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Review

Recent Progress and Future Perspectives for Zero Agriculture Waste Technologies: Pineapple Waste as a Case Study

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Abstract: Worldwide, a huge production of agro-industrial wastes is observed every year in the milling, brewing, agricultural, and food industries. Biochemical and bioactive substances can be produced from these agricultural wastes. Pineapple by-products, which consist of the peeled skin, core, crown end, etc., account for 60% of the weight of pineapple fruit and are disposed of as waste, causing disposal and pollution problems. The bioconversion process can utilize these wastes, which are rich in cellulose and hemicellulose, the main components, to produce value-added biochemicals/bioactive compounds such as pectin, citric acid, bromelain, ferulic acid, vanillin, and so on. Therefore, the sustainable solution for food and nutrition security can be supported by the utilization of pineapple waste. The proposed review article addresses approaches that do not generate waste while adding value. This can be achieved by using innovative biorefinery techniques such as green extraction and the use of green solvents. Microbial fermentation with an effective pretreatment (such as hydrothermal treatment and enzymatic treatment) to convert complex waste (pineapple fruit) into simple sugars and later fuel production are also discussed. The proposed review also provides a concise overview of the most recent research and developments in the field of advanced pineapple waste processing technologies.

Keywords: pineapple waste; zero waste; bioconversion; pectin; phenolic; biochemical

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1. Introduction

There are several critical points reported for the management of plant waste and this is due to increasing plant production in agricultural sectors at the global level, including in Malaysia. Due to rapid development and increasing agricultural activities, Malaysia generates almost 1.2 million tons of agricultural wastes and these are disposed of every year in Malaysia alone [1]. In Malaysia, there are different types of wastes which are also burned/decomposed with increasing environmental problems. There is an increased awareness of the environment and sustainable practices. There is a need to seriously address the long-term effects of plant waste, such as the burning of pineapple leaves [2]. Many researchers have already taken serious steps to solve these problems. The transformation of plant waste is continuing with the synthesis of value-added products with a wealth-based approach to create a sustainable agricultural industry [2,3]. In this context, it is noted that pineapple waste is generated worldwide and is disposed of as waste. Recently, researchers have worked to utilize pineapple waste as a valuable resource for economic development with a zero-waste concept [3]. In the applied efforts, pineapple leaves have been used for transforming tasks that serve to develop wealth and also produce good environmental awareness that can contribute to the concept of turning waste into money. In Malaysia, several initiatives have been working to obtain valuable pineapple products from pineapple leaves. This is a good approach for converting pineapple waste into commercial products [4]. In valuable by-products, development processes are found that involve the utilization of pineapple leaves with the development of high-quality fibers in terms of structural and mechanical properties. In the current context, published works are discussed for effective technologies that deal with the production of sustainable pineapple leaf fibers (PALFs) as a valuable waste material source, focusing on the reduction in environmental pollution through more practice at local, national, and international levels [3,4]. The use of PALFs can minimize the huge accumulation of waste that needs to be burned or disposed. Moreover, energy and natural resources can be conserved by the justifiable manufacturing method of PALFs with a maximum quantity. It can also contribute to the development of a green environment and promote economic growth in a world without waste [1,4].

Pineapple (*Ananas comosus*) leaf fibers (PALFs) are discussed as a waste-derived biomass and are used for the synthesis of valuable products, with the largest productive system in the agro-industrial field, and it has now been shown to be a very promising source for use in compost form [5]. PALFs from pineapple waste have shown future prospects for a practical application in the construction and automotive sectors. Additionally, efforts have been made to explore these prospects, but their use in practice has been limited. This review paper discusses information from published works on wastes and their respective products and examines the discrepancy between the proposal and actual implementation with a range of options [6]. Nevertheless, it has been shown that there are still many limitations to industrialization and that significant efforts need to be made in practice. There are a number of considerations and recommendations that can help overcome these problems. These include the arrangement of fibers in composites, new matrices, and also the development of hybrid materials. Additionally, these are also necessary to develop the interest of high added value at the industrial level [5,6]. Many efforts have been made to minimize the environmental problems associated with the production, disposal, and recycling of synthetic fiber-based polymer composites, and high development efforts are needed to replace them. The development of pineapple-based fibers began with immediate efforts to develop environmentally friendly fibers from natural sources [7]. It is now reported that jute, oil palm, cotton, flax, banana, hemp, sisal, and pineapple leaf fibers can be used to develop various valuable products with different applications in automotive, biomedical, furniture, packaging, and infrastructure materials [8]. In the current context, PALFs have depicted themselves to be a valuable material that can be used for the development of non-structural industrial products using natural and synthetic fibers with various matrix products. Some evaluation studies have been conducted to determine the mechanical properties of PALFs, and these properties were dependent on various factors such as void space, the matrix type, fiber length, type of various wastes, fiber orientation, and porosity content [7,8]. We mentioned other countries that produce pine fruit in large quantities; Costa Rica, Indonesia, and also the Philippines are the main countries that produced a large amount of pineapple in 2021, according to the Statista report [9]. The proposed review focuses on pineapple sources as a case study with the exploitation of the composition, technology application, and development of different products, with the goal of zero-waste. These can help with creating various bio-based products in a sustainable way.

2. Waste Biomass Potential of Pineapple

Some advanced research has looked at improving the mechanical properties of PALF through advances in process/material addition and then discussed reinforcement with thermoset, thermoplastic, and biodegradable resins. Some attempts were made to properly characterize PALFs as hybrid composites developed with natural and synthetic fibers. Additionally, some surface treatments were carried out to improve the interaction between PALFs and the matrix [10]. Later, some considerations on coupling agents were made to improve the mechanical strength of the fibers. Due to some limitations noticed in the proper efforts, engineering solutions have started to be found for the traditional problems in processing natural fiber composites and their tensile strength. Durability, an improvement of the structural components, thermal stability, and an improvement of the interfacial incompatibility are also technical problems in the use of natural fibers, but efforts are being made to solve these problems [6,10]. Some research articles have highlighted the gaps identified in previous work with solutions to minimize these gaps. Additionally, it needs to focus on using resources data in tabular form with a future research plan in a different stream with PALF strengthening efforts with more applications [7,10].

