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Valorization of Anaerobic Digestate from Biowaste to High-Value Bioproducts: A Review †

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Abstract: Vital research has been carried out on the sustainable organic fraction of municipal solid waste (OFMSW) stream management in the last five years. In addition to the traditional approach to reducing its environmental side effects, considering OFMSW as a feedstock to produce bioproducts, such as enzymes, bioplastics, biopesticides, and other high-value products, represents a key component in the transformation of OFMSW treatment plants (biogas or mechanical–biological treatment (MBT) plants) into biorefineries. This short review is intended to assess and analyze the current state of knowledge of OFMSW treatment technologies, suggest practical solution options, and identify future research and development needs to help promote more sustainable management of this underutilized and ever-growing waste stream.

Keywords: municipal biowaste; biorefinery; anaerobic digestate; applications

1. Introduction

As the world's population has grown and prosperity increased, municipal solid waste (MSW) generation has increased worldwide [1]. Food processing and consumption produce large amounts of food waste, which has become the main constituent of MSW [2]. Therefore, strategies for its processing and value-added reuse are needed to enable a sustainable utilization of feedstocks and reduce the environmental burden [3].

Anaerobic digestion (AD) of biowaste not only reduces the environmental burden but has a key role in sustainable energy supply [4]. The literature points out that, among the biological treatments of the organic fraction of MSW, AD has the best environmental and economic performance [5–9]. There are more than 17,000 biogas plants in Europe, mainly in Germany (with more than 50% of the total production) and the United Kingdom and Italy (each with 14% of the total production). About 1000 of these plants are fed with biowaste from MSW [10]. Despite AD's good performance, new technologies need to be developed to reduce the volume of biowaste, minimize deleterious effects on the environment, and produce high-value byproducts to make biowaste handling economically achievable [11]. Cascade approaches are required to maximize biomass valorization. Hence, in a manufacturing scenario governed by the concept of a circular economy, biowaste-derived materials are attracting a lot of interest [12].

2. Review Methodology

The scope of this literature review is limited to literature reported in English and published after 2013 (i.e., in the last five years). The review only examines the organic fraction of MSW (OFMSW). This review does not cover homogeneous organic side streams from food processing or agricultural waste and wastewater treatment processes. The most common valorization processes for OFMSW anaerobic digestate include the production of organic acids that are extracted from volatile fatty acids (VFAs) [13]. Scientific literature was identified through the search engine Scopus [14] using such keywords as "bioeconomy", "biowaste", "biorefinery", "organic waste", "food waste", "anaerobic digestion" "bioplastics", "biopesticides", "enzymes", "organic fraction of municipal solid waste", and "PHA".

3. Enzymes, Bioplastics, and Biopesticides

The OFMSW contains various microbial enzymes that are responsible for the breakdown of complex organic matter (i.e., lipids, proteins, and carbohydrates) into smaller compounds. If OFMSW-derived enzymes could cost-effectively substitute for commercial medium ingredients in such industries as detergents, food, pulp and paper, dairy, agrochemistry, cosmetics, pharmaceuticals, diagnostics, and fine chemicals, the economic benefits could be significant. Conventional chemical production of enzymes is expensive due to the high cost of the substrate that is used to cultivate them [15,16]. Representative laboratory-scale studies on enzyme production from the OFMSW are listed in Table 1.

Table 1. Representative studies on enzyme extraction from organic fraction of municipal solid waste (OFMSW)-derived media.

Process	Products	References
	Glucoamylase	[17]
Solid state fermentation	Cellulase	[15,18]
	Holocellulases	[19]

Polyhydroxyalkanoates (PHAs) are polyesters of hydroxyl fatty acids that are stored by a variety of bacteria as intracellular carbon and energy reserve materials [20]. PHAs can be synthesized by over 75 different bacterial genera as an intracellular carbon and energy reserve and/or as a sink for reducing redundant power consumption or electrons under unfavorable environmental and nutritional conditions [21]. Literature-reported experimental (laboratory-scale) studies on PHA production from the OFMSW are listed in Table 2.

The aerobic spore-former *Bacillus thuringiensis* (Bt) is one of the most commonly used and studied biopesticide—called δ-endotoxin—producers. Despite extensive usage in the agriculture, forestry, and public health sectors, its production is constrained by a synthetic medium that contains carbon, nitrogen, yeast extracts, and protein sources, high equipment investment requirements, and complicated operational procedures [22,23]. Reported studies on biopesticide production from the OFMSW are listed in Table 2.

Table 2. Reported experimental (laboratory-scale) conditions for polyhydroxyalkanoate (PHA), biopesticide, and other high-value product production (extraction) from OFMSW-derived media.

Pretreatment	Process	Products	References
		PHA	[24–26]
		PLA fibre	[27]
Hydrolysis	*Fermentation*	Bacillus thuringiensis	[28,29]
		Probiotics in animal feed	[30]
		Graphitic carbon (GC)	[9,31]

4. Current Challenges

This review highlighted the potential of biorefinery production using the OFMWS to maximize the valorization of the structural and energetic potential embedded in biomass. This review may help to pave the way to the application of the OFMSW as a feedstock in biorefineries that produce high-value products that can potentially find application as sustainable alternatives in the circular bioeconomy. Current issues and challenges associated with biorefinery production from the OFMSW include:

1. the complexity of biologically produced products;
2. the optimization and scale-up studies that need to be carried out in order to transform OFMSW treatment plants (biogas or mechanical–biological treatment (MBT) plants) into biorefineries; and
3. it not being possible at present to conduct an economic viability analysis of biorefinery schemes because the market size and value of some of the niche products are not easy to obtain.

The technical feasibility, risks, costs, and benefits need to be assessed to determine the viability of transforming each biogas or MBT plant into a biorefinery involving the OFMSW. The full techno-economic performance of these processes must be fully investigated and understood.

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

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