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Review

Sustainable Food Waste Recycling for the Circular Economy in Developing Countries, with Special Reference to Bangladesh

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Abstract: Food waste management is a critical environmental issue in many developing countries, including Bangladesh, due to unplanned food waste disposal and lack of dedicated food waste legislation. In those countries, a significant amount of food waste is discarded to the environment rather than being recycled. In Bangladesh, food waste is traditionally often used for composting, landfilling, and feeding animals, as there is no valorization option. In addition, food waste and food waste streams of food industries are utilized for the recycling and production of diverse economically valuable bioactive compounds. Therefore, we conducted a detailed literature review on food waste management and valorization options in Bangladesh and discussed the findings in the context of global status. The amount of food waste in Bangladesh is quite high, and it needs to be recycled to promote the circular economy of this developing nation. In this study, it is revealed that various research uncertainties and gaps regarding sustainable food waste management exist in Bangladesh, which should be investigated as priority research. Furthermore, a logical and global synchronization of the contemporary approach to food waste valorization with policy advocacy is proposed, to ensure efficient food waste decontamination and recycling in Bangladesh. This is the first and most comprehensive evaluation of the present research trend and prospects for sustainable recycling of food waste for the circular economy of Bangladesh.

Keywords: food waste; waste valorization; circular economy; developing country; policy management; sustainable recycling

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1. Introduction

Food waste (FW) management is regarded as a critical environmental issue in developing Asian countries due to a lack of scientific knowledge and specific legislation for protracted management [1,2]. Owing to favorable climatic conditions, Bangladesh is one of the main vegetable- and fruit-producing countries in South Asia [3,4]. However, a large

volume of these perishable goods was reported to be destroyed because of the inadequate availability of efficient packaging, processing, and conversion technologies [3,4]. As a result, unintended food losses during production and postharvest processing are a serious concern in the country. Furthermore, management of this huge agricultural waste is a big burden for this nation, both in terms of the environment and the economy [5,6].

FW and FW streams are treated as an excellent array of hidden bioactive molecules and bioenergy [1]. Globally, FW streams are converted into bioenergy and utilized for the production of valuable products through integrated biorefinery [7]. This integrated food waste valorization approaches toward the circular economy are now being in practice in most developed countries as waste management solution [8,9]. The FW streams have already been reported as useful input to a circular economy [10], not only as a source of bioenergy, but also as a source of recycled products. In emerging Asian markets, the circular economy through FW valorization may play an essential role, which has yet to be extensively investigated [1,11]. The worldwide FW dilemma and its long-term management through integrated and novel biorefinery and repurposing technologies have been discussed in many reports [12,13]. However, scant information is available on the potential of sustainable recycling of FW for the production of valuable products in developing Asian countries, including Bangladesh.

Several reviews of the literature reveal that the majority of the waste management research and policy legislation in Bangladesh focuses mainly solid waste (MSW) [14]. In addition, the environmental impact of existing waste management strategies was also reviewed in some studies [15]. However, the urban and municipal waste management seemed to be the focus area for research regarding Bangladesh, leaving behind the whole country scenario [16,17]. A large number of reports have been published on policy and the sustainable MSW management of major cities, with some valorization options [18,19]. Following the trend, some MSW involved technology to use the solid waste potentiality in terms of energy and bioproduct as well [20,21]. In addition, for clean city development in Bangladesh, certain waste-to-energy (WtE) technologies for biogas, biohydrogen, and other resource recovery have been investigated [22–24]. Surprisingly, FW and its management were not independently explored in Bangladesh [2,4]; except for a few studies which were focused on restaurant food waste and marine waste management [6,25]. It is possible that the FW valorization and the prospects of bioconversion of value-added products from the FW and FW streams in Bangladesh is poorly understood. Therefore, a comprehensive review of FW management and the potential of utilizing FW materials for the circular economy through sustainable recycling is needed.

It is estimated that approximately 1.11×10^7 metric tons of FW are produced annually in Bangladesh [2]. Several lines of evidence suggest that FW represents a hidden source of bioactive compounds and bioenergy, which have not yet been appropriately utilized [2,4]. Considering the best practices in the world, there is a high potential for exploring FW valorization in Bangladesh for extended resource recovery and promoting the circular economy of this developing country [10,26,27]. Although numerous sustainable valorization options for FW management have been documented in many reports, including a significant number in several Asian countries [7,28]; current research in Bangladesh has not been expanded toward sustainable FW recycling. A recent policy study in Bangladesh identified a wide range of laws and acts concerning FW management, including a lack of a long-term FW management strategy [2]. However, it overlooked the novel biorefinery and valorization possibilities of FW. We therefore conducted a thorough literature review to critically analyze the existing situation following the discussion on policy, legislation, and technological options for sustainable FW recycling in Bangladesh. To the best of our knowledge, this is the first extensive study to identify the existing research gap and prospects for sustainable FW management through a merger of demands for policy implementation and advanced biotechnology approaches in developing Asian countries, with special reference to Bangladesh.

2. An Overview of FW and the Current Scenario in Developing Countries

2.1. FW in Developing Asian Countries

FW management systems are mostly indigenous in some developing countries with agricultural economies [29]. The current FW management systems in these countries are poor compared to the practices in developed countries, which leads to environmental and hygienic concerns [26,30]. The estimated rate of FW generation in low-income Asian countries is about 11 kg per capita per year [29]. In emerging Asian economies, FW generation rates are influenced by several factors, including the dietary transition to Westernized consumption patterns and urbanization, among others [31]. FW in developing countries is also influenced by increasing economic development and growing population [26]. Food easily degrades before it is collected in fields and farms or while in transportation. Globally, food losses at the manufacturing and distribution stages account for two-thirds of all FW. For example, Indian agriculture produces 28% of bananas globally, but only 0.3% reaches the global market [32]. According to the FW Index Report 2021, there are 5.3 billion tons of food available for consumption, but approximately 931 million tons of which total is thrown away. These waste materials come from many sources, including 13% from retail, 26% from food services, and 61% from residences [33–35].

