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The Growing Biorefinery of Agricultural Wastes: A Short Review

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Abstract: Fruits and vegetables from agricultural sectors are the most utilized commodities among horticultural crops. They are consumed raw, partially processed and entirely processed owing to their nutritional values. Living in the growing population and fast-developing world, the demands production from this sector are also increasing which lead to inclining quantity of wastes and residues day by day which strongly affected our health, economy, environment and social community. The losses and waste in fruit and vegetables are the highest among all type of food as estimated by United Nations Food and Agriculture Organization (FAO), and it may reach up to 60%. Realizing this fact, there is demand for each agricultural sectors for proper waste management of these agro-materials residues through waste recycling approach. These residues constitute various valuable by-products such as phenolic compounds, fibers, cellulosic and vitamins which can be further exploited into biogas, bioenergy, biofuel, biocomposite and biomaterials that can be implemented into industries of textiles, food safety and packaging, medical tool, building blocks and many more. Hence, there is in-depth attention of research and studies for agricultural waste biorefinery as well as their recycling methods. This article presents a review on classification of these residues, several refinery products of agro-industrial wastes and their challenges needed to overcome in the future.

Keywords: Agricultural waste, biogas, biomaterials, biopolymer, biorefinery, circular economy

1. Introduction

Agro-based industry can be described as any activities related to cultivation, under controlled conditions of agriculture and horticultural crops, including floriculture and vegetables cultivation as well as post-harvest operation of all fruits and vegetables. Geographical coordinate of Malaysia near the equator, surrounded almost by the sea and its climate throughout the year, can be categorized as hot, wet and rainy. Agricultural activities such as plantation, fruits, vegetables and other are thus suitable in this high temperature, humidity and accompanied by rain. Department of Statistics Malaysia (DOSM) stated that, agricultural sector generates 7.4% to the Gross Domestic Product (GDP) in 2020 as compared to 7.1% (RM101.5 billion) in 2019. Exports value of agricultural sector increased by 0.9% in 2019 with RM115.5 billion in comparison to RM114.5 billion in 2018. While total imports amounted to RM93.5 billion comparable to RM93.3 billion in 2018 with an incline of 0.2% [1]. These numbers indicated that agricultural sector plays a significant role as one of the economic pillars to the country's economy at the early stage of development until now. In addition, it proven the importance of these sectors to comply human needs and our livelihood. These agro-industrial residues have gradually become the spotlight of various researches worldwide due to their potential to produce raw materials for diverse industrial products.

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In line with their growing production, agro-industries generates an abundant number of wastes. 998 million tonnes of agricultural waste are produced per year globally and from these, Malaysia disposed 1.2 million tonnes of agricultural waste into landfills annually. Along with that, it is estimated 15% from total waste generated in Asia classified as agro-waste. In Malaysia, agricultural waste generation in 2009 approximately 0.122 (kg/cap/day) that is projected to reach 0.210 (kg/cap/day) by 2025 [2][3]. It is highly belief that food and agricultural wastes particularly acute in lower-income regions. Contrary to this belief, wastes generation in middle- and high-income regions eventually occurs with 58% from the global farm-stage food wastes [4]. The main problem of agricultural activities is the improper agricultural waste management system. Most of these agro-wastes are intended for landfills, burnt outdoor or disposed in uncontrolled ways. Agricultural wastes from agro-based industries for instance, animal waste (manure, carcasses of animal, herbicides, etc), processed food waste, crop waste (pruning, vegetables, fruits, flowers, etc), hazardous and toxic waste (herbicides, pesticides and insecticides) have inflated by more than threefold [2]. These wastes could pose hustle in environmental, economic and social sectors if allowed to litter the environment as they are potential habitat for pathogenic microorganisms and leachate production [5]. If poor management systems prolonged, some of them may cause damage to soils and farmland, destructed the natural environment landscape, contribute to Green House Gas (GHG) emission [6] and lead to economic loss [7][8].