Another report discussed natural lignocellulosic fibers (LCFs), which are a good example of fiber development. Pineapple fibers can be used as a reinforcing material for the development of polymer composites by providing an alternative to reinforcement with glass fibers in the development of synthetic fibers [11]. Meanwhile, a number of scientific and technical methods have been applied to develop the best quality of natural fibers that can support the development of bio-based fibers. In the current context, the use of numerous LCFs in composites has been reported, and then the pineapple leaf fiber (PALF) is explored, which is derived from the leaves of *Ananas comosus* and is the best LCF source with the potential for composite reinforcing agents/tasks [12]. The use of pineapple fibers in composites can help to improve the specific mechanical properties and microstructural characterization (see Table 1). In some other published works, it has been shown that these aim to evaluate the flexibility and it can be measured by a three-point flexural test and also epoxy composite [13]. Additionally, these can be incorporated with up to 30% PALFs by volume. These efforts have shown some interesting results on continuous and aligned fibers and can significantly increase the flexible strength in fiber composites, which was confirmed by scanning electron microscopy. It can also confirm this by revealing the fracture mechanism responsible for the reinforcement task [11–13].

Table 1. Physical and chemical properties of pineapple wastes and generation of value-added products.

Pineapple Waste	Value-Added Products	Reference
Physicochemical properties (crown extract) pineapple variety N36: • Percentage of pulp: 2.41%, pH: 3.94. • TSS: 1.6-degree Brix, and percentage of acidity: 0.3%. • Percentage of fructose: 0.83%) and glucose: 0.51%.	From this waste, bromelain is extracted with purification by preparative HPLC (uses cation exchange resin column).	[14]
Physico-chemical properties (pineapple peel extract variety N36): TSS, pH values, TA, absorbance and pulp content	These properties can help to provide significant information on increasing the ripening stages of fruits.	[15]
Physicochemical properties (pineapple plant waste fibers from the leaves and stems of MD2, Moris, and Josapine: Cellulose, hemicellulose, lignin, proximate composition, dry matter, and nitrogen content.	These properties were analyzed using thermogravimetry analysis, helping to determine the nutrient contents (such as crude protein, crude fat, crude fiber, carbohydrate), in fruits.	[16]
Rheological properties of N36 pineapple waste were deciphered for, peel, crown, and core parts, and it has helped in the determination of different maturity indices.	It was studied at room temperature (25 °C). for total soluble solid contents and density with different maturity indices.	[17]
Mechanical strength and Young's modulus and chemical tests: composition of each fiber after extraction by water retting.	These mechanical tests help in fibers content determination, extracted from roots with better performance than those from leaves and stems.	[18]
Optimal physical and chemical properties of pineapple waste can be helped for a decomposable pot selection. This task can provide possible method for waste management.	These properties were checked for pineapple waste to binder: 1:0 ratio. It needs a coarse structure, and a pot thickness of 1 cm.	[19]
The pineapple leaf waste was analyzed for its nutritional values (protein, fiber, ash, fat, and sugar) using standard AOAC met.	The physical properties such as friability, bulk density, true density, hardness, and porosity of pellets and it has increased the milk production in dairy cows.	[20]

3. Zero-Waste Technologies

In the modern era, the growth of the world's population has spawned other trends with a simultaneous enormous generation of agricultural waste. These trends of waste generation and accumulation in the environment have negative impacts, which is a cause for great concern. Recently, some review articles have discussed the link between the concept of circular bioeconomy and the development and use of waste-free technologies [21]. This can help to promote the sustainable development of biocomponents, biorefineries, and also alternatives to conventional products. With some advanced research efforts, it can lead to a less negative impact on the environment. Regarding waste recovery, a brief analysis of the Ecuadorian industry and export process was made, highlighting more the reasons to improve the Ecuadorian trade balance. It is also necessary to increase industrial competitiveness [22]. New technologies and innovation efforts can be used to promote the replacement of the use of fossil fuels with the use of renewable resources. It can help in developing greener processes and industries to produce sustainable and bio-based products [21,22]. Some researchers have analyzed in depth the status of biomass research and conversion in Ecuador, along with current research efforts on biomass pretreatment. These can help to generate and promote clean fuels, and also the extraction of secondary plant materials using green solvents such as deep eutectic solvents and technologies [23]. These efforts can help to obtain high-quality materials with an improved quality and functional properties. Some publications emphasize the need to develop technologies and markets for the commercialization of high value-added products that can help in the development of biorefineries with the sustainable production of bioproducts [24]. These efforts can be increased in both rural and urban areas by strengthening the productivity and profitability of Ecuadorian agribusiness. Additionally, the goals that have been achieved to improve Ecuador's trade balance and contribute to the circular economy by promoting the sustainable development of organic products have been discussed [22,24]. Pineapple leaves are a good source of high-quality natural fibers, and pineapple-based fibers are not properly exploited at the commercial level. PALFs have shown many potential applications, such as other sources of natural fibers and how they can be used for plastic reinforcement, as well as sound and thermal insulation [25]. People have used the conventional methods for the extraction of PALFs and in an applied approach, they used the scraping, rotting, and decorticating with as the decorticator start approach. Then, the removal of long fresh leaves has been achieved using mechanical force. The applied task can remove soft cover materials for providing long fibers. The conventional method may result in the low yield of fiber bundles, making them difficult to scale [26]. Some research has also been conducted using novel extraction methods called mechanical milling, and the current efficiency has been compared with the conventional methods. The new/advanced method starts by crushing fresh lead and then mechanically grinding the material into a paste. Then, the soft cover material is removed to break it into fine particles [21,23]. The resulting fibers can withstand the force due to their strength and maintain their length in the form of bundles that can be defibered into smaller diameters. These fibers can be separated directly by screening after drying. The new and advanced method is simple and can be easily extended for the large-scale production of short PALFs [23,25]. An applied approach was compared with the conventional methods and it was found that the new method provides a higher yield of PALMs and finger PALM material. Short PALFs can be used to reinforce polypropylene, and the potential application can be demonstrated with a superior PALF quality compared to other approaches [21,26].

