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Sustainable bioprocess technologies for urban waste valorization

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ABSTRACT

Industrialization and rapid growth of population have led to an increase in the generation of urban wastes. A significant portion of this waste constitutes the organic fraction which could be utilized as a bioresource for recovery of value-added products (biofuels, biochemicals, enzymes, bioplastics, bioelectricity), via bioprocessing technologies such as anaerobic digestion, microbial fermentation and bioelectrochemical systems. Bioprocessing of urban waste is the most reasonable method among the existing diverse methods of waste management in terms of its cost, potential and generation of non-toxic products. This review exclusively covers the strategies adapted for bioprocessing of urban waste. The microbes used during the bioprocessing of these wastes, are known to have a significant potential for degradation of organic waste fractions. In addition, bioprocessing technologies could be combined with other waste treatment methods to enhance the efficacy of waste management. However, these technologies could be successfully implemented only when they receive the support from the national and local governments.

1. Introduction

Sustainable development goals (SDGs) launched by the United Nations, are relevant for making more efficient, effective, and equitable usage of current bioresources [1]. The SDGs have identified urban waste as a valuable resource for the recovery of value-added products [2,3]. The utilization of urban waste is well-aligned with some key objectives defined by the SDGs such as SDG 7 (affordable and clean energy), SDG 12 (ensure sustainable consumption and production patterns), SDG 13 (take urgent action to combat climate change and its impacts) [1]. Urban waste in the developing countries mostly goes into unorganized dumping grounds while a major portion of such waste gets burnt onto open fields [4,5]. There is an urgent need to develop economic, environment-friendly and socially acceptable approaches for efficient management of the urban waste [2]. Low and middle-income cities mostly generate organic waste which is biodegradable in nature while the high-income cities lead to highly diversifies composition of waste with a large share of plastic waste [6]. In developing countries, the practices associated with urban waste management often focus largely upon collection of such wastes followed by dumping in landfills. Fewer attempts have also been made to adapt to integrated waste management practices involving: (i) waste reduction at the source, (ii) reuse, (iii) recycling and (iv) recovery of valuable resources [5,7,8]. All of these would be advantageous in terms of reducing the volume of waste and the emissions of greenhouse gases [3,4,9]. Energy recovery methods could serve as alternative waste management options for the non-recyclable combustible wastes [10,11]. Besides reducing the environmental and public health impacts, these urban waste valorization methods could extensively contribute to the creation of new employment opportunities [6]. The valorization strategies are dependent upon the composition of the waste. The significant kinds of urban solid wastes include food scraps, plastic, paper, glass, metal, clothes, batteries, electric lights etc [12]. These waste streams originate from family units, workplaces, shopping complexes, schools, road cleaning and others [13]. The urban waste streams often include all kinds of modern solid wastes, municipal wastewater, stormwater and hazardous wastes [14,15].

In this review, the authors have highlighted the importance of sustainable bioprocessing strategies for valorization of urban wastes over traditional thermochemical or physicochemical methods. The bioprocess technologies such as anaerobic digestion, microbial fermentation (enzymatic process) and microbial bioelectrochemistry have been discussed in subsequent sections. Further, biorefinery approach is proposed for effective valorization of urban wastes.

2. Overview of urban waste treatment technologies

Efficient management or treatment of urban waste has always been on priority due to the limited availability of landfills and dumping

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grounds. The urban waste treatment technologies have been categorized into three major categories:

2.1. Physicochemical treatment

Physicochemical treatment includes the conversion of feedstock into value-added products via physical and chemical processes. Transesterification of utilized vegetable oils, fats and similar feedstocks into biodiesel or fluid fills is an example of physicochemical treatment [16].

2.2. Thermochemical treatment

Thermochemical treatment involves application of heat to the natural wastes for creating heat energy or for transforming such waste into biochar or gas or oxygenated fuel oil. This treatment is apt for the urban wastes containing a significant level of natural non-biodegradable matter [17,18]. Burning, gasification and pyrolysis are among the fundamental innovative choices under the thermochemical treatment. Urban waste could be heat transformed via ignition using an oxidant such as oxygen which leads to the production of steam and carbon dioxide [19]. Raised temperature and incomplete air is required for gasification to generate gases and synthetic substances as co-products. Pyrolysis requires absence of oxygen and elevated temperature as essential prerequisite [20,21].