Therefore, an integral waste is necessary for sustainable agricultural management, by suggesting a concept of circular economy (CE) to exploit the renewable resources. Circular economy is a closed loop system, away from traditional linear production model which operates using "extract-manufacture-disposal" approach. It is constructed on the concept of biorefinery and valorization, waste's reuse, reduce and recycle with the aim to recover the wastes-derived materials into renewable resources. In the context of agricultural sector, circular economy is implemented with the aims in reducing generation of wastes while increasing their value using economically viable process, in order to make the best use of the wastes produced [3]. Exploitation of agricultural residues could generate a widespread of valuable metabolites, energy and materials which can be further commercialized for bioproducts technologies' development [3][9].

2. Agro-Industrial Waste Classification

2.1 Agricultural Waste

The wastes and residues of agro-industries can be separated into two different group; the agricultural residues and industrial residues. Two types of agriculture residues which are field waste and process waste. Residues or waste present in the field after the harvesting of crop processing is called as field waste. These residues are including the stems, stalks, leaves and seedpods. Process waste on the other hand, residues present even after the processing of crops into alternate valuable resource. Husks, seeds, roots, pulps, straw, stubble, bagasses and molasses [10] are examples of process residues [2][4]. They are commonly used for animal feedstocks, soil improvement, organic fertilizers, manufacturing and many other processes with specific purposes. Agricultural wastes including waste shell of oil palm, palm oil fuel ash, coconut shell waste, coconut fiber and waste of rice husk are also being utilized for green concrete industry, which is concrete exploited from industrial by-products [5]. Globally, annual food waste is roughly around 30% of cereals, 40-50% of root crops, vegetables and fruits while oil seeds are 20% of them [4]. Field residues are generated in abundant amount and most of the time they are underutilized. Such harmful residues are increasing in number days by days and eventually considered to contribute to harmful effects on the environment [11].

2.2 Processed Agricultural Waste

Myriad vegetables and fruits that are not consumed raw as a result of the commodity morphological characteristics, poor proper handling or discarded for various reasons, are initially processed to obtain the desired products. Agricultural processing industries into food products like juice, chips, snacks, meats, and confectionary also contributed a significant number of organic wastes and effluents. As far as the wastage is concerned, papaya peels wastes are produced about 8.5% from the dicing stages, 16% of mandarin peels are generated during the peeling process. Processing of pineapple and mangoes yield about 14% and 11% of peels respectively [12]. Cloudy apple juice which is treated as waste compared to clear juice, are reformulated using ultrafiltration (UF) into another value added products that reduced sugar content, beneficial for human comsumption [13]. In some countries, the processing of agricultural products increasing due to arising population number and to fulfill the demand. These agricultural processed wastes constituents a various biocomposite such as cellulose, hemicellulose, phenolic compound, ash, carbon and nitrogen. They can be reuse and utilized as they have potential to biochemically digested into another form of bioproducts and new sources of energy like biogas, bioethanol and biopolymer [4]. Orange peels, potato peel, banana peel, cassava starch, oil cake of ground nut, coconut and soybean are some examples of agricultural processed residues [11][14].

