-tripolyphosphate nanoparticles [56]. Another pigment produced from bacteria grown in pineapple waste was also reported by Aruldass et al. [57]. The maximum yellowish-orange pigment was produced using *Chryseobacterium artocarpi* CECT 8497 in LPW, L-tryptophan, and potassium phosphate (K_2PO_4).

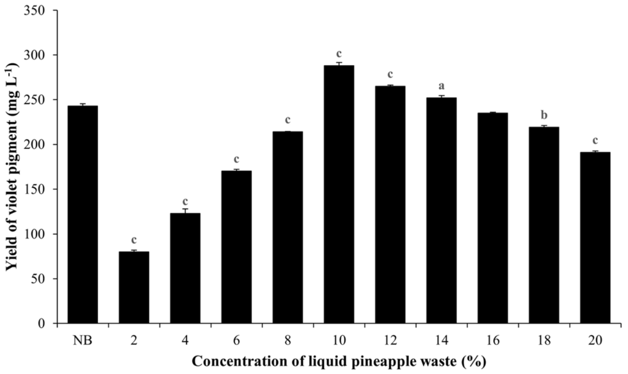

Fig. 2 Pigment production in various concentrations of LPW; results are expressed as mean ± standard deviation ($n = 3$). a$p < 0.05$, b$p < 0.01$, c$p < 0.001$ compared to control concentration, *t*-test [47]

Aerobic/Anaerobic Microbial Biotransformation of Food Processing Waste

Two of the most common types for the treatment of food processing waste are aerobic digestion (composting) and anaerobic digestion. These approaches would normally yield valuable final products that can be utilized in various processes [58]. Aerobic digestion, also known as composting, is an environmentally beneficial treatment process that make use of microbial cultures (bacteria, yeast, fungi, or archaea) to degrade organic waste in the presence of oxygen. Typical biodegradation process of heterogeneous solid organic material takes place in a controlled environment. Nevertheless, the application of food waste as a composting feedstock might not be a straightforward solution due to some of its features such as high water content, high electrical conductivity, high ammonia emission, high nitrogen emission into compost, high nitrification index, and low organic matter which must meet certain conditions in order to be used as soil amendment [59, 60]. The Environmental Protection Agency recognizes five composting types which are on-site, vermicomposting, windrow, static pile, and in-vessel composting [61]. For households or businesses that create small volumes of organic waste, on-site composting is perfect. Vermicomposting is another way to use worms to break down organic waste while for large-scale composting operations, windrow composting is the most frequent approach. The organic trash is stacked in vast mounds and mechanically aerated by big machines. Yard clippings and food waste, as well as fats, liquids, and animal by-products, can all be composted using this method, which are typically not acceptable for small-scale compost piles. Windrow plants produce a significant volume of leachate that must be treated to protect groundwater contamination. Large-scale composting facilities also use aerated static pile composting. It generates a finished product in 3 to 6 months, significantly faster than windrow composting, although it is not suited for oil or animal by-products. In-vessel composting is a more compact technique that can take in a wide variety of organic waste, including meat and biosolids, in a controlled environment [61, 62]. A plug flow reactor, rotating drum reactor, rectangular linked reactor, cylindrical reactor, or batch reactor is used for aerobic digestion [63].

Agitation, forced aeration, and rotating are the three most important characteristics in aerobic composting treatment. For improved treatment, these factors are combined, such as agitation with tumbling and stirring, followed by forced aeration, in which air is allowed to infiltrate the composting mass in all directions. This promotes microbial growth equilibrium, which benefits the many stages of food waste composting, including the lag, log, stationary, and mature phases. Microbes acclimate to their new environment in the lag phase, and then multiply in the log phase. Furthermore, in the stationary phase, these bacteria are allowed to breakdown the organic materials without causing any harm. Finally, the mature compost is removed as a valued end product in the last phase. If these conversion operations are carried out in a well-planned manner, organic waste can be successfully converted into a hygienic value-added product such as mature compost that can be employed as an organic fertilizer source, enhancing ecological agriculture that is also cost-effective [62]. The aerobic digestion of different types of food wastes by mixed microbial cultures is shown in Table 1.