2.3. Biological treatment

Biological treatment or bioprocessing of urban wastes includes the production of liquid or methane gas via enzymatic treatment of urban waste. The biochemical conversions are usually favoured for urban wastes having higher biodegradable organic content along with significant levels of moisture which reinforces microbial action. Such conversion is often known as anaerobic processing/biomethanation [22]. The high water content of the organic fraction of urban solid waste often makes its heat transformation wasteful in terms of energy recovery which can be taken care of through anaerobic digestion or microbial fermentation [23,24]. Biological treatment strategies or bioprocessing technologies such as anaerobic digestion and microbial fermentation have been proposed for valorization of urban solid wastes. Microbial electrochemistry is another recent bioprocess technology specifically proposed for urban liquid waste streams.

3. Bioprocess technologies for valorization of urban waste

3.1. Anaerobic digestion

Anaerobic digestion of urban wastes is a promising valorization approach used worldwide to effectively manage/dispose this waste. Bioprocessing of urban waste streams via anaerobic digestion minimizes the future ecological effects these waste streams. This valorization method involves the conversion of urban solid waste into energy with natural manure rich in supplements. During anaerobic processing, specific microbes are used for converting organic fraction of urban waste into biogas (a mixture of methane and carbon dioxide) and digestate. The removal of the digestate from an anaerobic digester in a landfill has an advantage of minimizing the mass and volume of waste, followed by inactivation of organic and biochemical substances, reduction of landfill gas and immobilization of poisons that pollute the leachate [25]. The anaerobic digestion of the organic fraction of urban wastes has been comprehensively reviewed in literature [23,26–28].

3.2. Microbial fermentation and enzymatic processes

The heterogenous composition of urban wastes is often a challenge while processing this waste.

The specific presence of glass, metals and plastics, makes it difficult to efficiently utilize the biodegradable fractions of this waste. Strategies such as anaerobic digestion and thermal gasification often require the fractionation of urban solid waste which results in the possible loss of biodegradable material while removing the inorganic matter. Consonni et al., have reported that 30–70% of the organic fraction was lost during mechanical fractionation done prior to anaerobic digestion [29]. The literature also supports that there is a requirement for a simple technology which could efficiently fractionate the organic waste from the inorganics without the loss of substrate [30,31]. Jensen et al. have reported a simple enzymatic liquefaction process where the liquefied biological components of the urban solid waste could be separated from plastic, glass and metals. The pumpable slurry of biological components could readily be applied to biochemical or thermo-chemical conversion processes [32]. The enzymatically degraded organic fraction can then be converted into biofuels and biochemicals via fermentation. However, the main challenge associated with the establishment of microbial biorefineries on an industrial scale is the development of a suitable strain [33]. Different aspects need to be taken into account during the development of strain by metabolic engineering. A successful cell factory development includes selection of appropriate feedstock, bioprocessing steps and downstream processes. Fig. 1 represents a schematic of engineered microbial cell factory for production of value-added products from urban wastes. The rapid advances in this field promise a successful establishment of microbial biorefineries which could produce biofuels and biochemicals from organic fraction of urban wastes and other similar biomass. Metabolic engineering could be a game changer in creating commercial microbial cell factories by engineering strains that can produce target products efficient enough to meet the requirements for large scale bioprocessing of urban wastes.

3.3. Microbial electrochemistry

Microbial electrochemistry is the technology that utilizes the ability of bacteria to generate electric current [34]. Initial goals of microbial-bioelectrochemistry or bioelectrochemical system (BES) were focussed upon treatment of urban waste streams and generating electricity [35,36]. However, so far the portfolio of applications of BES has increased to various areas such as bio-electro remediation, desalination of xenobiotic substances, biodegradation of urban waste water and polluted soil, nutrient retrieval, metal recovery or the bio-electro-synthesis of value-added products, amongst other applications [37,38]. Table 1 summarises the bioprocessing of urban waste streams for energy recovery via bioelectrochemical systems. The extensive progress made in the areas of BES has led to a significant shift from the laboratory-scale to the pilot-scale studies [39] getting closer to the commercial expansion [40]. BES could pave the way for multiple uses which is contrary to the traditional fermentation industrial routes where a single product is of major importance. When BES is focussed upon production of value-added chemicals, the electric energy provided gets converted into chemical energy and stored in the form of value-added products such as hydrogen, methane, formic acid, acetic acid and others [41,42]. Research has been carried out to generate value-added products via BES using urban wastewater in particular. Such waste streams could directly be used for this purpose or might undergo pretreatment for converting complex waste feedstock into simple sugars and volatile fatty acids (VFAs) [43]. VFAs and simple sugars can then be used as potential substrate for the synthesis of value-added products.