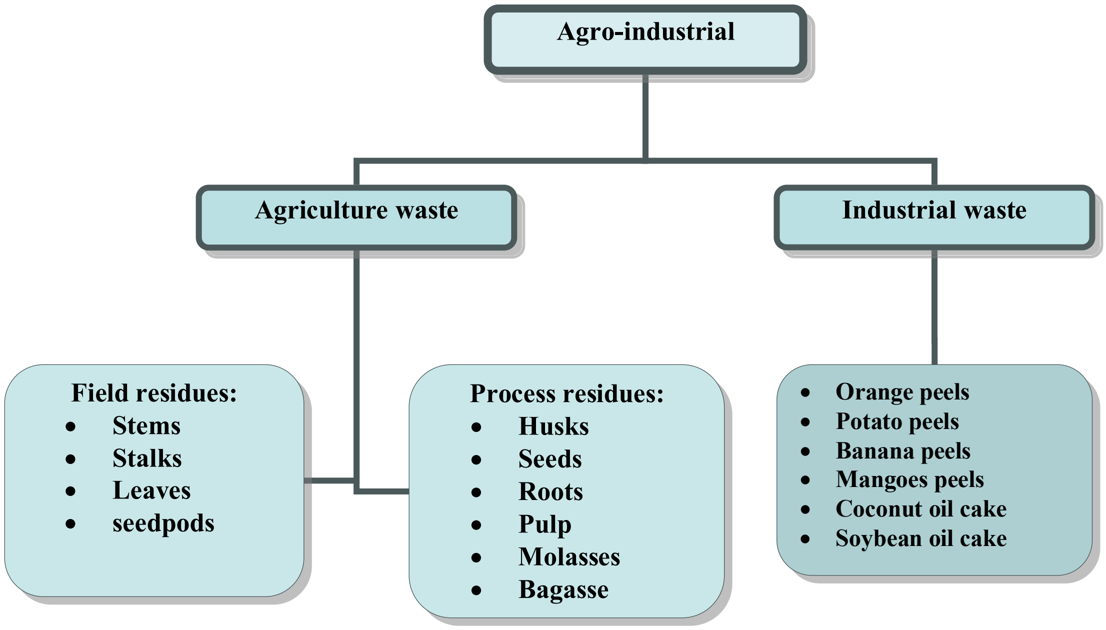

Fig. 1 - The type of agro-industrial wastes and by products forms

3. Biorefinery of Agro-Industrial Residues

3.1 Biomaterials and Biocomposites

Polymer matrix and natural fibers, that act as reinforcement, formed a biocomposites. Natural fiber can be derived from plants, animal and mineral. In the field of agriculture, there are six types of natural fibers derived from plant particularly used in biocomposite, which are grass and reed fibers (wheat, corn and rice), core fibers (hemp, kenaf and jute), bast fibers (ramie, hemp, flax and jute), roots and wood fibers, leaf fibers (pineapple, agave, sisal and banana) and seed fibers (kapok, cotton and coir). Cellulose, hemicellulose and lignin are the major composition of natural fibers. The stability and strength of plant's cell walls primely comes from the cellulose and this component directly influences the production of biocomposites in a vast industrial application including textile, automotive and packaging. Cellulosic fibers have been used as reinforcement agent of various thermosetting and thermoplastic resins and these fibers profitably used in fiber manufacturer or particulate polymer reinforced the composites as they possess interesting physical and mechanical properties [15]. Fibers with high amount of cellulose has low level of lignin. This is due to a highly cross-linked of lignin structure will modify and influences the structure and properties, morphology, hydrolysis rate and also fibers flexibility. The characteristics highlighted by these materials such as low costs of production, light weight, eco-friendly, ease workability, excellent thermal insulation and mechanical strength have attracted numerous research studies. Nevertheless, there is poor interfacial interaction as natural fiber is hydrophilic while polymer matrix is hydrophobic in nature. Eventually, deterioration of mechanical properties occurs. As a result, chemical and physical treatment is developed to modify natural fiber's surface and promote interfacial adhesion with the polymer matrix [1].

Growing concerns of environment and necessary for more renewable materials, there appears to be a great shift of synthetic polymeric materials into renewable biopolymers. Biopolymer offers high adaptability and more functionality over traditional synthetic polymers although they are cheaper and easier to mass produce. Proteins (e.g., hemoglobin and ferritin) act as an excellent binder with metal ion such as iron. Ferritin have been utilized as a scaffold in gold nanoparticles' synthesis. A stable thermal films development often used chitin and cellulose. While on another study, cellulose is used for optically clear glasses and papers. Possessed several disadvantages do not claim it is perfect, in facts biopolymer also require improvement by adding them with synthetic materials for example inorganic nanoparticles. Difficult processability is one of the drawbacks taken into consideration for future improvement as it is time-consuming and costly recovery methods [16]. Cellulose, starch, pectin, cutin-based materials and biocomposite are part of the natural sources of biopolymers [17]. Employment of natural fruit wastes minimized the environmental problems and threats and more importantly, some of the fibers proven almost equal strengths and resistance as traditional synthetic fibers [15].