Anaerobic digestion of organic food waste and composting were found to be comparable in their global warming, acidification/eutrophication, and carcinogenic impacts. Due to its potential to produce biogas and biosolids, which may be utilized as a soil amendment, anaerobic digestion has been a more favorable technique of treatment than composting, despite its long start-up time, particular start-up conditions, and high cost. Anaerobic digestion creates a mixture of methane and carbon dioxide from the microbial degradation of organic waste in the lack of oxygen, similar to landfill gas collection. Biogas from anaerobic digestion, like landfill gas, contains pollutants including water vapor and hydrogen sulfide. This gas can be cleaned and used for a variety of purposes, including heating and power generation. Thermophilic and mesophilic temperatures are the two settings in which anaerobic digestion can take place. The digester is kept between 122 and 140 °F in thermophilic conditions. These higher temperatures are necessary for disease eradication and the production of “class A” biosolids. The EPA has certified these biosolids as appropriate for use on farm fields and household gardens with no restrictions. The temperature of mesophilic digesters is kept between 86 and 100 °F. They are simpler to operate, but the biosolids generated are subject to more stringent rules due to their inferior quality. As the diversion of food waste from landfills grows more important, anaerobic digestion is seen as a viable option among alternative waste disposal strategies [62]. Table 2 shows the microorganisms present in anaerobic digestion of food waste.

High-performance Biofilm Reactor Technologies for Organic Nitrogen Removal

Organic nitrogen is derived from not only municipal but also industrial wastewaters. Nitrogen source is comprised of protein, amino acids, and amino sugars mainly in food-processing, textile, explosive, slaughterhouse, livestock, and refinery industries. The choice of treatment technologies depends on wastewater compositions targeted. For treatment of wastewater with a COD/N ratio higher than 12.5, the amount of which nitrogen is assimilated into a bacterial cell, i.e., 8% of nitrogen incorporated into a microbial cell [64], the bioreactor configuration consisting of merely an anaerobic process is not sufficient to remove nitrogen from wastewaters. Therefore, biological nitrogen removal for organic nitrogen-containing wastewaters is essential to avoid nitrogen discharge into water bodies, eventually causing eutrophication. For nitrogen removal from these industrial wastewaters with nitrogen concentrations ranging from 20 to c.a. 3000 mg-N L^{-1} [65•], a choice of a bioreactor type should be carefully made. An activated sludge system has been broadly implemented over the years to remove organic carbon and nitrogen in industrial wastewaters. A biofilm system, where multiple layers of bacterial cell aggregates and their excreted polymers are either self-immobilized or grown onto a substratum, is another choice to strengthen high-performance nitrogen removal. Currently, novel biofilm systems, i.e., an aerobic granular sludge and a membrane-aerated biofilm reactor, have been broadly implemented [66, 67]. For biological nitrogen removal, there are several options such as the conventional nitrification–denitrification or the partial nitritation-anaerobic ammonia oxidation, anammox (PNA) [68]. To accomplish these nitrogen-removing processes, establishing anaerobic and aerobic conditions is imperative. Such distinct redox conditions can be created in a temporal and/or spatial manner (Fig. 3).

To temporarily create distinct redox conditions, a sequencing batch reactor (SBR) with intermittent aeration has been implemented for nitrogen removal from industrial wastewaters. SBR-based technologies employ a fill-and-draw mode where organic nitrogen-containing wastewater is intermittently supplied, followed by mixing for an anoxic condition, aeration for an aerobic condition, and decanting. An SBR is suitable for facilities periodically discharging wastewater and brings benefits because it only requires a single reactor vessel, therefore ensuring a small footprint. In contrast, anaerobic and aerobic conditions can be created by two independent reactor vessels and spatial distribution within bacterial aggregates, e.g., granules and biofilms. The dedicated reactors for nitrification and denitrification, and PNA allow the independent

Table 1 Aerobic digestion (composting) of different food wastes by various microorganisms

Food waste	Microorganism present	Composting types	Bulking agent	Decomposition period	Reference
Synthetic food waste—mixed commercial rabbit food and cooked rice	Mesophilic yeast strain *Pichia kudriavzevii* RB1	Bench-scale composting reactor	Sawdust	3 days	[93, 94]
Household wet biodegradable waste (HWBW)—cooked and uncooked wet waste	Lactic acid bacteria, yeast, and phototrophic bacteria	Recycled plastic drum composting	Grass trimmings and leaves	30 days	[95]
Sugarcane leaves	Thermophilic ligno-cellulolytic microbial consortium (Proteobacteria, Firmicutes, Bacteroidetes, Ascomycota)	Pile-turning composting	Nil	3 days	[96]
Synthetic food waste alone—mixed rice, meat and fish, vegetables and fruits, oil, sauce, distilled water	Effective microorganism (EM)	Home composting	Dried leaves and rice bran	8 weeks	[97, 98]
Food waste—bread and cooked waste and garden waste—grass trimmings, leaves, and small plant	Lactic acid bacteria, yeast, phototropic bacteria	Drum composting (modified composting drum)	Nil	60 days	[99]
Food waste alone—obtained from canteen	Commercial inoculum (Firmicutes, Proteobacteria, Bacteroidetes, Actinobacteria)	Fed batch aerobic composting	Rice bran	30 days	[100]
Synthetic food waste—mixed bread, rice, cabbage, fully boiled pork	Thermophilic	20-L bench-scale reactor composting	Sawdust	35 days	[101, 102•]
Food waste—vegetable and bakery waste	*Salmonella enterica* serovar Typhimurium	Aerated, static, and plowed composting (new closed loop heating system or in door composting system)	Nil	70 days	[103]
Food waste alone—obtained from the dining room of the University of Science and Technology of Beijing, Beijing City, China	Ammonia-oxidizing bacteria (*Nitrosomonas europaea*/eutropha)	Lab-scale composting reactor	Mushroom residue	15 days (under aerobic conditions)	[104]
Vegetable waste	Culture tube media with lauryl tryptose broth and EC medium	550-L batch-scale rotary drum composting	Dry leaves	20 days	[105]
Vegetable and fruit waste	Thermophilic	Home composting system (batch fed)	Nil	150 days	[106]
Food waste—mixed uncooked vegetables (70 kg)	*Salmonella* sp., Actinobacteria, *Bacillus* sp.	Full-scale rotary drum composting	Nil	100 days	[107]
Food scraps and dry leaves—mainly vegetable, rice, and noodles collected from a canteen at Faculty of Engineering, Chiang Mai University, Chiang Mai, Thailand	Lactic acid bacteria, photosynthetic bacteria, and yeast	Passive aeration bins	Nil	2 weeks	[108]