Figure 1a shows the annual food wastage rate in developing Asian countries at the household level. To calculate the household food wastage rate, this graph covers Bangladesh, India, China, Bhutan, Nepal, Maldives, and Sri Lanka. Bangladesh has an average food wastage rate of 65 kg per capita per year, whereas India has 50 kg per capita per year. China and Bhutan have an average food wastage rate of 64 and 79 kg per capita per year, respectively. The household wastage rate in Nepal is as high as Bhutan, which is approximately 79 kg per capita per year. On the other hand, the Maldives and Sri Lanka have the highest rate of household waste generation with 71 and 76 kg per capita per year, respectively. Developing countries, especially China and India, make up 37% of the world's total population, whereas the FW generation and food consumption of developing countries are low, their overall FW generation is nearly equal to that of industrialized countries [26].

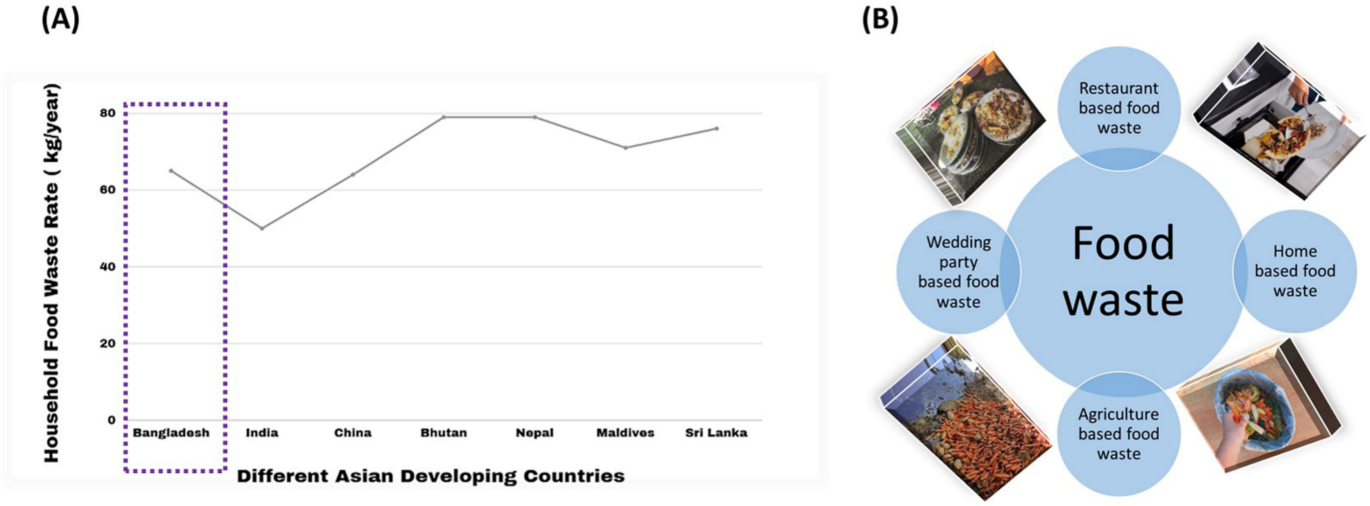

Figure 1. Household food wastage generation by developing Asian countries (adapted from FW Index Report 2021) (**A**), and current FW status in Bangladesh (**B**). Data were adapted from previous studies [2,6,34,35].

2.2. FW: A Hidden Sink of Nutrients, and Bioactive Molecules

Macronutrients and micronutrients are required for the growth, repair, maintenance, and reproduction of all animals and human beings [36]. Bioactive compounds, which are present in food at lower concentrations, exert beneficial effects on human cells and

tissues [37]. These substances protect human health from cancer, diabetes, neurological disorders, aging, and cardiovascular diseases [36]. FW results in the loss of nutrients and bioactive substances. The nutritional makeup of FW is largely determined by its source. Ethnicity and nutritional preferences are two consumer-related characteristics that influence the nutritional compositions of FW [37]. Previous studies have identified several nutrients as well as bioactive chemicals in various types of FW [37–42]. FW is a source of high-quality nutrients and bioactive compounds and can be used as animal feed, as "building block molecules" for the production of a wide range of specialty goods [9,37,41], and as raw materials for the production of a wide range of high-value products such as biofuels, bioplastics, biocompatible and biodegradable surfactants, enzymes, and organic acids [12,41]. Phytochemicals can be recovered from FW and used in food, medicine, pharmaceuticals, and cosmetics [40].

3. Current Status of FW and Its Management in Bangladesh

3.1. FW Status in Bangladesh

FW has become a big concern in Bangladesh due to the country's rapidly growing population and changing food habits. According to a previous study, total household food waste in Bangladesh is approximately 10.62 million tons each year, which could be a great problem if the FW was not managed properly [33]. The fraction of FW in aggregated MSW of Bangladesh ranges from 68.3% to 81.1% [5]. In Bangladesh, FW generation is primarily linked to restaurants, agricultural operations, kitchen trash, and related residential activities and social parties. Thousands to millions of tons of food are wasted every year as a result of these anthropogenic activities that are not addressed by any comprehensive regulation. Harvest losses of 7.82 and 7.58 million tons, distribution losses of 2.36 and 2.13 million tons, and consumer waste of 3.78 million tons are all included in this FW rate [34]. The situation is different in the case of restaurant-based FW, where consumers are accountable for 56% of the waste following meal preparation and cooking [6]. The percentages of various types of FW are shown in Figure 1b. The food production and consumption cycle generated around 23.69 million tons of FW in the years 2016 and 2017 [35].

In general, Dhaka produces the least MSW (68.3 wt% of FW) among eight districts, while Barisal federates produce the most, accounting for 81.1 wt. percent of FW in the country's total MSW [23]. The quantities of FW produced in various regions of Bangladesh including rural and urban areas are shown in Figure 2. Dhaka alone disposes of approximately 1,241,133.23 tons of FW every year [5]. According to official estimates, the food wastage rate in the industrial city of Chittagong is 421,330.45 tons each year [2]. Although the food wastage rate increases or decreases depending on the season, these values incorporate the FW rates in both the dry and wet seasons in tropical countries [43].

