Bioresource Technology 347 (2022) 126739

Contents lists available at ScienceDirect

Bioresource Technology

journal homepage: www.elsevier.com/locate/biortech

Bioconversion of waste-to-resources (BWR-2021): Valorization of industrial and agro-wastes to fuel, feed, fertilizer, and biobased products

ARTICLE INFO

Keywords
Bioconversion
Organic wastes
Agri-residues
Bioeconomy
Value-added products

ABSTRACT

The mitigation of greenhouse gas (GHG) emission is one of the major focuses of The Glasgow Climate Pact, a global agreement that is believed to accelerate climate action. Following the energy sector, industrial and agro-wastes are the major contributors to global GHG emission. With the rapid growth in population, affluence, and urbanization, the GHG emission from waste sector is likely to be further aggravated if timely measures are not taken to address this burning issue. Thus, a significant research and development efforts are being made in shifting conventional waste treatment approach to resource recovery from waste, incorporating a circular bioeconomy concept. There have been significant advances in technologies such as anaerobic digestion, composting, pyrolysis, algae farming, and microbial fuel cell for recovering resources from organic wastes. This virtual special issue (VSI), "Bioconversion of Waste-to-Resources (BWR-2021)", contains 25 manuscripts covering various aspects of wastes and residual biomass valorization to high value products, including development of new technologies, optimization of current technologies for more efficient utilization of wastes and residues. The key findings of each manuscript are briefly summarized here, which can serve as a valuable resource for researchers in the field of resource recovery from wastes.

1. Introduction

The 26th United Nations Climate Change Conference (COP26) held at the SEC Centre in Glasgow, Scotland, United Kingdom, from 31 October to 13 November 2021, brought together 120 world leaders and over 40,000 registered participants. The representatives from almost 200 countries in the COP26 agreed on The Glasgow Climate Pact, a global agreement that is believed to accelerate climate action. The mitigation of greenhouse gas (GHG) emission is one of the major focuses of The Glasgow Climate Pact. One of the major outcomes of COP26 is that over 90% of world gross domestic product (GDP) and around 90% of global emissions are now covered by net zero commitments, while 153 countries have put forward new or updated emissions targets (Nationally Determined Contributions), which covers around 80% of the world's GHG emissions (UN, 2021).

Following the power sector, which accounts for a quarter of global GHG emissions, organic waste (3.2%), burning of agricultural residues (3.5%), and livestock and manure (5.8%) are the other major contributors to the global GHG emission (Ritchie and Roser, 2020). In addition, waste generation will increase significantly with the rapid growth in population, affluence, and urbanization, especially in low- and middle-income countries, thereby further aggravating the waste management issue and GHGs emission. For example, as per the recent World Bank report, nearly 2017 million metric tons of waste was generated in 2018 worldwide and is expected to increase to 2586 million metric tons and 3401 million metric tons in 2030 and 2050, respectively (Kaza et al., 2018). With stringent regulation on disposal of organic wastes in landfill coupled with several environmental concerns such as GHGs emissions, surface water and groundwater contamination, odor emanation, transmission of vectors via birds and insects, there has been significant efforts to eliminate or reduce the disposal of organic wastes into landfill. At the same time, large amounts of liquid and gaseous wastes are also generated as a result of our increasing demand for resources. Thus, there is a critical need to valorize these waste streams into plethora of useful resources including food, feed, fuels, fertilizer, and biobased products.

In recent years, there has been a paradigm shift in the field of organic waste management, from treatment to resource recovery from wastes. There have been significant advances in technologies such as anaerobic digestion (AD), composting, pyrolysis, algae farming, and microbial fuel cell (MFC) for recovering resources from organic wastes, incorporating the concept of a circular bioeconomy. This virtual special issue (VSI), "Bioconversion of Waste-to-Resources (BWR-2021)", contains 25 manuscripts covering various aspects of wastes and residual biomass valorization to high value products, including development of new technologies, optimization of current technologies for more efficient utilization of wastes and residues. Based on their similarity, manuscripts have been grouped into different categories, and the major findings are highlighted in the following sections.

2. Anaerobic digestion

AD has been at the forefront of the organic waste treatment with

https://doi.org/10.1016/j.biortech.2022.126739

Available online 17 January 2022

simultaneous generation of bioenergy (biomethane) and digestate as an organic fertilizer. In recent years, research and development efforts in AD field have been directed towards co-digestion and promotor addition (e.g., biochar, hydrochar, nanoparticles etc.) for process stability and enhancement, process modeling, microbiomes, innovative bioreactor design, bio-electrochemical systems including direct interspecies electron transfer (DIET), machine learning, process control and automation, among others.