3.1. What Is Zero-Waste Technology

Zero-waste technology is based on a set of principles focusing on the prevention of waste and helping to redesign resources so all products can be reused in an effective way. People are exerting a lot of effort to apply zero-waste technology to avoid waste ending up in landfills, incinerators, or the ocean [27]. Currently, only 9% of the world's plastic is used for recycling purposes without generating waste. In a zero-waste system, any plant waste material (such as pineapple leaves/other parts) can be reused at an optimal/maximum consumption with a good yield of the desired products. In a zero-waste strategy, the production processes can be improved and also the avoidance strategies that take greater and more innovative steps have to be standardized to maintain a good environment in a sustainable way [28]. Zero-waste technology can support sustainability with all three recognized goals, such as sustainability, economic well-being, environmental protection, and social well-being. Another advantage of a zero-waste strategy is the use of less new raw materials and the generation of no waste in landfills [27,28]. In recent years, any waste material can return as a reusable or recycled material and be more suitable for conversion into valuable products by using composting processes. There are so many zero-waste conversion strategies that can be applied for reusing bottles with more beneficial roles [29]. Additionally, the material usage per trip is found to be less than in other systems. One case study was done within a primary input/resources nature and it was applied on silica sand with the capability of becoming glass, and it was then converted into a bottle. The bottle goes to be filled with milk and can be utilized for milk distribution to consumers. In reverse logistic returns, the bottles undergo cleaning, inspection, sanitization, and reuses [19,22]. Finally, the heavy-duty bottle can be found to be more/not suitable for further uses and can then be recycled. Hence, waste and landfills usages can be minimized with a good example of the zero-waste generation concept. The material waste is mainly the wash water, detergent, transportation, and heat, namely, the bottle and bottle caps. The zero-waste status of a life cycle assessment task for calculating the waste quantity at each phase of each cycle can be calculated [29,30].

3.2. Role of Zero-Waste Technologies in Environment

In recent years, researchers have focused on the zero-waste biorefinery concept and they have applied it for inspiration for the green oleo-extraction approach for the production of natural volatile and non-volatile compounds. In categories of natural volatile compounds, they discussed the borneol, camphor, o-cymene, limonene, terpinen-4-ol, eucalyptol, and a-pinene compounds, but in categories of non-volatile compounds, carnosol, carnosic, and rosmarinic acid are good examples [31]. These types of compounds exhibit a bioactive nature with health benefits, and some of these compounds derive from rosemary leaves with vegetable oils and their derivatives with their amphiphilic nature. These compounds are simple food-grade solvents with increased applications in food industries [32]. Further discussion was had regarding soybean oil, which was reported as containing a higher quantity of total phenolic compounds (TPCs). Some of the TPCs are derived from twelve refined oils, and these are obtained from rapeseed and rapeseed waste and peanut-, sunflower-, olive-, avocado-, almond-, and apricot-based wastes [31,32]. Some more examples have been reported, such as corn, wheat germ, and hazelnut oil. Additionally, there has been efforts to add the oil derivatives of soybean, and these derivatives are glyceryl monooleate (GMO), glyceryl monostearate (GMS), diglycerides, and soy lecithin. The additions of these compounds of refined oils/derivatives can enhance the oleo-extraction of non-volatile antioxidants (by up to 66.7%) and also help to improve the solvation of aroma compounds (VACs~16%) in refined soybean oils [33]. Critical information was reported in some published works, and this has provided some interesting results for claiming a good consistency and relative solubility with a good prediction via the application of sophisticated COSMO-RS (conductor-like screening model for real solvent) stimulation [34]. Another article explained the simple procedure of using vegetable oils and their derivative as a bio-based solvent for simultaneously improving the extraction yield of natural antioxidants and flavors from rosemary waste products, with claims of zero-waste generation [33,34]. Next, there has been a recommendation to use green techniques (such as MAE and UAE) as they have the potential to up-scale the generation of large-scale natural products. New/advanced efforts can promote the zero-waste biorefinery development from waste biomass matter, such as in the use of pineapple waste. Applied efforts can help in the extraction of value-added products, with the development of future functional food and applications in the cosmetic sector [31,34].

In another report, the yield of non-edible oilseed plant species was discussed with huge numbers of plant species with other biodata. These plant species can produce non-edible oils with a lesser economic importance. Recently, people have become more interested in renewable energy generation (i.e., bioenergy/biofuel) and also the promotion of this. In the current effort, the utilization of non-food resources has been reported as potential feedstock for biofuels and non-edible oil seed has gained more attention by researchers at a global level [35]. There are many non-edible oil seeds containing tree species and most of them are reported to scatter from different agro-ecological regions such as forest, non-forest, wetland, desert, and also hilly areas across the globe, including in India [36]. These plant species are found more in northeast India; this location is known as a biodiversity hotspot harboring a larger number of non-edible oil seed groups. Next, effort was exerted to extract non-edible oils, which, depending on their chemical characteristics, can be utilized for biodiesel production; this has been analyzed by various standardized techniques. Different types of biodiesel production processes have been produced by the utilization of the different natures of biowastes, including seed covers and de-oiled seed cakes [35,36]. These biowastes can be found in lignocellulosic nature with more utility as potential and important feedstock for bio-oils and biochars' synthesis via the application of pyrolytic valorization techniques. Some efforts have been exerted on the utility of de-oiled seed cake for numbers of other industrial applications and uses such as the preparation of improved feed materials, mosquito repellents, and others [37]. Biochar generation is reported as co-products of pyrolysis and it can have various uses, such as soil amendment, drinking water filtration, the remediation of heavy metal contaminated water, and some catalyst preparation [38]. There is currently an imperative need for research work using a cascade of approaches in the applied process of waste biomass, which has a lesser economic importance. However, a variety of bioproducts and services in biorefinery development can generate more utility without any waste matter generation [37,38]. Others have detailed the information status of non-edible oilseeds that can be yielded by several plants, and various approaches have been discussed for the exploration of zero-waste non-edible seeds and also envisions for non-edible oil seed. These waste sources can be made more useful for the possible synthesis of useful products for our needs [35,38].