3.2. Management of FW in Bangladesh

In general, no specific FW management policy is followed in Bangladesh. FW is usually managed as a component of MSW [2]. However, there are some basic and traditional management strategies for FW disposal and further utilization in Bangladesh. The general mechanism is storing the FW from different sectors through waste collectors and making the best use of it to ensure compliance with the general waste management policy. However, the appropriate knowledge of the two types of FW and their common management in Bangladesh is not well established. In the case of restaurant-based FW, waste is first stored in a small room with fan ventilation (for 80% of large restaurants and 69% of small restaurants) [4] and is then collected by collectors for disposal. Another important aspect is that some of this FW is composted, which is highly beneficial. Household FW is also used for composting and as animal feed, and this does not require any storage processing.

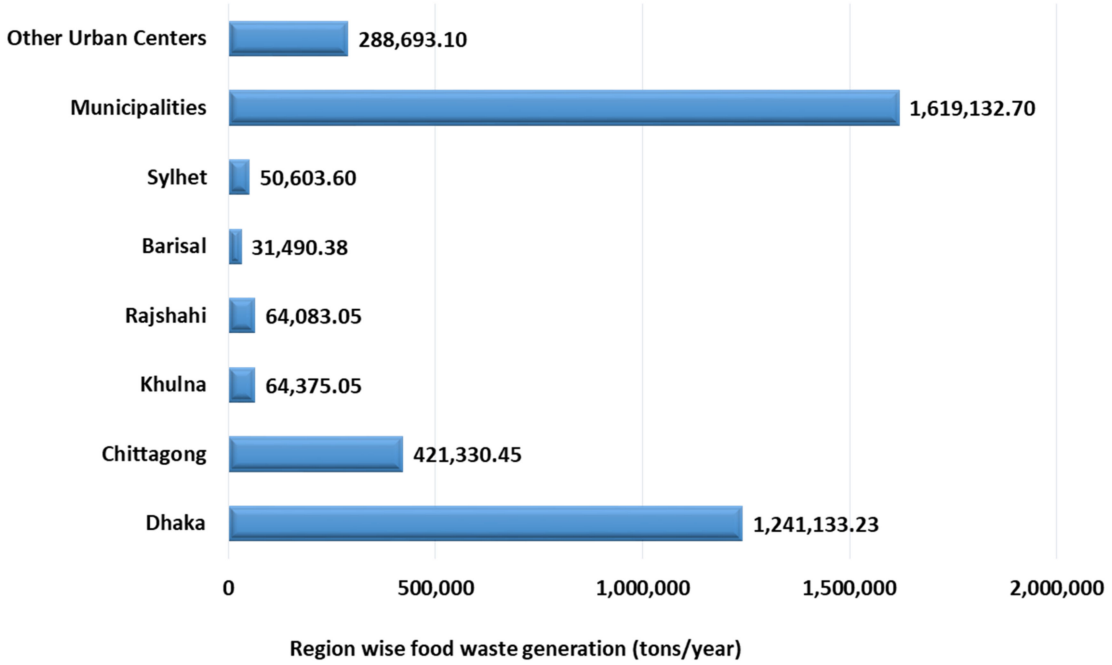

Figure 2. FW generation data of the different regions of Bangladesh. Data were adapted from earlier studies and references dealing with FW generation [2,5,16,17].

3.3. Existing Strategies of FW Management in Bangladesh

Three general waste management strategies are currently used in the urban community of Bangladesh [2,4], namely, (1) a formal system, where the city government is responsible for waste management; (2) a community initiative, where voluntary actions are required for waste management; and (3) an informal system, where a large number of informal workers are responsible for organic waste management (Figure 3) [2,23]. After taking action through one of the three organizations, a few steps should be followed. Waste bins are used in homes, restaurants, and other establishments for this purpose [4,6]. The FW from households is gathered by waste collectors. This is usually done by the government or by individuals without any specific legislation. The FW is then disposed of or minimized through the three most common procedures, which include landfilling, open burning, and sometimes open dumping. Recycling of FW is very limited. It is accomplished through three traditional methods, namely, aerobic digestion, animal feeding, and composting [44]. These solutions can be applied to any sort of FW that occurs in our environment, but the disadvantage is that they require a processing area. Food waste refers to unavoidable food waste, but avoidable food waste is the only option to prevent FW generation [29,45]. There is a clear lack of adoption of innovative and sustainable FW management systems in Bangladesh, whereas global research has already expedited several cutting-edge policies and valorization approaches to managing and recycling global FW [12,46]. Therefore, Bangladesh needs policy formulations and research for the utilization of the vast amount of FW as a bioresource for the production of economically useful products.

