BIOVALORIZATION OF FOOD AND AGRO-INDUSTRIAL WASTES: PRESENT AND FUTURE

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Valorization refers to the process of enhancing the value of a material, product, or resource that is often considered waste or of low economic worth. Biovalorization refers to the process of converting biological waste or by-products into valuable products, such as energy, chemicals, or materials, through biological methods. This approach leverages the capabilities of microorganisms, enzymes, or biotechnological systems to recycle and upgrade waste streams in an environmentally sustainable and economically viable manner.

The food industry generates a vast amount of food waste (FW, either dry or wet), which is attracting a lot of attention not only because of the environmental and economic impacts but also because of the growing concerns for food due to the ever-increasing population on the earth, the changing population demographics, and the effect of climate change on food production [1,2].

The agricultural sector is also one of the leading generators of massive amounts of waste, which has raised public concern and has threatened the sustainability of agricultural regimes. According to the Food and Agriculture Organization (FAO) agriculture produces over 140 billion metric tons of biomass every year, with over 2 tons per day in rural areas [3]. Of the huge quantities of annual global generation of agricultural residues, cereal crops are a major contributor at 66%, where sugarcane stems and leaves are the second largest contributors [4].

Biovalorization of Food Waste

Food waste is becoming a growing and important concern at both local and global levels [5]. According to the Food and Agriculture Organization of the United Nations (FAO), one-third of all food production is lost or wasted globally, equivalent to 1.3 billion tons of food produced for human consumption wasted per year with an economic loss of EUR 800 billion [6]. Regions in the East and Middle Asia, and Europe contribute up to 43% of global waste. On the other hand, the Central East and North African areas generate the least waste, making up 15% of global organic waste production [8]. About 44–47% is represented by fruit, vegetable, meat, and fish produced every year and wasted [7]. Because of the large availability and the composition of food waste, there is an increasing interest in their recycling and valorization. Food wastes are rich in carbohydrates, proteins, lipids, and inorganic components, making them sustainable precursors for microbial fermentation to produce chemicals, bioenergy and other bioproducts [9].

In order to hydrolyze the materials of food waste, hydrolytic enzymes have been used, for example, cellulases, glucoamylases, proteases and phosphatases. Yan et al. (2012) used α-amylase and glucoamylase for hydrolysis, which resulted in complete digestion of the starch in the fed-batch process [10]. Anaerobic fermentation using food wastes as substrates has been utilized for the generation of methane, hydrogen, and volatile fatty acids like acetic, propionic, butyric, valeric and isovaleric acids. In this process, various steps like hydrolysis, acidogenesis, dehydrogenation and methanogenesis are achieved. Multiple studies have been conducted to generate bioelectricity that integrated the anaerobic fermentation principles with the bio electrochemical system [11].

Table1. Composition of food waste [12,13,14]

Sr. No.	**Component**	**Percentage (Dry Basis)**
1.	Carbohydrates	50-60%
2.	Proteins	15-25%
3.	Lipids	10-15%
4.	Fiber	5-10%
5.	Moisture	70-80% (Wet Basis)

Biovalorization of Agricultural waste

Agro-industrial waste, a significant by-product of farming and agro-industrial activities, has become a global environmental and economic concern due to its immense volume and underutilization. According to the Food and Agriculture Organization of the United Nations (FAO), approximately 998 million tons of agricultural waste are produced annually, with key sources including crop residues (straw, husks, stalks, and shells), animal manure, and agro-processing by-products such as fruit peels, sugarcane bagasse, coffee grounds, and oilseed cakes [15]. Asia, with its extensive agricultural activities, accounts for nearly 45% of global agricultural waste production, followed by Europe and the Americas. These wastes are often rich in lignocellulosic materials, starches, proteins, and lipids, making them ideal raw materials for biovalorization. However, a significant portion of this waste remains untreated, leading to environmental issues like methane emissions, water pollution, and loss of soil nutrients.

Biovalorization of agricultural waste involves advanced technologies such as anaerobic digestion, microbial fermentation, pyrolysis, and enzymatic hydrolysis. Anaerobic digestion is extensively used to convert animal manure and crop residues into biogas (methane and hydrogen), which can be used as a renewable energy source [16]. Microbial fermentation of sugar-rich residues such as molasses, fruit peels, and starchy wastes produces bioethanol and other valuable compounds like lactic acid and citric acid. For instance, *Saccharomyces cerevisiae* is widely used for bioethanol production, while *Lactobacillus spp.* is employed for producing organic acids. Enzymatic hydrolysis, using cellulases and hemicellulases derived from *Trichoderma reesei* or *Aspergillus niger*, breaks down lignocellulosic materials into fermentable sugars, which serve as precursors for biofuels and bioplastics [17].

Applications

- ***Bioethanaol.*** A significant rise in fossil fuel usage, along with their exhaustion, results in an energy crisis. This results in demand for energy generation approaches. Not only has hydrogen production using biowastes attracted attention but so has the production of liquids like ethanol and bio diesel [18]. The United States, Brazil, and China produce bioethanol in large quantities. In 2009, the United States produced around 39.5 ×109L of ethanol utilizing corn as raw material, while Brazil generated about 30 ×109L of ethanol utilizing sugarcane [19].
- ***Biohydrogen.*** Hydrogen in its totality is the cleanest, non-polluting fuel available in the world since the only substance produced on burning it is water vapor [20]. Biological production of hydrogen poses various advantages as opposed to chemical production, for instance, fermentation of organic materials or bio-photolysis of water by algae, among others. The biological methods for the production of biohydrogen might be classified into light-dependent (Photofermentation, Biophotolysis) and light-independent methods (Dark fermentation (DF) and via microbial electrolysis cell) [21]. A novel system–hybrid approach has also been investigated over the years.
- ***Enzymes.*** Enzymes are biological catalysts, which ensure the successful completion of biochemical reactions, hence playing an important role in several aspects of life and its inherent process [22]. Natural sources of enzymes include plants, animals, and microorganisms. However, the surging prices of enzymes have paved the way for researchers to focus and explore the various methods for the pro duction of enzymes, in addition to improving the existing methods for the production of enzymes in an economical and sustainable way [23]. As compared to plant as well as animal sources, microbial sources have been favored due to technical benefits such as shorter fermentation times, higher yields, along with economic viability [24]. With advances in the arena of biotechnology, several bioprocesses are ensuing for the utilization of various industrial wastes for the generation of enzymes. One of the major industries contributing to the same is the agro-industry.
- ***Biogas.*** Biogas is a mixture of methane, CO_2, H_2S, moisture, and siloxanes, generated by AD of organic waste materials, which is the cost-effective means of generating biofuels. Anaerobic conversion of food waste to biogas is a great alternative [25]. Previously, the spotlight was on AD of municipal waste, but lignocellulosic waste could also be utilized to produce biogas-rich biomethane; however, this waste transformation method involves a preliminary treatment as well for the yield enhancement [26]. Hydrolysis, acidogenesis/acetogenesis, and methane generation are the 3 stages of biogas production [27].

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