4. Zero-Waste Technologies for Pineapple Wastes

A number of efforts have been untaken by researchers for techniques for zero-waste in the validation phase via studying the impact of the materials along with approaches to control the rancidity of packed fresh food such as red meat, which needs a longer life cycle. In other aspects, research is ongoing which studies the aroma-enhancing active components incorporation mechanism and its impacts [39]. Some efforts were done for pineapple wastes to recover the bioactive of the industrial importance, thereby helping to improve the consumer's sensory experience via a sense of smell. In the current context, the development of an edible film of a natural origin, such as the source of pineapple waste, has been discussed which possesses antioxidant properties, with a subsequent application to the food packaging industry [40]. Pineapple waste residue can be used as good sources of antioxidant compounds and it can help in the prevention of the oxidative deterioration of fatty foods. Sources of a fruity and sweet aroma can be used as additives into food particles/products and active packaging as aroma-enhancing additives in food and beverages [39,40]. An applied effort has provided a second life to residues which can exceed to 50% of the total weight of each piece of waste matter. In the same context, pineapple waste residue can be used as a good source of antioxidant compounds as it helps in the prevention of the oxidative deterioration of fatty foods and provides fruity/sweet aroma sources [41]. Additionally, an applied effort of product generation has also aided in food product/active packaging with aroma-enhancing additive properties in food and beverage products. As has been discussed regarding the second life of waste matter with a contribution of more than 50% of the total weight, in the current period, many efforts can help in the utilization of food waste (i.e., 1.3 billion tons/per generation capacities at a global level) for the generation of value-added products [42]. Additionally, complex waste utilization is a big challenge due to its huge generation of quantity and worrying associated problems, such as 8% greenhouse gasses, 20% freshwater consumption, and 30% of global agricultural land uses as it has been reported. So, what has been detected is a massive waste resources and related environmental impact [41,42]. Additionally, food waste recovery needs to be designed with an increased importance in the mitigation of economic losses and also in achieving the sustainable development goals (SDGs). Now, a potential effort has been made to utilize the food waste and plant origin residue (such as the husk, stem, leaves, bran, seed, and other parts) for the extraction of valuable flavor compounds, phytochemicals, and bioactives with nutritional properties [43]. Antimicrobial/antioxidant compounds and other value-added products can also be generated with a promotion in a few functional materials, which also has beneficial effects for food preservation [44]. These compounds are very necessary to the food industry and have made a contribution to society via the zero-waste generation effort. The utilized efforts for the mitigation of waste matters can address sustainability objectives with an integration into the concept of the circular economy. It can promote new material with an active natural compound/antioxidant capacity [43,44]. In the current context, the generation of bioplastic from food/plant waste matters can help to provide an alternative option to synthetic plastic containers that can directly interact with food through its storage and enhanced preservation capacity and shelf-life [39,45]. Figure 1 discusses the zero-waste technology with the principles of the SDGs.

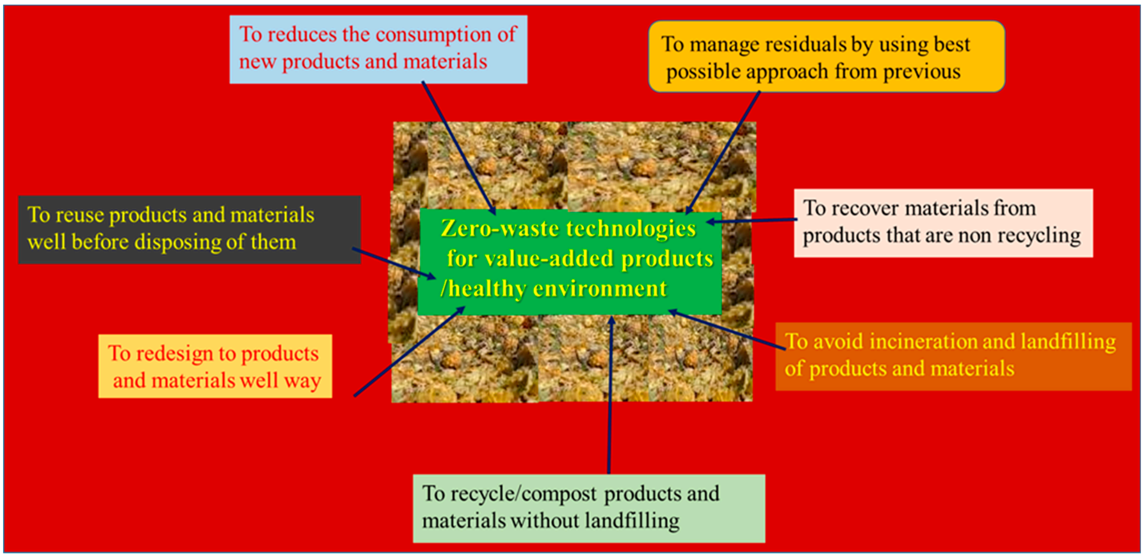

Figure 1. Zero-waste generation technology for pineapple waste.

In this context, what has been discussed first is a technology called hydrothermal (HTT) treatment which can be utilized for the conversion of waste biomass (such as pineapple waste, i.e., stem, leaves, and crown parts) into bioenergy, similarly to ethanol development [46]. This biomass waste is a good source of cellulose, hemicelluloses, and lignin, with some amount of pectin based on the parts used. These are promising candidates for the production of ethanol via the digestion of celluloses into sugar first, which is then converted into ethanol by a suitable fermentation and microbial system [47]. The HTT technique used water in the form of a liquid and a vapor that helped to heat with an effective treatment for biomass hydrolysis, which has broken down this complex biomass, such as lignin. This technique process can cause cellulose/hemicellulose degradation with lignin transformation at a high temperature (around 100–300 °C) [47,48].

Another technique, enzymatic treatment, has also been discussed to be applied in the conversion of pineapple waste into value-added products. In this treatment, the cellulolytic action/mechanism can become involved in the breakdown of the internal bonds of the cellulose crystal structure. After hydrolyzing the chain ends, it breaks the polymers, celluloses, into small sugars and then the β-glucosidase enzymes can hydrolyze the celluloses into sugars such as glucose, fructose, and other sugars [48,49].