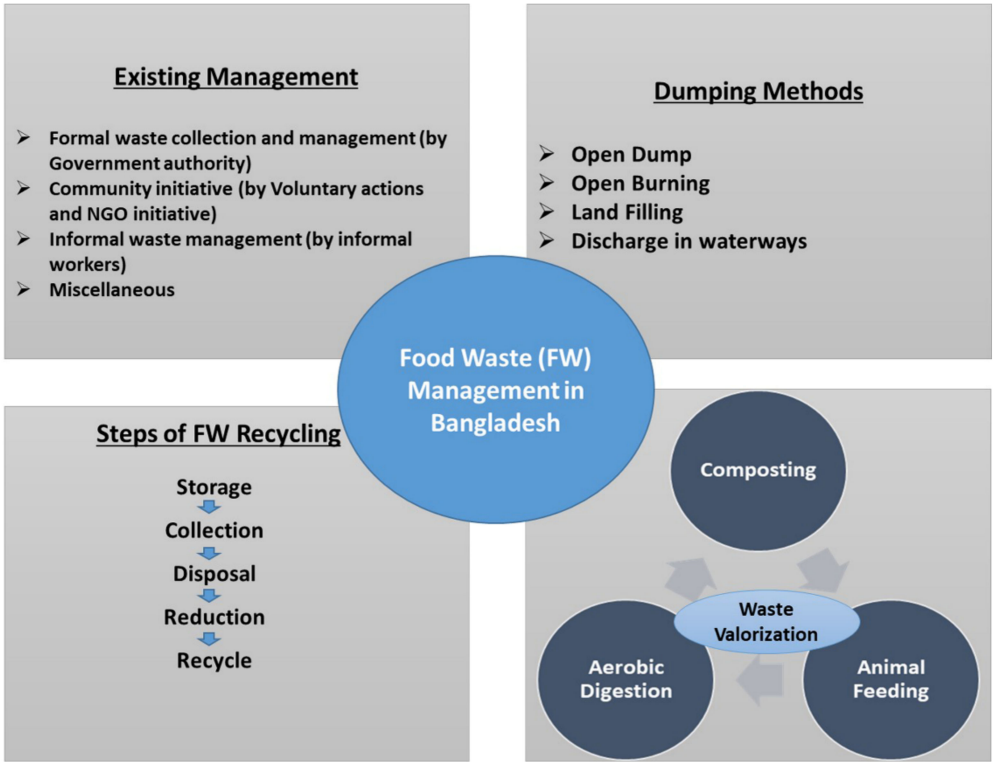

Figure 3. Existing strategies for FW management in Bangladesh.

4. Food Loss and FW: A Global Debate

4.1. Debate between Consumer and Agribusiness Stakeholders

Food loss and waste are two intertwined topics that are regarded as global concerns due to diverse responses from consumers and agribusiness stakeholders [33]. Food loss or damage occurs at every step of the farm-to-fork food supply chain, that is, from agricultural production to human consumption [29]. Although unavoidable FW, such as the peel and seeds of major vegetables and fruits, is thrown away on a routine basis, the generation of avoidable FW (i.e., food or food portions are thrown away even if they are still edible) is evident in almost every region of the world due to ignorance and research scarcity of food valorization technologies [26,44]. In developed food markets, significant losses can occur at any point in the supply chain, whereas in low-income countries, food is primarily wasted in the early and middle stages but considerably less toward the ends of the food supply chain [30,47].

Although there is a cognitive and perspective dispute over the production of FW and the loss of food materials, an average global estimate of 121 kg FW per capita is recorded at the consumer level, with 74 kg of this waste coming from households [41,48]. However, 91 kg of food each year is disposed of by people in their homes in low-income countries compared to 76 kg for upper- to middle-income countries and 79 kg for industrialized ones. Domestic waste production and kitchen trash are interwoven and regarded as a major challenge to sustainable waste separation and treatment [29,48].

Earlier surveys and policy papers showed that agricultural production and postharvest processes account for a significant amount of food loss, whereas the Food Loss Index of the Food and Agriculture Organization revealed that around 14% of the world's total food production is lost during the postharvest period, and this figure does not include food loss at the consumer levels [47]. This may be due to a lack of accurate food loss statistics and source apportionment of FW, particularly in developing nations where food safety and associated authorities are lacking. A comprehensive FW database, sustainable management policy, and contemporary valorization approaches for FW management are still in the early stages of research in Bangladesh [2,4]. To minimize food loss and implement a valorization

approach toward a circular economy from a linear economy, pervasive and meticulous advisory policies are required. Global synchronization of waste valorization strategies will improve sustainable FW management in developing Asian countries [8,45].

4.2. Misconception and Negligence about Good Policy for FW Recycling in Bangladesh

In general, waste is created through a complex interaction of multiple stakeholders, including producers, distributors, consumers, food industries, food chain entry points, waste collection authorities, nongovernment organizations, and government agencies involved in FW management, and local governments alone are unable to manage the growing volume of municipal and FW [17]. Except for a few restaurant-based FW studies, the sustainable and good policy of FW recycling in Bangladesh has received little attention [4,22]. However, in developing Asian countries such as Bangladesh, several misconceptions, poor legislation, ignorance of food policy, lack of government and stakeholder initiatives, lack of funding, inappropriate technologies, and insufficiently skilled staff resources on FW management issues have all hampered the planning and application of novel approaches to achieve a wise FW management system [22].

Proper community education is a crucial influencing factor on consumer behavior, which impacts FW generation and control [49,50]. According to the World Bank, developed countries spend over 90% of their budgets on waste management programs, treatment facilities, or specific initiatives to raise public awareness about the effects of garbage on the environment. On the other hand, developing countries spend about 80% of their budgets on garbage collection and disposal [49]. People may play a critical role in sustainable FW management if education, awareness, and government enforcement are coordinated [2]. Last year, the total budget deficit was BDT 214,681 crore, or 35.5% of the total budget. This funding gap suggests that the government is having difficulty making significant investments in FW management [34]. Although it will be challenging, Bangladeshi authorities may seek international money and public–private partnerships to assist them in achieving long-term FW management.

In developing countries, traditional technologies such as anaerobic digestion (composting), open dumping with MSW, animal feeding, and landfilling have been used to handle food waste [29]. Contemporary recycling technologies such as valorization strategies (i.e., WtE approach, extraction of bioactive compounds, and integrated biorefinery) are not included in emerging regions such as Bangladesh due to a lack of technical capabilities [3,20]. In Bangladesh, municipal waste management authorities do not have a specific strategy for collecting and processing FW, which is intermingled with MSW management and not segregated for separate trash management [2]. However, certain nongovernment groups (e.g., Swisscontact BD) have sustainably undertaken a few efforts to handle municipal garbage and related FW with the help of international organizations [15,19].

The lack of utilization of novel and appropriate technology for the specific goal of FW extraction has been identified as a significant obstacle to FW management efficiency in developing countries [45,49]. Due to the absence of understanding of sustainable technologies, FW at entry points during the manufacturing to retailer stages is substantially higher in developing Asian countries than in developed countries [1,35]. Therefore, implementing sustainable and innovative FW recycling using advanced and technical approaches is vital and still needs to be explored in Bangladesh.

According to a recent study, FW reduction in many countries is hampered by surplus food for guests, friends, and family due to hospitality [4]. Bangladesh is undoubtedly considered a hospitable country. The offering of abundant meals for visitors is frequently viewed as a symbol of social standing. Thus, food is regularly discarded in large quantities, especially at family reunions and other festivities. The government should approach a comprehensive FW management strategy for Bangladesh as soon as possible to avert the looming food crisis. A master plan for FW reduction and management should include new regulations to limit FW generation and infrastructure to support long-term FW manage-

ment. Comprehensive and significant training, socialization, and communication effort among all stakeholders will drastically reduce FW.