Among the different bioresources, crop stalks are one of the most readily available bioresources which has significant potential for generating bioenergy including biomethane through AD, and other biobased chemicals. However, similarly to other lignocellulosic biomass, complex biomass structure hinders the efficient conversion of crop stalks into biomethane through AD. In the review, Guan et al. (2021) summarized the recent research and development efforts in realizing the potential of crop stalks for biomethane generation, including biomass pretreatments and important digester operating parameters. The authors have further discussed the future development efforts for efficient AD of crop stalks.

Apart from complex biomass structure, seasonality of substrate availability is another challenge of AD plants digesting crop residues. To address the seasonality of substrate availability, Luo et al. (2021) examined the potential of co-densification of agricultural residues such as rice straw, sorghum straw, and pig manure as an effective technique for biomass storage. The results revealed that such co-densification not only effectively stored the biomass, but also improved the biodegradability of the agricultural wastes during AD for enhanced biogas production.

2.1. Anaerobic co-digestion

Anaerobic co-digestion (i.e., the digestion of two or more feedstocks) has been applied for over 30 years at industrial scale for successfully digesting a number of different feedstocks. Anaerobic co-digestion has been found effective for enhancing the biomethane production through improved substrate degradability, nutrient balance, buffering capacity, and process synergy and stability. In the review, Kunatsa and Xia (2022) critically reviewed current status and perspectives of biogas technology primarily focusing on anaerobic co-digestion, modelling, and process optimization. The authors have emphasized on the need for further investigation on optimizing the mixing ratios of varieties of co-substrates, seasonal variation in availability of co-substrates, process control, techno-economic analysis, and hybridization of biogas technology with conventional and non-conventional sources of energy.

In another study, Karki et al. (2022) investigated the co-digestion of various organic wastes including coffee pulp, cattle manure, food waste, and dewatered sewage sludge using two different inocula for biomethane production. Furthermore, the study evaluated different kinetic models for predicting anaerobic co-digestion performance and any synergistic effect during anaerobic co-digestion of the selected organic wastes. Compared with the co-digestion ratios tested, the results from biochemical methane potential (BMP) tests showed that mono-digestion of coffee pulp and food waste performed better in terms of methane yield. Furthermore, no synergistic or antagonistic effect was observed for any of the co-digestion ratios tested. Moreover, co-digestion models showed the best-fit for predicting the methane yield during co-digestion of selected co-substrates compared to the conventional mono-digestion models.

2.2. Promotor addition in anaerobic digester

In recent years, there has been significant research and development efforts in improving the performance of AD process through addition of conductive particles including biochar, hydrochar, and nanoparticles, among others. Addition of such promoters have been reported to mitigate AD process inhibition, improve AD stability, support microbial growth, and enhance DIET, thereby improving methane yield and digestate quality. In the review, Hassanein et al. (2021) provided insights on the correlations among DIET, electro-conductive nanoparticles, and AD process stability and efficiency when nanoparticles were added into AD systems. Furthermore, the review explored the interaction of anaerobic microorganisms and DIET, the effect of electro-conductive nanoparticles on microbial community shifts and syntrophic metabolism. Additionally, the authors pointed out limitations and considerations of adding nanoparticles into AD systems.

In another study, Li et al. (2022) assessed how the properties of spent coffee grounds-derived biochar and hydrochar affect AD process for methane production. The results showed that addition of biochar and hydrochar in the digesters enriched the microorganisms genera such as *Pseudomonadaceae, Bacillaceae,* and *Clostridiaceae* which likely participated in DIET. Moreover, redox aromatic hydrocarbons of the biobased carbon materials may be involved in the electron transfer process between microorganisms, thereby enhancing substrate digestion and subsequent methane production.

Kim et al. (2021) investigated the formation and characterization of conductive magnetite-embedded granules in the upflow anaerobic sludge blanket (UASB) reactor treating dairy wastewater. The added submicron magnetite particles self-embedded into anaerobic sludge granules, thereby enhancing the performance and stability (e.g., integrity, settleability, and retention of sludge) in the UASB reactor through the promotion of DIET-based electric syntropy in the methanogenic community.