A study of orange peels reinforced polymer composite shows a new potential class of epoxy-based composite with fruit waste. The results shows that the composite's tensile, flexural strength and hardness is maximum with association of 20% weight percent of orange particle. SEM analysis illustrates that most particles were broken instead of pulling out from the matrix which indicate a good particles and matrix bonding occurs [15]. Another study by Awasthi et al (2019) also agreed with ideas by revealing that orange peels which were considered as wastes, can be integrated in main stream materials and as a replacement of some engineering materials for light duty applications [18]. The suitability of corn and rice starch-based bioplastic as an alternative packaging material were also well proven. The bioplastic samples shown better biodegradability (48.7%, in 15 days) over existing plastic materials. The shelf-life of the materials improves as well as the mechanical properties with the addition of citric acid. The results suggests implementation of bioplastic for packaging materials as alternative to LDPE and HDPE plastic bags while it can also be used as poly bags [19].

3.2 Bioenergy, Biofuel and Biogas

Agriculture and agro-based industries wastes have been a major biogas sources specifically in areas and countries where agriculture plays important role in the economy. Animal wastes, straws, spent grains, wastewaters and others are part of these wastes, have been converted into biogas. Biogas formed through a process known as anaerobic digestion, where the microorganism degrades the biological matter (biomass) in the absence of oxygen. Biogas consists a mixture of mainly methane (60-70%) and CO2 (20-40%) with other traces of gases such as CO, H_2S, NH_3, N_2, water vapor and many more. The waste sources and digestion process management affect the percentage composition of each gas in the mixture. Biogas technology grasp the advantages of environmentally friendly and inexhaustible [7].

The blending of Brewery Spent grain (BS), sludge of carbonated soft drinks (CS), soya bean cake (SB) and powdered rice husk (PR) shown an encouraging biogas production with specific ratios. The results indicate that, BS and CS drink sludge with the presence of either powdered rice husk or soya bean cake will enhance the production of low biogas and/or flammable biogas. The mean biogas production of BS: SB (4:1) and BS: PR (1:1) increased to 11.40 and 18.90 L from initial BS production, 7.5 L respectively while rise of 5.78 L from combination of CS: SB [8]. In a study, olive mill wastewater (OMW) and liquid cow manure (LCM) co-digestion in a system of two-stage mesophilic (35ºC) acidogenic-methanogenic CSTR. This system successfully demonstrates a sustainable and environmentally-attractive technique to treat these agro-wastes from society' burden into useful and valuable resources. The OMW-LCM biogas production can be used for heat and/or electrical generation. Another beneficial output from this co-digestion are solid and liquid effluents as they retain primarily of their nutrient constituents, including nitrogen, phosphorus and others. This second-level output can be reuse and recycle back into agricultural field as fertilizers and soil improvers. In addition, the use of co-substrate LCM exhibits several advantages over OMW in the anaerobic digestion, which are process stability and minimization of nutrients addition, methane yield improvement by diluting its phenolic content and stable year-round operation as a solution for seasonal problem of OMW management [20].

Cassava starch by-product and wastes have been considered as viable option for the circular economy concept adoption where it is converted into biogas production. In Thailand, it was reported that approximately 21 million m^3 and 9.5 Mt for the annual generation of wastewater and cassava pulp. Thus, it becomes the key drivers and challenges for implementing circular economy concept in unison to fulfill high demand for biogas system. From the result, a factory applying both cassava pulp and wastewater as raw materials for biogas system generated the lowest greenhouse gas (GHG) emission of 0.14 kg CO_{2eg} kg^{-1}, highest net present value per period od 10-ye operational and lowest payback period. Implementing cassava starch production process (CSPP) for CE take the advantages of energy security and resource efficiency improvement and also reduction of environmental issues such as emission of GHG, stench and disturbing odor, and also inefficient land use. Nevertheless, the cost and technology for pretreatment of cassava pulp is a barrier needed to be overcome for this biogas production [21]. Five potential raw and processed agricultural wastes; soybean residues, papaya peels, sugarcane bagasses, rice straws and greater galangal were evaluated and investigated for conversion into biogas using both processes of batch digestion and continuous digestion. The highest biogas generation observed at various hydraulic retention times (HRT) recorded are from residues of soybean (25 days) and papaya peels (15 days), followed by sugarcane bagasses (25 days), rice straws (20 days) and greater galangals (25 days) which correspond to 560.47 ml, 404.24 ml, 363.20 ml, 3.62 ml and 45.83 ml respectively. Papaya eels can be concluded as the promising feedstock due to its low HRT, high production of biogas and composition. The other lignocellulosic materials however better converted into other renewable energy for small scale production [22].