5. FW Valorization and Circular Economy

5.1. Prospects of Advanced FW Valorization Strategies in Bangladesh

The current level of FW production in Bangladesh is a worrisome concern. In most cases, the FW management system is limited to animal feeding and landfilling [35]. These outdated practices obstruct the more effective utilization of FW from various sources, such as industrial FW, agricultural waste, and domestic garbage. FW valorization, which has been increasingly popular in recent years, is a valuable strategy for residue management that avoids disposal or landfilling (Table 1) [30,51]. FW valorization produces valuable chemicals, biofuels, and other products. Composting, recycling, and energy recovery are widespread valorization processes although they are unable to convert 50% of trash into valuable products [52–54]. As a result, sophisticated valorization techniques, such as hydrothermal carbonization, fermentation, and combination chemoenzymatic approaches, that involve the synthesis of useful high-value goods are in higher demand from an economic and long-term sustainability standpoint. Some examples of modern technologies for FW valorization are presented in Figure 4.

Table 1. Global FW management and valorization toward circular economy (as arranged based on study region).

Study Region	Food Waste Source/Materials	Employed Methods or Techniques	Valorization Approach	Experiment Type	Reference
North America and Europe	280–300 kg of food waste	Peel and seeds of fruits and vegetables	Supercritical extraction, and Bioconversion	Pilot-phase study	[55]
USA	Wastewater	2400 m^3 per capita	Agriculture production and energy resources (16% consumption)	Footprint	[56]
	Tobacco-waste	Scrap, dust, midrib	Extraction of bioactive compounds (phenolic compounds and solanesol from leaves)	Industrial processing	[57]
UAE	Orange peel waste	Presence of methyl esters	Water-soluble pectinic acid	Jam, jelly, nutritional product	[58]
	Orange peel	Orange peel residues, enzymatic hydrolysis	Supercritical carbon dioxide method, bioconversion	Flavor and pharmaceutical industries	[58]
India	Mango peel	Enzymatic extraction	40% higher lactic acid concentration, biosurfactant production	Fermentation	[59]
	Banana fibers & stem wastes	Pseudo stem biomass	Hybrid biocomposites	Fillers or composites	[60]
	Rice and sugarcane waste (cereal wastage)	Decomposition	3.4 kg CO_2 equivalents/kg (carbon)	Large scale	[47]
	Organic waste (slaughterhouse, fresh market waste)	Anaerobic digester, biodigester, or a bioreactor	Biogas production	Large scale	[61]

Table 1. *Cont.*

Study Region	Food Waste Source/Materials	Employed Methods or Techniques	Valorization Approach	Experiment Type	Reference
Thailand and Southeast Asia	Rice husk	Decomposition	20,000 kW/year of electricity	Leading state-owned power utility	[62]
Thailand	Sugarcane waste (bagasse and molasses)	Biochemical production, use of substrate in bioethanol production	Feedstock (microbial growth and bio-based products production), electricity, and steam generation	Large scale, industrially	[63]
	Pineapple cannery waste	Biotransformation	Vanillic acid and vanillin	Large scale	[64]
	Pineapple cannery waste	Bacterial growth	Commercial media (Mann, Rogosa, and Sharpe (MRS))	Fermentation	[65]
Indonesia	Liquid pineapple waste	Chromobacterium violaceum UTM5, tryptophan supplementation	16.256 ± 0.44 g/L violacein (violet pigment production), bioethanol	Large scale	[66]

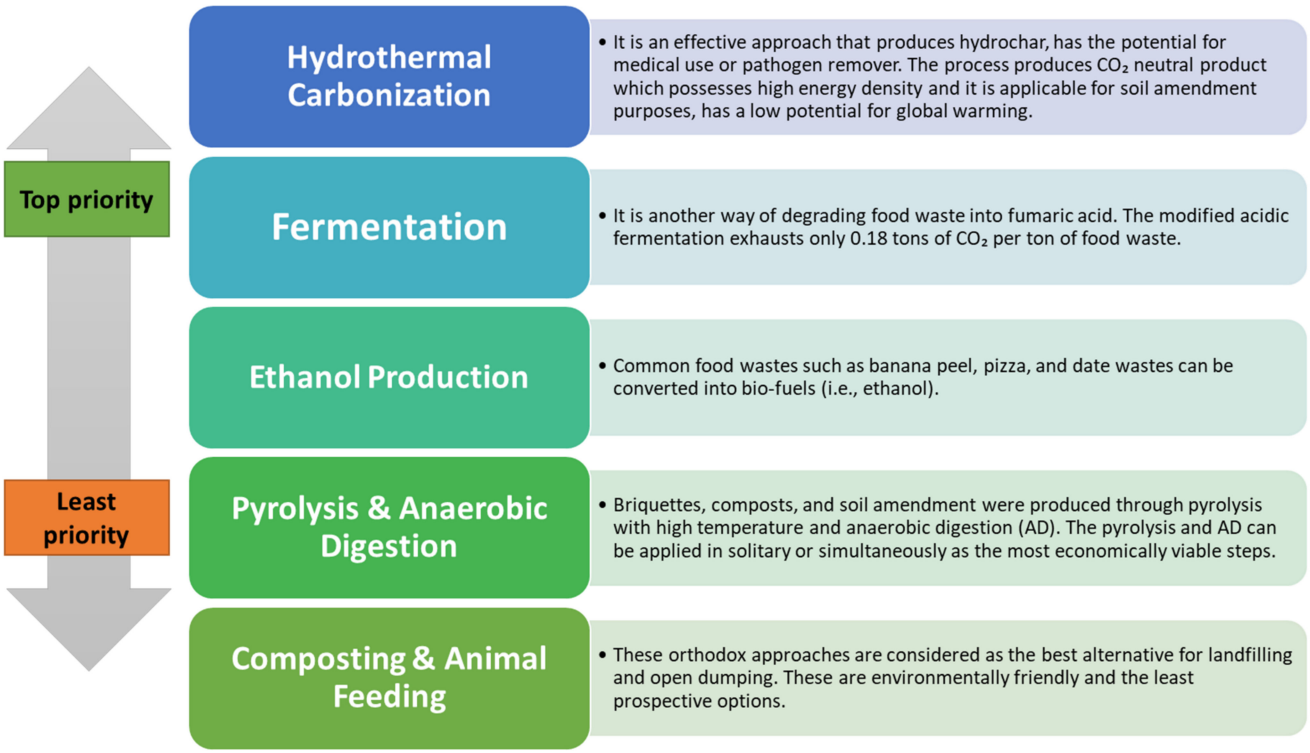

Figure 4. Modern FW valorization technologies based on environmental and economical priority.