3. Composting

Composting is one of the oldest biological approaches for organic waste valorization. In recent years, research efforts in composting field have been directed toward the amendments of different additives such as nanoparticles, biochar, and digestate, among others for speeding up the composting process as well as improving the compost quality. Zhang et al. (2021) assessed the effect of iron oxide nanoparticles addition on the dynamics of microbial community structure and their roles in organic matter degradation and water-soluble organic carbon formation during agricultural waste composting. The results showed that addition of iron oxide nanoparticles enhanced the relative abundance of thermophilic microorganisms, organic matter degradation, synthesis of water-soluble organic carbon, and amino acid metabolism. Moreover, the properties of compost matrix were closely linked with the microbial communities and their metabolic functions during composting.

In another study, Wang et al. (2021a) investigated the effects of biochar and digestate amendment on enzyme activities and their stoichiometry during composting of agricultural wastes. The study found that such amendments changed the physiochemical characteristics (e.g., nutrient profile and moisture content) of the composting substrates, thereby significantly increasing the activities of functional enzymes involved in carbon (C), nitrogen (N), and phosphorus (P) conversion during composting. Furthermore, the stoichiometry of C:N:P acquisition ratios were close to 1:1.5:1.5. Digestate amendment significantly decreased the potential C:P and N:P acquisition activities, suggesting microbial communities secreting phosphatases were stimulated.

In another study, Wang et al. (2021c) examined the dynamics of physicochemical characteristics and bacterial communities during the co-composting of distilled grain waste and distillery sewage sludge. The results showed that, compared to mono-composting of distilled grain waste, co-composting resulted in the significant improvement in organic matter degradation as well as quality of compost. Microbial community analysis revealed that co-composting with sewage sludge accelerated the rate of bacterial community succession and improved their stability. These findings provide valuable information for optimizing the co-composting process of distillery byproducts for recovering resources, high quality compost.

4. Polyhydroxyalkanoates (PHA) and polyhydroxybutyrate (PHB) production

Biodegradable plastics, such as polyhydroxyalkanoates (PHA) and polyhydroxybutyrate (PHB), production has gained significant research and development interest in recent years. Although studies have shown than PHA and PHB are naturally produced by various microbes, lower yield and higher production cost are the major challenges for the commercial production of PHA and PHB. Thus, research efforts are being made in improving the yield and reducing production cost of PHA and PHB through engineering design, selection of appropriate microbial strains, and using organic wastes as feedstocks, among others. A review by Chavan et al. (2021) provided a comprehensive summary of current knowledge on polyhydroxyalkanoates (PHA) production by various thermophilic and thermotolerant microbes utilizing pure as well as waste substrates. Moreover, the review emphasized research efforts to better understand the microbial community for the efficient conversation of substrate into PHA as well as techno-economic analysis of such bioprocess.

In another study, Hou et al. (2021) evaluated the effects of process and metabolic limiting factors during bioconversion of acid whey into biodegradable PHB using recombinant *Escherichia coli* LSBJ. The results showed that the recombinant *E. coli* LSBJ could efficiently utilize the acid whey to produce PHB (95% of substrate utilization efficiency, up to 85% PHB accumulation, and PHB concentration of 4 g/L). The results also pointed out that pH, C/N ratio, lactose to lactic acid ratio, and essential nutrients were the main limiting factors in acid whey bioconversion to PHB. The yields were increased by pre-adjustment of pH, inorganic nitrogen sources, and addition of minerals and salts.

5. Algae farming

Algae farming on agro-industrial waste (water) is another advancement in organic waste valorization into feed, fuel, fertilizer, and other biobased products with concurrent waste remediation. Research efforts in algae cultivation have been focused on selection of appropriate algal strain, selection and pretreatment of substrates, designing bioreactor, among others. Wang et al. (2021b) investigated the growth, community composition, and digestate treatment performance of a local algal consortium that was adapted to the dairy manure or municipal sludge digestate pretreated with aerobic bacteria. The performance of the adapted consortium in terms of growth and nutrient removal from digestates were compared with *Chlorella sorokiniana* as a model organism. The results showed a dramatic restructuring of the consortium when subcultured on the digestates, in which *Scenedesmaceae* and *Chlorellaceae* almost completely replaced *Euglena*. Although the consortium was less productive and removed nutrients more slowly compared to *C. sorokiniana,* digestate pretreatment with aerobic bacteria significantly improved both growth and nutrient removal by the consortium.