There is high dependent on various fossil energy sources such as petroleum oil, coal and natural gas for daily our purposes including generate electricity, fuel and other purposes. Consumption of fossil fuel in excessive amount increased the high level of pollution over the years. Import fuel and annual production of oil globally will decline within the near future. Thus, renewable sources such as wind, water, sun, geothermal and biomass serve as an alternative option. Thus, utilizing biomass from agro-industrial wastes for bioethanol production is a suitable and feasible replacement for fossil fuels. As reported by Kim et al, 442 billion L of bioethanol was estimated to be produced from lignocellulosic biomass and in a year, that total crops residues capable to produce 491 billion L bioethanol. This number shows about 16 times higher in comparison to actual bioethanol production world. Bioethanol production from agricultural wastes can be achieved by various process such as fermentation, pyrolysis, physical and physic-chemical treatments, degradation by enzyme, treatments assisted by ultrasound and others [8].

4. Challenges for Agricultural Wastes Biorefinery

The expected growing population by 50% in 2050, signifies that 70% more food and 100% more energy will be needed. Implementation of circular economy could improve the resources efficiency by turning the linear supply chain into closed-loop and contribute to Sustainable Development Goals. However, the biorefineries of agricultural wastes at times facing various problems and challenges on account of chemical and physical variability of the wastes stream which lead to complex process operations, high costs of processing and low conversion yields [23]. Certainly, agricultural waste is not automatically sustainable, pretreatment process and biorefineries technologies are required [24]. Precise blending ratios, transport and handling of the biomass, high-cost pretreatment for the residues by-product and efficient method required during pretreatment for total delignification of biomass. Pretreatment method plays an important role as proper step will increase the fermentable sugars' concentrations after enzymatic saccharification thus, efficiency of the whole process improved. In-depth knowledges and studies is indeed required for producing bioproducts derived from these agro-industrial residues in order for cheap, cost-effective and complementary technologies can be developed [8].

Food industry is one of the significant waste producer, accounting of 70% of agricultural waste in the world [14]. Agricultural wastes a good source of proteins, carbohydrates and vitamins, however these sources are limited to be reuse in food industry due to presence antinutritional factors (ANF) in the crops. ANF is substances generated by plants secondary metabolisms to protects themselves from predator, concentration varies depending on the crop's species, season of the year and post-harvest treatment. The adverse effect of consuming these substances damages the body, thus treatments is required to decreased the ANFs to permissible level. Physical, thermal or biological type of treatments to be applied depending on the equipment availability, facilities, costs and mainly the type of ANF to be eliminated [6]. Work on regulatory frameworks by government need to be strengthen in order to encourage greater exploitation of agricultural wastes. In order to guide potential investment in innovation and infrastructure, policy strategy and prediction tools is essential, but it should also foster awareness among consumer to make them adopt a morally right perspective and behavior with respect to waste [23]. Life Cycle Assessment (LCA) is a methodology widely used for quantifying the effect of a products and services to the environment. In spite of LCA applicability, it is linked with certain data limitations that will be needed by research and development purposes, more precisely the agricultural residue chain inventory data, which are not easily accessible or missing in general [25]. Supportive regulations and financial support mechanisms are also necessary for investors for sustainable progress from the stage of early business-planning to operations and lastly commercialization [21].

5. Conclusion

Circularity of bioeconomy is closely related to sustainable valorization of bioresources. Residues of agricultural sectors proven rich in nutrients and valuable by-products. They could be considered as a new form of raw materials and bioresources for further sustainable valorization processing instead of waste. The anaerobic digestion of microorganisms also increases the degradability of agro-industrial residues which assists in avoiding the environmental contamination and any other pollution-associated problems. The circular economy concept is one of the best alternatives to overcome the agro-based industrial residues' problems. The use of the 'raw materials' from underutilized wastes helps minimizing the production cost and contribute to waste recycling for eco-friendly environment. Biorefinery of agro-industrial waste is profitable in commercial market with huge potential and larger applications in new sectors in the future. The accomplishment of this circular bio-economy is possible with more research and innovations efforts and a wider cross-sectoral collaboration, both in local, regional and international levels.

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