The priority and category of current FW recycling and valorization procedures are demonstrated as a remarkable policy campaign for Bangladesh (Figure 4). However, the waste management authority of Bangladesh can apply advanced technologies for the sustainable recycling of FW from households and food industries. Hydrothermal carbonation and fermentation are ranked as the top priority approaches for FW valorization, although they are not used in Bangladesh [2]. Similarly, other least-priority approaches

that are categorized based on life cycle assessment (LCA) and other related environmental indicators (i.e., bioconversion potential into value-added products) could also be used to achieve sustainable recycling of FW in the country [7,67,68]. Therefore, it is urgent to synchronize policy legislation and adopt global contemporary FW management approaches to boost FW valorization in Bangladesh instead of the current landfilling and open dumping approaches.

5.2. Sustainable FW Valorization to Enhance the Circular Economy

FW recovery and recycling are practical methods for maximizing the value of FW. They contribute to a circular economy and are sustainable approaches in terms of reducing FW losses [7]. The main goal of the circular economy concept is to reduce environmental, social, and economic costs while increasing economic competitiveness and reducing poverty and hunger [69]. In a circular bioeconomy, renewable biological resources are converted into high-value items including bioactive components, bioplastics, and bioenergy, while simultaneously ensuring future resource conservation, reducing waste, and lowering greenhouse gas emissions [10,44]. According to [70], compared to a linear economy, a circular economy aims for a "waste-to-wealth" concept that provides innovations, employment, and livelihood while simultaneously improving the environment. Based on existing knowledge, a simplified idea of a circular economy through FW valorization is illustrated in Figure 5 [10].

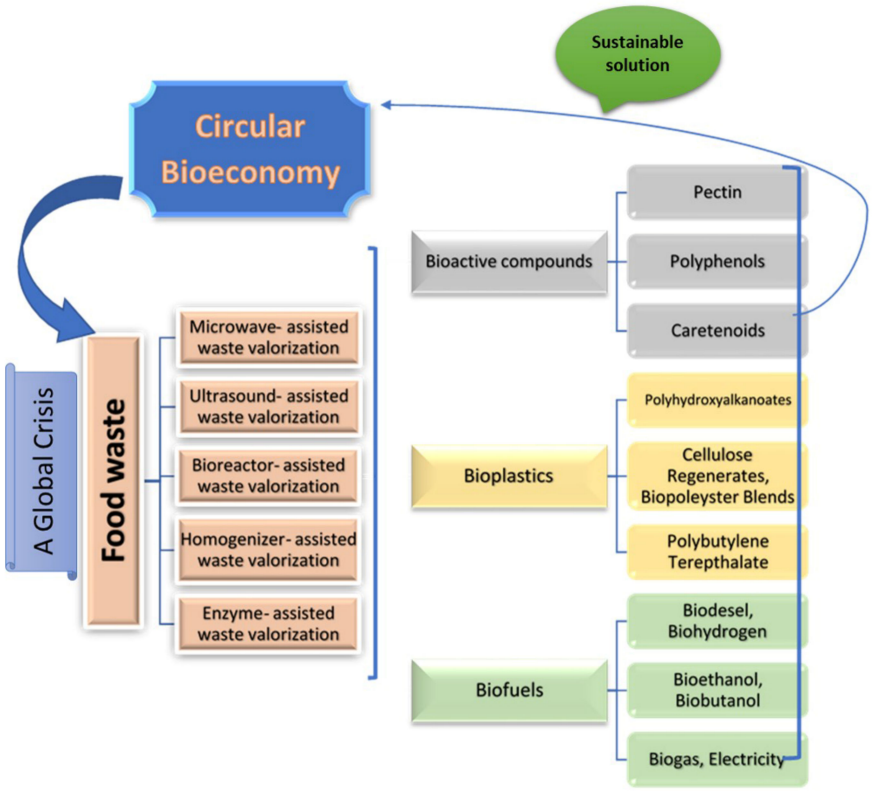

Figure 5. Simplified concept of a circular economy through FW valorization (Revised and modified after prior research data).

Approximately 40–50% of freshly produced fruit and vegetable is wasted at various stages, including harvest, processing, and consumption, resulting in a capital loss of $1 trillion. This loss can be much higher if we consider social and economic losses. A circular economy is a framework for minimizing the losses through waste and generating economic growth from natural resources through resource recovery [10,71,72]. According to [73], food and kitchen waste provide a variety of value-added goods, such as fuels

and chemicals, bioethanol, biohydrogen, biobutanol, biodiesel, bioelectricity, organic acids (e.g., acetic acid, citric acid, fumaric acid, succinic acid, lactic acid, propionic acid, and gluconic acid), biopolymer, vanillin, xanthan gum, sugars, chitosan, wax esters, pectin, biosurfactants, quercetin, pigments, and vinegar, among others. FW output in Bangladesh is at an all-time high, which requires the introduction of systematic and efficient waste management. To establish a circular economy, advanced management approaches are needed that will reduce FW by converting it into valuable products [74]. Figure 6 depicts the promotion of circular economy approaches by FW valorization.

Figure 6. Value-added products and bioenergy are derived from FW through adopting a circular economy.