4. Biorefinery concept applied to urban wastes

The concept of biorefineries comprises of integrated biobased industries focused upon complete utilization of bioresources applying a wide range of processing strategies [52]. A biorefinery is similar to petroleum refinery where crude oil is fractionated into a wide portfolio of products such as fuels and raw materials for the petrochemical

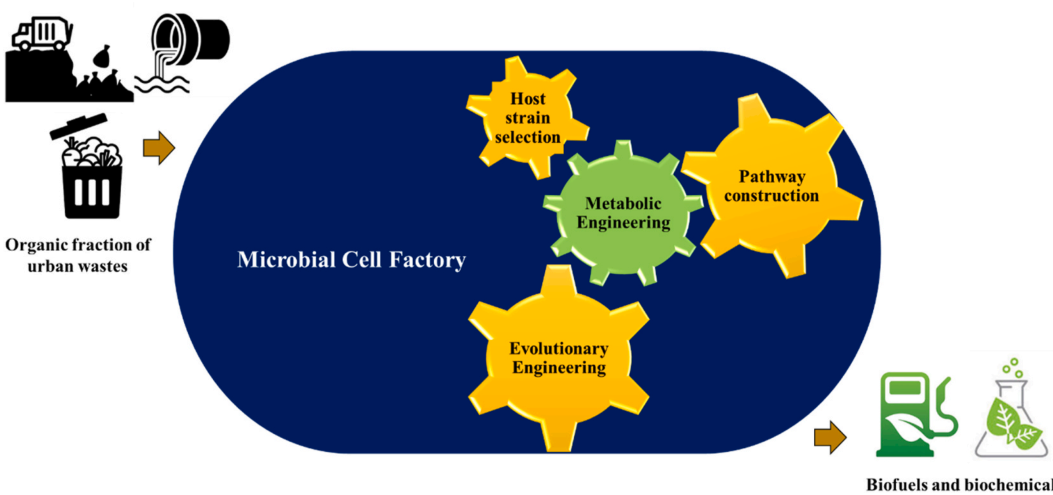

Fig. 1. Schematic representation of microbial cell factory for production of biofuels and biochemicals from organic fraction of urban wastes.

Table 1
Bioprocessing of urban waste sources (wastewater) for energy recovery via bioelectrochemical systems.

Urban waste stream (s)	Microorganism (s)	Type of reactor	Bioelectricity	COD removal efficiency	Reference
Wastewater from brewery	Geobacter species	Double chamber MFC	0.35 W/m^3	83%	[44]
Wastewater from fish market	Ochrobactrum (26%), Marinobacter (21%), *Bacillus* (15%), Rhodococcus (11%), Flavobacterium (8%), Martelella (5%), *Pseudomonas* (6%), Stenotrophomonas (4%), Alicyclobacillus (3.5%) and Xanthobacter (0.5%)	Air cathode MFC	420 mW/m^2	90%	[45]
Silver laden artificial wastewater	*Pseudomonas aeruginosa* (MK 163529)	Double chamber MFC	3006 mW/m^3	83%	[46]
Landfill leachate	Geobacter sulfurreducens	Single-chamber MFC	344 mW/m^3	90%	[47]
Seafood wastewater	halophiles such as Ochrobactrum, Bacillus, Alicyclobacillus and Marinobacter	Air cathode MFC	570 mW/m^2	58%	[48]
Vegetable oil industrial wastewater	mesophilic microorganisms	Double chamber MFC	2166 mW/m^2	90%	[49]
Agro-food industry wastewater	electroactive bacterial species	Double chamber MFC	27 W/m^3	83%	[50]
Urban wastewater	exoelectrogenic bacteria	Single chamber MFC	13.2 mW/m^3	86%	[51]

MFC means microbial fuel cell.
COD means Chemical Oxygen Demand.