The next technique was to apply the protease enzymes in pineapple waste matter; this made the exaction of bromelain easy and with a good recovery and purification, providing it with a utility as a suitable raw material. As has been discussed, this waste matter contains a high quantity of cellulose, and this material can be utilized for the production of nanocrystals, biodegradable packaging, and also bio-adsorbent material [46–48]. In this context, researchers have discussed the utility of the two-stage foam fractionation approach that helped to achieve the high specific activity of the bromelain enzyme, and it has shown a specific activity of 165.6 U/mg with a good recovery rate (45.2%) [49,50]. Bromelain enzyme showed the best protease activity and it is found more in the stem parts of pineapple compared to stem bromelain. Additionally, there are many techniques which can be utilized for the determination of the composition, enzyme quantity, and antioxidant activity in this bromelain, and the stem extract contained a higher bromelain than the peel and fresh extract [51]. Next, the peel and stem of pineapple waste contains a higher quantity of reducing sugars and soluble fibers. Various authors have discussed many effective techniques in different sectors in product development [48–50]. So, the authors only highlighted the important techniques for this topic of pineapple waste. For pineapple waste matter utilization, researchers have exploited various valorization approaches and extraction approaches (MAE/UAE) for bioactive compounds and functional ingredients/groups. These approaches with value-added products have shown many advantages in many areas, such as in industries [50,52]. This waste utilization can provide more benefits from a socio-economic perspective with new material sources for industries. This can help in replacing current expensive and non-renewable sources [51,52]. Further, pineapple wastes can be exploited for the extraction of prebiotics oligosaccharides and also bromelain enzymes. Next, many products/bioactives, such as organic acid, phenolic antioxidant, biogas, and ethanol, and low-cost fibers are generated from these wastes [50–52].

4.1. Biochemical Sector

Plant origin and bio-based products can be derived from forest, animal, and microbial cell systems, with uses in different elements such as air, water, and land resources. These products can be found in natural products and their yield efficiency can be enhanced by technological advances. The number of developments is reported in terms of their economic advancement, and this can impact our strategies/technologies utilized for waste matter decomposition [53]. Due to industrialization promotion, there are various natures of waste matter generation with big challenges in terms of mitigation into value-added chemicals. This is well-known for waste matter generations with a higher accumulation in our environment components, such as water/soils. These waste matters have become more of a problem due to threats to air [54]. It can harm human, animal, and plant growth and survival. It is necessary for the maintenance of agricultural byproducts that are generated during the harvesting of crops and also many activities in food separation in very huge quantities [53,54]. Now, we have put forward efforts for these waste matters/its residues and applied the best and effective technologies for conversion into value-added products with zero-waste generation [55]. In the proposed effort, we can develop the bioeconomy and it can be based on necessary knowledge and also the biological diversity used with the production of sustainable goods and services to all the sectors for a worldwide economy [56]. The bioeconomy concept can embrace/develop two important aspects, such as climate protection, with the shift from being a fossil fuel-based society to a sustainability society, and also we can change from being users of fossil fuel-derived raw materials to users of renewable raw materials. Bioeconomy tasks with its principles are related to zero-waste generation from any resources and it can help in transforming the chemical industry with feedstock that comes from the processing and conversion of agriculture and a silvicultural biomass [55,56]. These biomasses can be efficiently converted/transformed into biofuels and chemicals with the generation of opportunities for the creation of a value chain and also interconnectedness between various natures of biomass, come various regions and industrial centers [57]. These efforts for the development of bio-based products can lead to innovation and market expansion. In the process, there will be more chances of in-turn to generate creative challenges for research institutions and new opportunities for manufacturing companies [58]. Innovative research effort/task can help in creating a circular bioeconomy for shifting to a linear fossil-based paradigm. Additionally, the world has more chances to become accustomed to the industrial revolution, with good results of global socio-economic and technological development [57,58]. Sometimes, unsustainable activity by humans can cause a risk to the planet's environment. People are now taking the challenging socio-economic shift to a new paradigm with the gaining of the SDGs of the 2020 agenda. A waste minimization goal can be gained via the production of materials and products that can complete food production and also minimize the negative environmental impacts [59]. Further, it can favor the low/zero environmental footprints. These tasks can be gained via designing and developing sustainable processes for recycling, reusing, and recovering the valuable chemical with the good utilization of technologies for a transformation into the chemical platform and final products [53,59]. These products can enter the process of the value chain to make biomass processing activities/tasks and it can achieve a more efficient and competitive form with the ultimate goal of using plant-based waste such as pineapple waste matter/biomass. In the current context, the future circular bioeconomy in any part of the world can be seen with a visualization, which encompasses efficient uses of natural materials [60]. It can be done by the application of valorization techniques for product development that can be transformed from the feedstock from forest, agriculture, zoo-technical, fisheries, and municipal waste. These waste matters have the concept of social participation. Next, society needs to design a production system via helping environmental conservation tasks. The zero-waste generation concept can work with effort to reduce the waste quantity via the elimination of the waste generation system; then society can easily move in the direction towards the utilization of zero-waste technologies [61]. Current/innovative effort can occur via shifting to the development of second-generation biorefineries and then it can ensure the clean production of consumer goods which can be widely distributed to the population [59,60]. Once these goods are in use in society, then it can reuse/recycle/recover valuable components/products. This can be achieved via the promotion of recovery technologies utilization. All these efforts can help to overall economic gain with the utilization of biological diversity. We can increase via the action of producers and consumers both actions to achieve sustainability for society [60,61].