Table 2 Microorganism present in anaerobic digestion of food waste

Food waste	Microorganism present	Treatment condition	References
Vegetable waste	Bacteroidetes and Firmicutes	Effluent recirculation	[109]
Food waste	*Methanosaeta*, *Syntrophomonas*, *Proteiniphilum acetatigenes*	Biological co-treatment	[110–112]
Food waste	*Methanosaeta*, *Methanosarcina*	Microwave pretreatment	[113]
Food wastewater	*Petrotoga* (assigned to phylum Thermotogae), *Petrimonas* (assigned to phylum Bacteroidetes)	Thermophilic and mesophilic anaerobic digestion	[114]

control of the reactors, ensuring robust reactor performances [69, 70•] and faster startup for nitrogen removal from municipal wastewater [70•]. However, setting two separate reactors necessitates a relatively large footprint and capital expenditures. Another choice to create spatial distribution in a single reactor vessel is granular sludge and biofilm onto a substratum. By using a steep gradient of dissolved oxygen concentration within such dense bacterial aggregates, redox zonation can be herewith established. Bacteria responsible for nitrification, denitrification, and anammox would be spatially distributed in favor of preferable redox conditions. The system can be compact and does not require a large footprint. Usually, biofilms are grown, decayed, and detached depending on substrate, environmental, and shear conditions [71, 72]. Controlling biofilm thickness and architecture, i.e., a key to control redox zonation and resultant reactor performances, is a long-standing challenge [66].

Aerobic granular sludge is a powerful and promising biofilm-based technology to achieve a smaller footprint [71]. Dense self-aggregate provides an ultra-fast sedimentation, making it easy to separate biomass and treated water. More importantly, the very dense architecture allows steep redox gradients, resulting in high-performance organic carbon and nitrogen removals. Granulation requires a feast-famine condition; hence, most SBR technologies are preferably employed, whereas a few continuous reactors also exist [72–74]. The technology can be extended not only to nitrification and denitrification but also to PNA [75]. A technology harnessing aerobic granule sludge, i.e., Nereda®, has been commercialized [76] and implemented in more than 70 full-scale municipal wastewater treatment facilities [77]. Broad dissemination to nitrogen removal from industrial wastewaters is highly expected. A membrane-aerated biofilm (MABR) reactor is an innovative technology to achieve energy-efficient nitrogen removal. The reactor consists of a cassette of hollow-fiber bundles or flat-sheet gas-permeable membrane, soaked into a reactor. A gas-permeable membrane achieves bubbleless aeration to the other side where a biofilm is grown, allowing the direct oxygen supply to the biofilm especially for nitrification [78] and partial nitrification [79]. Direct oxygen delivery accomplishes much higher oxygen utilization efficiency than a conventional aeration system, improving aeration efficiency. The excellent oxygen delivery by a gas-permeable membrane was achieved at 10 g-O_2 kWh^{-1} in a pilot-scale MABR [80], approximately five times larger than conventional aeration. Because of this merit, an MABR is currently being commercialized as an energy-saving and cost-effective organic carbon and nitrogen removal technology. Benchmarking of an MABR is ongoing [81]. Another trait of an MABR lies in a counter-current substrate diffusion geometry where oxygen is supplied from the biofilm bottom whereas contaminants from the biofilm surface. This is entirely distinct from a co-current substrate