For the continuous cultivation of microalgae, Tham et al. (2021) investigated the fabrication and optimization of smart photobioreactor and extraction tank incorporated with the Internet of Things (IoT) for remotely monitoring the critical operating parameters including liquid level, temperature, and pH condition. In the up-scaled photobioreactor and extraction tank, water-proof sensors were deployed using Arduino NodeMCU board, where sensors were linked with a smartphone application, Blynk, that allowed monitoring the operating parameters remotely. The results showed that sensors were highly accurate in monitoring the critical parameters except for photobioreactor liquid level.

6. Reactor configuration

In the wastewater treatment field, a significant research and development efforts have been made on microbial electrochemical system (MES) as an alternative to energy-intensive conventional processes/technologies for efficient removal of pollutants with concurrent electricity generation. Among such research efforts, use of microbial cathode and microbial separator as an alternative to costly conventional ions exchange membrane is believed to significantly reduce the capital cost of MES technology. By employing the microbial separator installed biocathode MES in wastewater treatment, Li et al. (2021a) investigated nitrogen removal efficiency, functional bacteria composition, and nitrogen metabolism routes. The results showed that nitrogen metabolism was dominated by cathode compartment and restricted by ammonia oxidation reaction; simultaneous nitrification and denitrification was main route for nitrogen metabolism; and microbial separator compensated simultaneous nitrification and denitrification.

In another study, Siddiqui et al. (2021) assessed the integration of self-forming dynamic membrane (SFDM) filtration module and membrane-aerated biofilm reactor (MABR) for autotrophic nitrogen removal. Compared to the MABR reactor without SFDM, the reactor with SFDM resulted in the better reactor performance in terms of total nitrogen removal (more than 80%) and effluent suspended solids (less than 1 mg/L). Incorporation of SFDM in the MABR also retained the more slow-growing microbes such as annamox, in the bioreactor. 16S rRNA-based microbial community structure analysis revealed the difference in abundance and composition of microbial communities in the two MABR, while principal component analysis showed a positive correlation between reactor performance, membrane characteristics, and microbial communities.

Similarly, Saket et al. (2021) used an innovative integration of earthen separator-based dual-chambered unplanted constructed wetland and MFC for treating high molecular weight diazo Congo red dye (as a model pollutant) with concurrent electricity generation. The study found that the innovative design was not only effective in chemical oxygen demand removal (96%), dye decolorization (90%), and phytotoxicity abatement, but also in generating high power density (235.94 mW/m^3) and current density (1176.4 mA/m^3). Results manifested that dual-chambered constructed wetland coupled with MFC has a high potential of wastewater treatment with simultaneous bioelectricity generation.

7. Production and application of biochar for removing pollutants

Conversion of organic residues to biochar and its application in agricultural and environmental sectors has gained research and development priority. In recent years, tailor-made biochars are being produced, characterized, and tested in diverse agricultural and environmental applications. Zhou et al. (2021) studied the potential application of biochar derived from manganese (Mn)-enriched *Phytolacca acinosa* Roxb. residue in removal of lead and tetracycline. More specifically, the authors investigated the effect of pyrolysis temperature on stabilization of heavy metals in the biochar and its effect on lead and tetracycline removal during pyrolysis of *Phytolacca acinosa* Roxb. residue derived from phytoremediation site. The results showed that 450 °C was the most suitable temperature for heavy metals stabilization in biochar. Furthermore, the presence of Mn in the biochar enhanced the removal of lead and tetracycline. Interestingly, binary adsorption showed that lead would serve as a bridge between biochar and tetracycline by complexation, thereby facilitating their simultaneous decontamination. Thus, the study revealed that pyrolysis could be an effective approach for the disposal of Mn-enriched plant residues after phytoremediation, thereby resulting in an alternative sorbent for wastewater treatment.

In another study, Yao et al. (2021) explored the potential of magnetic magnesium ferrite ($MgFe_2O_4$) biochar (MMB) derived from pomelo peel for effective elimination of antibiotics, levofloxacin, through persulphate activation. The study found that MMB could not only remove 88% of levofloxacin, but also it could be reused maintaining removal efficiency of 68% after reusing three times. The results further indicated that the active sites in MMB induced the persulphate activation, while both the non-radical pathway and the direct electron-transfer pathway advanced levofloxacin degradation.