From pineapple waste matters such as stem/fruit, bromelain is a group of protein digesting enzymes, and these enzymes can be found to be different based on plant parts used for their preparation; they also contain a different enzymatic composition. Normally, stem bromelain is a correct bromelain and it is a mixture of thiol-endopeptidase and other components [62]. These components can be found as phosphatase, glucosidase, peroxidase, and cellulases with several inhibitors. Researchers have conducted in vitro and in vivo studies with the demonstration of bromelain activities. Bromelain enzyme exhibits fibrinolytic, antiedematous, antithrombotic, and anti-inflammatory activity [63]. Furthermore, studies were done on the bromelain absorption capability in the body without losing its proteolytic activity and also without producing any major side effects. Next, bromelain can exhibit many therapeutic benefits such as the treatment of angina pectoris, bronchitis, sinusitis, surgical trauma, and thrombophlebitis and an enhanced drug adsorption [62,63]. Due to the advancement in urbanization and industrialization trends all over the world, there has been a sharp natural resources exhaustion with developing instability in the global economy which needs to be minimized with the adaptation of sustainable practices for our development and consumption of bio-based products. In the current period, most of the economies and industries can follow a take–make–dispose pattern in the production and consumption of any type of products (natural/synthetic nature) [64]. In the current period, the attitude of people can find a linear pattern with the magnification of the constraints on the resources' availability, which has also resulted in a price hike [65]. Further, it can promote an unsustainable overuse and economic volatility. Under such circumstances, developed and developing countries can look for new materials. Additionally, a sustainable and carbon-free economic model can help to make the planet livable [64,65]. To achieve the feasible advancement, scientific communities have worked to start via exploring the methods/technologies for reusing and recycling different waste components across the production and consumption succession. These efforts can put back the waste residues into the process cycle of product generation and these processes can be conceptualized into the development of zero-waste biorefinery sectors [66]. Now the researcher's expertise can help in designing the domain emphasis to integrate the bioeconomy into a closed-system recirculating loop system. Additionally, the current system sometimes can compensate for burgeoning the demand of humans [67]. Due to more fruits/agro-industrial processing/operations efforts, huge quantities of biomass waste matter have been generated and it has pushed shortcomings into the circular bioeconomy without adding an auxiliary value. However, innovative effort can articulate social and environmental concerns in a good way. Now, various approaches towards zero-waste biorefinery can be achieved via including sustainable technology to process the lignocellulosic waste (such as pineapple leaves/other parts), algal waste, and residue conversion into value-added products [66,67].

4.2. Bioenergy Sector

Honey pineapple generation is reported to reach nearly 27,162 tons/year in the Central Java location; it is a super product with great and reliable potential. However, sustainable products can be utilized for developing the regional economy for local people. There are several small- and medium-sized businesses involved in the production of processed pineapple honey and these can be made from pineapple juices, pineapple chips, pineapple meal, and also some small/medium-sized businesses that sell the pineapple peels [68]. These activities can produce huge quantities of pineapple peel wastes and complex wastes can be utilized for the biosynthesis of ethanol as we attempt to find more potential energy for household needs [59]. Pineapple skin waste contains carbohydrates and reducing sugars; these are enough as a potential substrate for the production of ethanol via the utilization of the fermentation and distillation process for a high quality and purities [68,69]. Normally, 1 ton of pineapple fruits can produce/generate nearly 250 kg of waste from pineapple peels; a study could be conducted into finding a raw material for pineapple skin waste with a liquid/submerged state fermentation approach and also the uses of distillation [70]. Finally, we can confirm that 2.5 kg of pineapple peel can produce 1 L of ethanol with a 27% yield capability. In some parts of the country, it is reported to generate nearly 4.125 tons/waste with 1650 L/day ethanol [69,70].

In the context to bioethanol production from pineapple waste matter, oleaginous yeast was utilized that was isolated from a local municipal wastewater outlet and it was then confirmed by the application of an 18S rRNA sequencing approach, where it was identified as *Candida tropicalis* MF510172 [71,72]. Additionally, the *C. tropicalis* yeast strain was used for ethanol production with a utilization optimum fermentation condition first for the lipid yield and these conditions were a 180 rpm agitation speed, 6% pineapple waste as a carbon source, 5% inoculum size, 48 h for the inoculum age, and a temperature of 40 °C/incubation of 72 h [73]. Additionally, the *Candida* species can produce 13 mL/liter lipid at optimal conditions. Extraction lipids were used for the transesterification process to form fatty acid methyl esters with confirmation via GCMS and FTIR spectroscopy techniques. Further effort was exerted for the identification of palmitic acid methyl ester and other supplementary hydrocarbon [71,73]. Additionally, the applied identification task for FAME was reported at 1740 cm^{-1} with a C=O stretching band of methyl esters. From this published work, the results demonstrate the waste resources that contained filter wastewater and pineapple waste with an effective utility for the production of quality oils for the production of biodiesel [74,75]; Table 2 shows an example of the biofuels sources.

Pineapple waste-derived biodiesel production has been found as a cleaner fuel for transportation sectors and it can help in the reduction in GHGs emission and also support economic development for the world. As it is discussed, several advantages for biodiesel production form significant amounts of pineapple waste used with water and glycerol sources with a combination or alone substrate [76]. The current bioenergy synthesis from pineapple waste can help to develop the circular economy via the integration of the biodiesel biorefinery design with a proper analysis and also assesses the lead to a better economic and a zero-waste context. In the current effort, SDGs can achieve one stand-alone and three integrated scenarios [77]. Further, it underwent an analysis for a stand-alone biodiesel production with the integration of the production of methanol from carbon dioxide. Further, some other metabolites were also produced, such as bio succinic acid alone or in an integration with methanol [76,77]. All these sources of metabolites have been evaluated in each scenario and these analyses were found on the basis of rigorous profitability, sensitivity, and environmental impact. The next task was the biodiesel minimum selling price in USD/kg and it was 0.30, 0.39, and 0.22/0.44, respectively, based on the fuel sources approach plan, and these led to the most/least profitable value [78]. Next, a sensitivity analysis was undertaken for the waste cooking oil process and the total capital investment was then reported as the most sensitive variable. Additionally, some published report discussed the sustainability perspective with the waste production capacity (0.68/kg-product) and it was found to be wastewater with 0.55 kg/kg products [79]. This report provides the concept for improving the sensitivity and sustainability via two main efforts, such as the implementation of multi-effect evaporation and wastewater treatment. With These two approaches, the waste quantity and its volume can be reduced by 81% to 0.13 kg-waste/kg-product [78,79]. In another report, renewable biological material was discussed with its conversion approaches for bioproducts and biofuel synthesis with the biorefinery approach concept. In the proposed approach, it was presented as a more sustainable alternative to conventional crude oil refineries. This report was focused on the pineapple waste utilization effort as the plant material origin waste for biofuel development. Additionally, it is compared with similar manners such as waste utility for a biorefinery development model via the exploration of circular bioeconomy benefits [80]. Similarly to other plant origin waste, pineapple waste is also reported to consist of peel, core, and leaves as the discarded materials after fruit processing and consumption task [81]. These pineapple waste residues are rich sources of sugars and also some quantity of celluloses, hemicelluloses/lignin (similarly to the other lignocellulosic biomass component). These components with a proper pretreatment and hydrolysis/fermentation approaches can be easily converted into value-added products and biofuel [80,81]. These articles assessed the development and implementation of high laboratory-based works from lower- to advanced-level research works. These need to stimulate a pineapple-based biorefinery effort with conversion in an effective and efficient way to biofuels with a proper fermentation approach of sugars [82]. Further, pineapple core and peel waste utilization can be converted to ethanol for fuel purposes with a proper analysis of the different process variables that can influence the quantity of bioethanol synthesis [81,82]. Figure 2 shows the bioenergy techniques from waste biomass utilization.