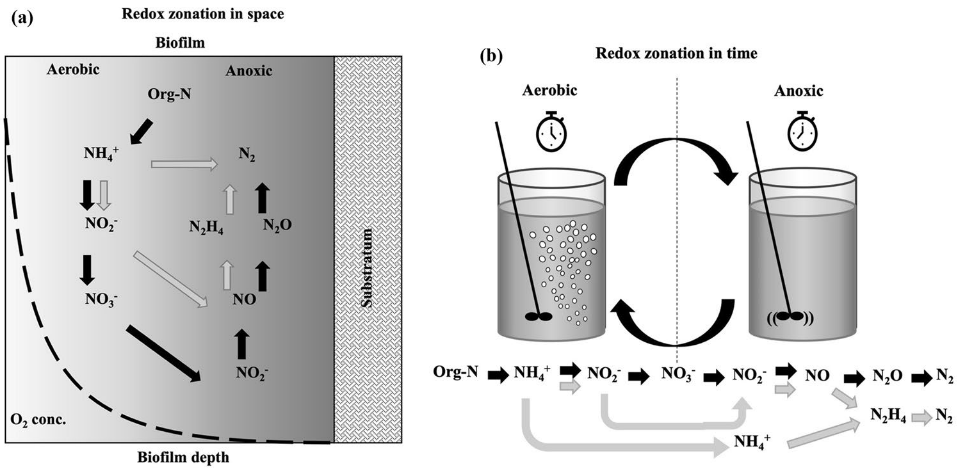

Fig. 3 Nitrification–denitrification process in a biofilm system; **a** redox zonation in space and **b** redox zonation in time

diffusion geometry, i.e., a conventional biofilm where oxygen and contaminants are supplied from the exterior [82]. The counter-current substrate diffusion geometry can achieve more efficient nitrogen removal than co-current substrate diffusion geometry when applied to organic nitrogen-containing wastewater with a low COD/N ratio [83, 84]. The higher nitrogen removal efficiency is ascribed to a hotspot for nitrification, located at a deeper region of a biofilm where DO concentration is high and organic carbon concentration is low. The conceptual model and simulation revealed that an MABR could be advantageous for PNA [85, 86] and experimental validations [87–89]. Furthermore, a counter-current biofilm geometry used as an MABR emits far less nitrous oxide (N_2O) [83, 90], known as a highly potent greenhouse and ozone-depleting gas [91]. One of the major challenges for the broad dissemination of MABR technologies lies in biofilm control [92]. A thicker biofilm increases the distance of ammonia diffused from the bulk liquid to a hotspot adjacent to the biofilm bottom, where oxygen is supplied from the ammonia from the bulk to the active zone. Several trials, e.g., scouring gas or imposing high-velocity liquid, have been implemented; however, generally acceptable strategies await more thorough investigations for implementation in practice.

Conclusions and Future Outlook

In conclusion, organic-rich waste emanating from mostly agricultural activities can become a valuable source for raw materials that can be utilized in various useful processes. This presents a very good opportunity to be explored further notably for agricultural-based countries such as those located in the Asian, South American, Latin American, Africa, and some parts of the Northern American regions. Nevertheless, accelerated processing of natural resources at the levels of over-exploitation implies a negative impact on the environment affecting the availability and cost of these natural resources. Therefore, it is easy to understand why the concept and purpose of a circular economy is taking hold around the world, mainly because it offers new ways to create a more sustainable economic growth model. In view of this, organic-rich waste offers excellent opportunity for scientific exploration, innovation, and technological development, mainly due to the need for its reduction and treatment, or where appropriate the use as valuable source for raw materials that can be utilized in various useful processes. This is envisaged to indirectly influence the overall economic scenario of a country where advancement in technology, knowledge in workers, agricultural practices, and management would promote the shifts in labor to higher productivity sectors which in turn resulted in higher overall household incomes. Full-scale implementation of a well-structured approach in the management of organic-rich waste would present immediate and long-term benefits. For instance, besides promising to be a cheaper alternative for natural resources, proper management of these organic-rich waste would also reduce hazards posed from the presence of non-biodegradable, highly oxidizing, or toxic compounds present, notably from long-term applications of pesticide and fertilizers. Another important focus in sustainable agriculture revolves on the increase in efficiency of biological processes that is integrated with livestock, nutrients, soil, water, and crops. This could directly assist in better nutrient recycling and improved biological nitrogen which would ultimately reduce the amount of organic materials present in our water system. Nevertheless, more studies need to be carried out at the demonstration-scale level prior to full utilization of the organic-rich waste as feed in industrial processes. On the other hand, sustainable agricultural practice also deserves a more serious attention from various stakeholders to ensure minimum impact from agricultural activities to resources, human health, and the environment.

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Compliance with Ethical Standards

Conflict of Interest The authors declare no competing interests.

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