8. Microbiome

Microbial community structure is one of the most important factors for the bioconversion of bioresources into value added products as well as biological waste remediation. By correlating microbial community structure with the operating parameters and performance of biological processes, bioreactor could be operated more effectively. For example, performance parameters could be controlled to facilitate the growth of the core microbial communities. While investigating the spatial and temporal development of microbial assemblages (granules, biofilms, planktonic) in the reactor treating long-chain fatty acids (LCFA)-rich wastewater at low hydraulic retention time (HRT) of 12–72 h, Singh et al. (2022) found that granular, biofilm, and planktonic assemblages differed in diversity, structure, and assembly mechanism, thereby demonstrating a spatial compartmentalization of microbiomes from the initial community reservoir. Furthermore, LCFA loading rates and HRT significantly affected microbial community dynamics and assembly (diversity, composition, and core and dynamic taxa). Such understanding of microbial community dynamics and assembly in the anaerobic digestors treating LCFA-rich wastewater will contribute to effective bioconversion of waste(water)-rich in fats, oil, and grease.

In another study, Cui et al. (2021) studied the impact of polyamide, a prevalent microplastics, on the performance of the partial nitrification system and dynamics of microbial communities including abundance of nitrifying functional bacterial and antibiotic resistance genes (ARGs). The results showed that addition of polyamide slightly affected the ammonia oxidation rate in the partial nitrification system, in which ammonia oxidation rate decreased slowly with the increase of polyamide concentration. More importantly, long-term addition of polyamide decreased the microbial diversity, altered microbial community structure, and facilitated the propagation of ARGs, thereby accelerating the risk of the ARGs spread including *fabI, intI1* and *Tn916/1545.*

9. Others

Some of the manuscripts included in this SI have covered very diverse topics on waste-to-resource recovery field ranging from characterization and valorization of agro-industrial wastewater to application of microbial electrochemical technologies (METs) for valorization of food waste, and volatile fatty acids (VFAs) production from grass waste to pyrolysis of waste surgical masks. For example, Martinez-Burgos et al. (2021) critically reviewed the global production of major agro-industrial wastewater, their physiochemical characteristics and environmental impacts. Moreover, the article discussed on potential of recovering resources including bioenergy and biobased products from such agro-industrial wastewater. The review has also pointed out the research gap and future perspectives for efficient bioconversion of agro-industrial wastewater into bioenergy and biochemicals.

In another review, Chung and Dhar (2021) provided a comprehensive critical review of the application of METs for recovering various value-added products such as bioelectricity, biogas, platform chemicals, algal lipids from food waste to promote a circular bioeconomy. Moreover, the review discussed existing challenges, ways to optimize the system performance, and future research needs.

By employing an 80-L bioreactor fed with grass wastes, Jones et al. (2021) evaluated a novel combination of solids separation and membrane technologies (e.g., solids screening, centrifugation, microfiltration, pervaporation, and electrodialysis) to recover VFAs, increase their yields, increase acetic acid proportions, arrest methanogenesis, and increase substrate utilization rates. The integration of the technologies resulted in not only the recovery of a VFA mixture of 4500 mg/L, but also increased VFA yields from 707 mg/g_{vs} to 875 mg/g_{vs}, acetic acid proportions from 49% to 68%, and substrate utilization rates.

In another study, Li et al. (2021b) investigated the potential valorization of waste surgical masks into fuels and bioenergy via pyrolysis and its environmental merits based on life cycle assessment. The study found that pyrolysis of the waste surgical mask occurred at the temperature range of 456–466 °C, resulting carbon-rich and oxygen-deficient liquid oil with a high thermal stability and high heating value of 43.5 MJ/kg. The life cycle assessment revealed that the pyrolysis of the waste surgical mask to generate liquid oil is more environmentally-friendly compared to conventional waste management practices.

10. Conclusions

There has been significant progress in the field of organic waste management, from waste treatment to resource recovery incorporating a circular bioeconomy concept. A significant research and development efforts have been directed towards the technologies such as AD, composting, algae farming, pyrolysis, and MFC for organic waste valorization into food, feed, fuel, fertilizer, and biobased products with concurrent waste remediation. This SI highlights these advances through research and state-of-the-art review articles. This special issue also provides challenges and future perspectives of the waste-to-resource field.

Acknowledgements

We are thankful to all authors of the selected manuscripts for sharing their works and also to all the reviewers for their valuable time and efforts in reviewing the manuscripts. Furthermore, we greatly acknowledge the full support of Prof. Ashok Pandey, Editor-in-Chief, the Publishing Editor, Dr. Adam Fraser, Journal Manager, Leonard Daniel, and SI Content Developer, Ms. Hannah Zhang of Elsevier for their relentless support in publishing this special issue in a timely manner.

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