A number of efforts have been exerted to develop a microbial energy generation system, such as the utilization of bioelectrochemical systems (BESs), and it is a very promising sustainable technology, with more applications in the biofuels production sector, biosensor, nutrient recovery, and removal of a wastewater treatment task/field/heavy metal [83]. In the current context, BESs have faced some critical challenges, such as a large-scale application in real time, low power performance, and suitable material for its configuration/designs [84]. The application of BES-like conventional microbial fuel cells (MFCs) is discussed with good examples of plant microbial fuel cells (p-MFC), sediment microbial fuel (S-MFC), and also constructed wetland-MFC (CW-MFC) with detailed information [83,84]. Recently, some more examples of MFCs have been discussed, such as osmotic MFC, photo-bioelectrochemical fuel cells (PBC), and an MFC-Fenton system with a focus on the effort of zero-waste generation technologies. Researchers have attempted to design the configuration and selection of electrode materials that can be found as the main variable for improving the MFC performance and zero-waste generation targets [85]. Normally, the zero-waste recovery process from solid and waste feedstock is discussed with energy recovery, such as in the case of electricity generation (up to 12 to 26,680 mW/m^2) and also fuel generation, such as in biohydrogen (170 lit/lit/day) and methane (107.6 m/lit/g) with nutrient recovery (of 100% for phosphate and 99% for nitrogen sources) [86]. The current report also provided pineapple wastes in wastewater sources and this waste utility can be done via the application of BES technologies with an economical option for a simultaneous zero-waste generation and high energy recovery; it has more feasibility for a large-scale production and also commercialization with the help of future and advanced research [85,86].

Table 2. Bioenergy sources from pineapple/others waste utilization by different approaches.

Bioenergy	Sources of Wastes	Technique Used	Reference
Cleaner manufacturing effort is encouraged for biorefinery products and bioenergy sources.	Large volumes of agro-industrial waste reported with negative impact on the environment.	Various research works are done on biomass and its transformation in Ecuador and discussed with n pretreatment methods such as hydrothermal/enzymatic treatments for biomass in order to produce bioproducts and biofuels.	[21]
Lignin was obtained with 93% purity and 82% yield by microwave-assisted acidolysis (MAA).	Biorefineries produce a variety of biofuels from lignocellulosic biomass hydrolysis efforts.	From MAA technique, the aqueous phase is formed followed to softwood acidolysis, It was characterized and tested for fermentation for biofuel for biorefinery system.	[24]
Fabrication of nanoporous microalgal biochar (NP-MBC) was generated/produced.	Microalgae feed on waste nutrients in wastewater and absorb carbon dioxide exhaust gas to develop biomass quickly.	Pyrolysis-prepared NP-MBC adsorbs ammonia content in effective way and it depicted maximal ammonia removal (72%) and adsorption (69 mg·g^{-1}).	[27]
Coralline limestone rocks were applied as heterogeneous catalysts for biodiesel development (i.e., jojoba oil methyl ester (JME) generation).	Jojoba oil, originates from the *Simmondsia chinensis* plant, and it can apply as an alternate, nonfood feedstock for the manufacturing of biodiesel.	JME was developed by using heterogeneous catalysts and then it as evaluated for its kinematic viscosity at 40 °C (6.78 Cst), acid value (034 mgKOH/g), flash point (154 °C), density (865 kg/m^3), and cetane number (53.33 min).	[36]
Phototrophic carbon dioxide assimilation phenomena occurred during microalgal growth, and it may upgrade biogas concurrently.	When phenomena happens, the microalgal biomass is created and then it can be used as a feedstock for biofuels development.	Waste biorefineries can integrate anaerobic waste treatment for microalgal culture development that can apply for bioenergy generation.	[65]
Biochar with improved thermal stability, aromaticity, pH balance, ash content, and yield is produced from various waste matters.	Seaweed, rice husk, as well as pine sawdust are used. It contains strong aromaticity, 40% higher ash concentration, very alkaline pH (10.3), and 1–2% greater level of nitrogen and sulfur.	In trials, *Sargassum* sp., rice husk, and pine wood were combined in a certain ratio and then went to be pyrolyzed to produce biochar products.	[77]
Oleaginous microalgal based biodiesel is generated	Cultivation of algae as well as downstream processing is involved with solving of technological with economical obstacles.	In a bio-refinery approach, wastewater is used as a nutrient source for microalgal biomass growth and then it is used to produce biofuel, charcoal, and bio-products. Zero-waste discharge idea with integration process is used.	[78]
Beneficial bioproducts as well as biofuels such as ethanol are generated from various waste matters	Biorefineries can extract sugars from lignocellulosic biomass such as pineapple trash.	Bioethanol production is found from pineapple leaves by fermenting the sugars from the core and peel waste via suitable microbial system fermentation processes.	[82]