industries [52]. The current studies have demonstrated the development of biorefinery concept based upon homogenous feedstock from industry and agriculture. However, the valorization of urban waste (including restaurant and kitchen waste) in a biorefinery concept is limited due to the mixed nature of such waste with a complex composition [53]. Variation in feedstock composition might be challenging to handle in a biorefinery approach [54]. That is why the use of urban solid wastes in biorefineries is studied less. Table 2 represents a few studies where the organic fraction of urban waste has been valorized via bioprocessing strategies in an integrated biorefinery approach. Vea et al., 2018 have reported a few examples where mixed urban waste was used as a feed-stock for recovery of value-added products [54]. The study provide evidence that urban waste (specifically the organic fraction) could be considered as a resource by estimating the efficiency of valorization efficiency and the potential revenue that can be generated out of it. The study also suggests that producing biopesticides and enzymes from the organic fraction of urban wastes in an integrated biorefinery approach could generate high revenues. However, challenges do exist while upscaling this technology due to the complexity of biological products being produced and hence, further efforts are recommended to be concentrated in technology development. In addition, there exists a need to address the technoeconomic feasibility, environmental benefits and impact of such emerging valorization approaches in the future.

5. Conclusion and future perspectives

The application of sustainable bioprocessing technologies is useful is the recovery of resources from the organic fraction of urban wastes. It helps to achieve a desirable shift from the traditional linear to circular (bio) economy. Sustainable bioprocess method such as anaerobic digestion is a realistic feasible process for effective management of urban waste. However, in order to commercialize this technology, tax reductions should be incorporated for the use of sustainable power or biogas. Further awareness should be created with the establishment of market for the co-products generated during anaerobic digestion. Similarly the microbial (enzymatic) conversion of urban solid wastes into biofuels (such as bioethanol and biobutanol) has also gained widespread attention due to the fact that the conversion process involves recycling of organic matter which has a positive impact on environ-mental conservation based on the waste to energy assessment. In a similar fashion, the bioelectrochemical systems could also contribute to circular economy by recycling the carbon (from urban waste stream)

Table 2
Bioprocessing of urban waste (organic fraction) with the application of biorefinery concepts.

Category of product	Bioprocessing method	Main product	Valorization of side stream	Reference
Bioplastics	acidogenic fermentation; culture enrichment; PHA production in fed-batch reactor	PHA	–	[55]
	acidogenic fermentation and H_2 production; culture enrichment; PHA production	PHA	H_2, wastewater remediation	[56]
	dark fermentation and bioH_2 production; culture enrichment; PHA production	PHA	H_2	[57]
	acidogenic fermentation; culture enrichment; PHA production	PHA	–	[58]
Biopesticides	semi-solid fermentation	Bacillus thuringiensis	–	[59]
	solid state fermentation	Bacillus thuringiensis	–	[60]
Enzymes	solid state fermentation	Glucoamylase	Glucose	[61]
	solid state fermentation	Cellulase	–	[62]
	solid state fermentation	Glucoamylase	–	[63]
Biofuels	prehydrolysis; simultaneous saccharification and fermentation	Bioethanol	–	[64–67]
	pretreatment, saccharification and fermentation	Biobutanol	–	[65,66]
Other	fermentation	Probiotics (for animal feed)	–	[68]
	Opoxidation of double bounds of methylated unsaturated fatty acids with peroxoformic acid (generated in-situ)	Plasticizer	Fatty acid methyl esters	[69]

PHA means polyhydroxyalkanoates.

back into electrical energy or renewable biochemicals. The interaction of electrochemically active microbes with electrodes creates valuable opportunities in terms of waste remediation along with the generation of energy. The concept of valorization of urban waste in an integrated biorefinery approach would be an effective measure of improving the environment by reducing the quantum of this waste that otherwise needs to be landfilled. Moreover, the integration of processes in a biorefinery could increase the efficiency of resource recovery and the final quality of the products obtained. Practical aspects such as economic and environmental costs should be taken into account in order to implement these technologies. Regulatory aspects along with the commitment of national and local government should also be considered. Developed countries have implemented different measures of urban waste management in the long term but the developing countries have limited themselves to composting and landfilling. Although there is a significant potential of resource recovery from urban waste in developing countries, the implementation of sustainable technologies as part of the national waste management plan is still lacking.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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