5.3. Prospects of Circular Economy through Waste to Energy Approach

Due to rising environmental, social, and economic concerns, climate change, and the shortage of fossil fuel supplies, food waste has received a great deal of attention from the local public, national and international organizations in recent years [8]. The generation of an increasing rate of solid waste is one of humanity's biggest issues today, due to an increasing urban population and a linear economy. Therefore, the concept of a circular economy has gained popularity as a means of building closed-loop technical and biological processes [75]. According to the Circular Economy Action Plan, "circular economy" is defined as the long-term conservation of product value, materials, and resources in the economy with minimal waste generation [7]. Raw materials such as fossil carbons, minerals, metals, and biomass will be converted into goods, traded, and used before being shared, repurposed, redistributed, and recycled [76].

When the circular economy relates to bio-based products such as food waste and biomass, it can be called a circular bioeconomy [76]. It is an economy that is powered

by nature. It is a new economic model that mainly emphasizes the utilization of natural and renewable sources. It also focuses on waste minimization by replacing the fossil-based, non-renewable products which are now in use. There are similarities and contrasts between 'circular economy'and 'bioeconomy'.The two terms are comparable because they share some of the same aims. The circular economy strives to improve resource usage efficiency and waste material recovery to reduce the emission of new fossil carbon during production and extraction activities. The bioeconomy concept has similar goals, but it focuses on alternative techniques of replacing fossil carbon with renewable biomass from agriculture, forests, and the ocean [76]. The bioeconomy is built on converting renewable carbon reserves from agricultural or forest biomass and organic wastes into a wide range of end-products and materials, such as food, feed, bio-based chemicals, biopolymers, fuels, and bioenergy through waste to energy (WtE) approaches [77]. In the circular bioeconomy, biomass, agricultural wastes, animal wastes, and used products are reused to generate renewable energy and biofuel through different processes such as anaerobic degradation, pyrolysis, and gasification.

The increasing demand of the ever-increasing population for energy and materials is forcing humanity to transition from a fossil-based linear economy to a sustainable circular bioeconomy [7]. The bioeconomy involves renewable feedstocks capable of producing a wide range of biobased goods, requiring transdisciplinary science, management, and engineering [78]. Biogenic waste is being investigated as a possible feedstock for developing the bioeconomy [79]. As a result, the massive volume of created food waste can be regarded a possible feedstock. Food wastage and management are key difficulties facing our civilization in a fast-growing world, due to the inherited high risk for human health and increasing environmental burdens [79]. The amount of avoidable food waste can be controlled by implementing three strategies: delete, minimize, and reuse. Because the development of unavoidable food waste cannot be prevented, suitable disposal and reuse techniques are essential [7]. Food waste management in this way provides a direct incentive for producing soil additives and liquid fertilizers from organic food waste [79]. Simultaneously, developed countries are encouraging themselves to move toward a sustainable society based on zero waste, circular economy concepts, and waste-to-energy recovery. A waste-to-energy (WtE) strategy for waste stream management in a city could be a realistic option for a city's transition to a waste-free future. The WtE not only eradicates the problem of urban land pressure but also generates power and heat and, thus, contributes to the circular economy [72]. Because waste from the urban human living system serves as raw materials for the energy generating system, the WtE approach is also aligned with the industrial ecology principle [22,72].

5.4. Knowledge Gap concerning Circular Economy

There exists a knowledge gap between consumers and food industries regarding FW management. In countries such as Bangladesh, the scenario is much worse. In developing countries, consumers are not very aware of the recycling and food valorization process of the produced waste [1,7]. This creates a major setback in implementing a circular economy during FW recycling. Most of the time, food industries also fall behind in the recycling and valorization processing of foods. Food industries are also not very concerned about recycling FW unless strong regulations are in place. There are three essential stages of a product's lifecycle, namely, purchase, use, and end-of-life management, and consumers are directly involved in all three stages. With the use of behavioral insights, the gap between circular economy concepts and consumer behaviors can be bridged without drastically altering product lifecycle systems [80]. From the harvesting process to manufacturing, a great deal of food is wasted. In developing countries, including Bangladesh, the rules and regulations to minimize FW and proper guidelines for FW management have not been developed much yet. Several lines of evidence suggest that FW is also affected by the income levels of consumers [81]. FW is lower among low-income families than among high-income families [82].

There are some reasons behind the knowledge gap between consumers and food industries, which include lack of awareness, lack of information on the bad impacts of wasting foods, poor relationship between consumers and food industries, unorganized plans for recycling FW, and extensive commercialization of food industries. For the implementation and adoption of a circular economy, the knowledge gap between consumers and food industries needs to be removed, which will start with the proper dissemination of adequate information. After that, food industries will recycle and valorize FW that can be used to generate energy or other value-added products. Ensuring all these processes are in place is necessary for an ideal FW management. There should be proper guidelines, regulations, and their proper implementation for the development of a sustainable society and to promote a circular economy. Thus, the knowledge gap between consumers and food industries will hold back the motives and objectives of adopting a circular economy. It is therefore very important to reconcile this knowledge gap for a waste valorization approach towards a circular economy.

6. Research Gap and Opportunities of FW Valorization in Bangladesh

In Bangladesh, FW management is a crucial and challenging issue due to concurrent management policy by the municipal authority for the management of MSW, coupled with FW [2]. This is a critical consideration for separating FW from MSW. To achieve specified resource recovery and extraction of valuable biomolecules from the FW streams, FW is now segregated according to category, i.e., fruits, vegetables, and mixed materials (e.g., horticulture waste and citrus waste) [45,83]. The undefined and partial database of FW generation in Bangladesh is the first knowledge gap in their FW management. This undefined database of FW generation needs to be structured with institutional regulations to estimate per capita FW generation and FW generation by industry or restaurant. Anaerobic digestion (AD) is a conventional FW management technology for the bioconversion of mixed food waste into value-added products [53,84]. The anaerobic digestion of food waste and the composting of the effluent alongside green waste decreases the total kg CO_2-eq. This environmental benefit is observed mainly due to the storage of stabilized carbon during landfilling and high added-value products such as compressed natural gas [85]. AD can be adopted as a holistic method to valorize mixed FW, including kitchen waste, for low-cost bioconversion [28].

FW is derived from several processing steps including harvesting, postharvest transportation, packaging, and domestic and industrial processing [86]. Developing a management system to address household FW and kitchen-derived FW is a global burden [86,87]. However, several innovative steps are known to limit household FW generation [88,89]. An FW-appropriate inventory database (including data on food waste qualities, technical treatment parameters, material flow, and monetary flow) may be built in order to enhance environmental and economic assessment methods for FW management [90]. Thus, an efficient source selection of FW is necessary for Bangladesh to connect with the facile management policy. Several innovative approaches and techniques for sustainable recycling of food wastes, such as LCA, WtE, waste-to-value products, sustainable extractions, and integrated biorefineries, are widely used in the global perspective (Figure 7) [72,83]. In Figure 7, the main feature of the contemporary perspectives on FW valuation is depicted. Establishing those global bioconversion strategies for efficient and sustainable FW management in Bangladesh is vital. Research is needed to optimize the strategies in the context of the current state of FW management in Bangladesh.

During food safety assessments in Bangladesh, the interaction of environmental pollutants such as pesticides and heavy metals in foodstuffs and the surrounding ecosystem was identified as a critical threat [91,92], which may persist in food waste due to unplanned FW management. Thus, the FW and related MSW management policies and legislations in Bangladesh are critically discussed by many earlier investigators [93]. The policy on FW management in Bangladesh, however, was described as resilient enforcement and requires regular updating for it to be synchronized with global environmental and food policies.

Therefore, regular updating and strict enforcement, as well as public awareness, should be adopted and executed to reduce the generation of avoidable FW through anthropogenic activities. In addition, adaptive and innovative valorization approaches should be employed for resource recovery and sustainable recycling while management of unwanted environmental contaminants therein. This technique has the ability to lessen the negative effects of waste on the natural environment, replace and reduce the usage of synthetic substances in farming, and pave the way for a more sustainable circular economy [93]. Finally, Bangladesh must implement synchronization of international innovation solutions such as integrated biorefineries and waste to value-added technologies that will simultaneously reduce the cost of traditional landfilling or incineration while increasing waste value through valorization bioconversion.

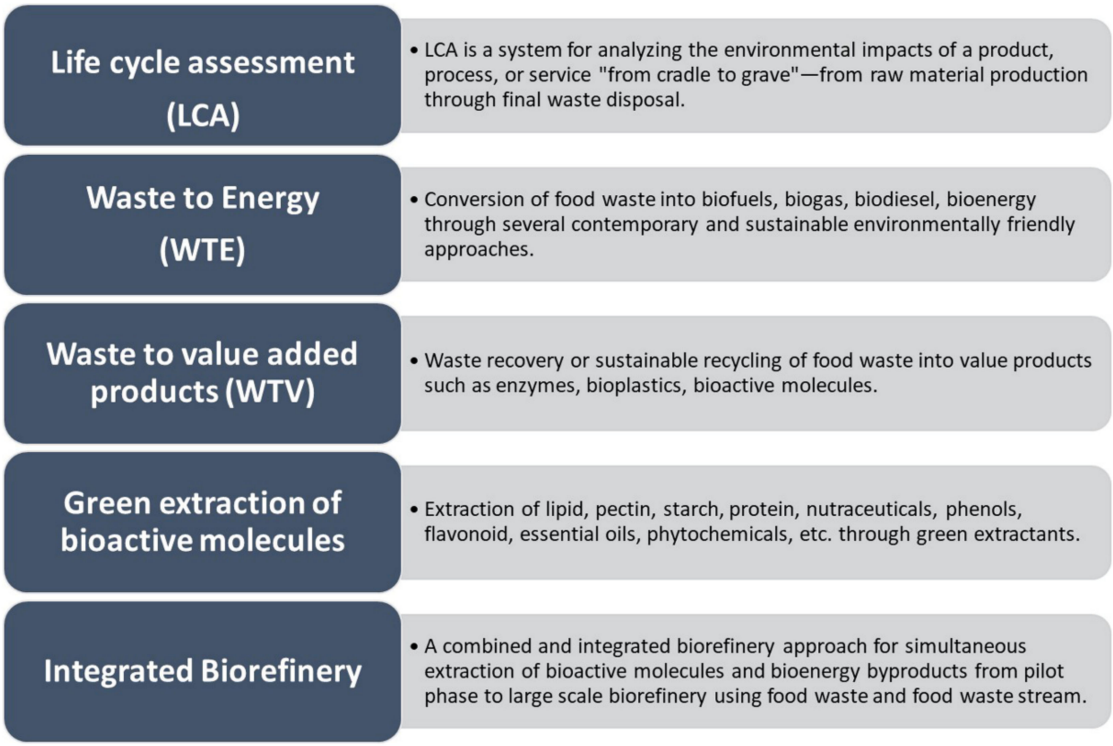

Figure 7. Global and innovative FW valorization and management approaches based on previous studies [8,83,89].

7. Conclusions and Recommendation

This review summarized and critically discussed the current state of FW management in Bangladesh and the opportunities for alternative approaches for recycling FW into valuable products to promote a circular economy. In general, several traditional waste management approaches are practiced in Bangladesh, while FW is not separately managed. This is a critical gap of FW management in Bangladesh. Thus, the existing traditional approaches to FW management have been strongly discouraged due to high cost and environmental and technological concerns. Several new and integrated global initiatives (e.g., waste-to-energy, and waste-to-value products) are prioritized to address the FW crisis in the highly populated Asian countries with special reference to Bangladesh. Although Bangladesh is a leading vegetables and fruits growing country in the global export market, the fresh agricultural products are not able to reach the export market due to technical and quarantine barriers. Thus, a huge amount of fresh and perishable foods, including horticultural and industrial products, is wasted due to unplanned FW management. However, adopting sustainable and novel approaches will expand research avenues for efficient FW management in Bangladesh. Rigorous, adaptive, and industrial-scale research should be de-

signed to explore the most effective valorization technique for FW management to attain the circular economy. Although the government is a powerful determinant in enforcing legal requirements, a holistic approach to FW valorization through a circular bioeconomy may be the most effective option for employing all the stakeholders in Bangladesh. The policy advocacy and related adoption of innovative approaches in this study will serve as a critical reference for future investigations in Bangladesh on FW bioconversion and valorization.

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