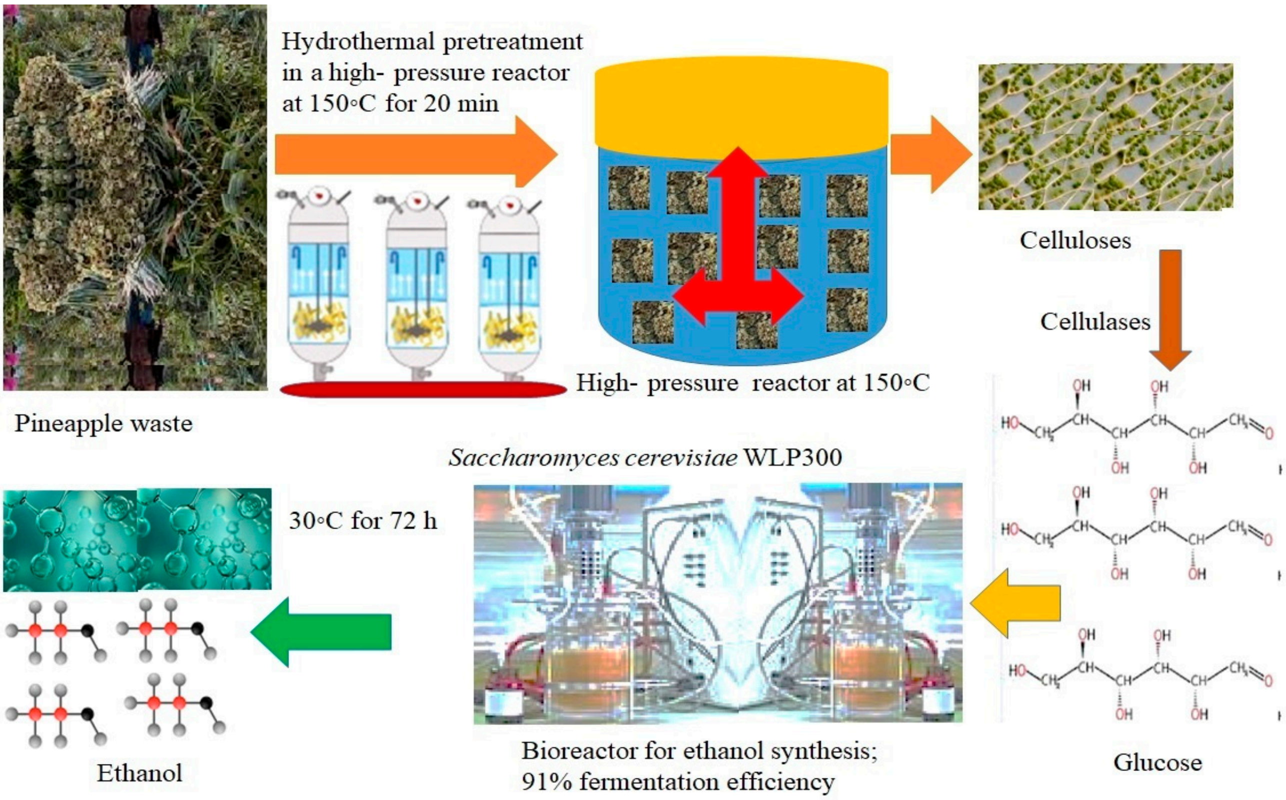

Figure 2. Bioenergy generation approaches is explored using pineapple waste matters promoting sustainable fuels.

4.3. Agricultural Sectors

Due to the huge quantity of crop production efforts all over the world, there is a huge quantity of waste matter/residue generation and accumulation being reported and it is a big challenge to convert this into value-added products such as biofertilizers and other by-products. A number of researchers have developed efficient approaches for waste utilization. These waste sources are now found from fruit and vegetable processing industries with a critical challenges and also crucial jobs across the world [87]. These waste matters can be converted into biofertilizer sources with a proper studying effort for their characters. In applied processes, the fruit wastes of selected sources undergo a components analysis and the composting process is executed under force aeration at a rate of 1 liter/kg/min; it is then maintained in various reactors with a C/N ratio of the fruit wastes [88]. In the composting task, waste was allowed to remain undisturbed in the reactors for 6 days to avoid thermal instability. The samples underwent an analysis once in the four days for a studying of the chemical, physical, and biological characteristics of waste matter in composting [87,88]. After the completion of 26 days, the desired quality of compost/biofertilizer was obtained and it was reported for a fruit biodegradability characteristic in the performed reactors. In the reactor, the non-flow aerobic composting technique can produce quality compost at a quick pace. In the applied technique of the composting effort, the optimum C/N ratio was maintained for fruit waste such as pineapple waste matter and this approach has helped to achieve high quality compost/biofertilizer for the agricultural sector for best crop growth and cultivation [89]; Figure 3. discusses the process of composting. The identification of waste from fruit and vegetable industries is discussed as huge quantity waste generation with a suitable C/N ratio. The pineapple/other plant-based waste has been explored for its composition and these sources of waste can be found to contain lignocellulosic, fiber, sugars, bioactive, and useful compounds [90]. Now the food industry can use these wastes in a variety of ways/processes and then they can apply it with some techniques, such as fermentation, drying, and extraction of bioactive and useful chemicals. In the field of agriculture, food waste can be utilized for value-added products, such as biofertilizers, with other products such as essential oils, herbal drinks, energy bars, and ointments [89,90]. Additionally, the applied effort for bio-based products can aid in good health promotion and nutrition with helping in zero-waste generation tasks. In the current year, authors have found many articles discussing pineapple waste utilization efforts [91]. Additionally, these tasks were focused on the extraction of bromelain and then the production of ethanol, phenolic antioxidants, and also the removal of heavy metals. The production of organic acid, biogas, and fiber at a low production cost, such as in the case of fermentation and drying, has been reported. With the help of scientific and technological advancement efforts, it can be a better way of making a profitable market for the creation of pineapple wastes [90,91]. Some articles have discussed the evaluation task/procedure for the suitability of pineapple waste for the production of decomposable nursery pots; they then discussed the results for the physical and chemical properties of pineapple waste matter and then they proved the suitability for the making of nursery pots at practical levels [92]. In these experiments, they discussed the optimal physical and chemical properties that can be more suitable for decomposition tasks in these pots with a 1:0 ratio of pineapple wastes and a binder (a coarse structure) with a 1 cm thickness pot. Further, these properties of the pots can help in the degradation of fruits waste in 45 days and then they have been determined for a nitrogen and phosphorus rate of 0.49% and 7.97%, respectively [18]. Next, the researchers have claimed an average absorption rate of 258.4%. In the current process, saturation was reported within 45 min and water evaporated in 444 h [18,87]. A further study was the cost-effective production of pots and it was found that the cost of fresh pineapple waste was USD 0.0075 for three-and-a-half-inch diameter compostable pots, but its cost did not include the logistic cost [93]. So, the current study of utilizing pineapple wastes provides an efficient method for waste management by achieving zero-waste generation [92,93].

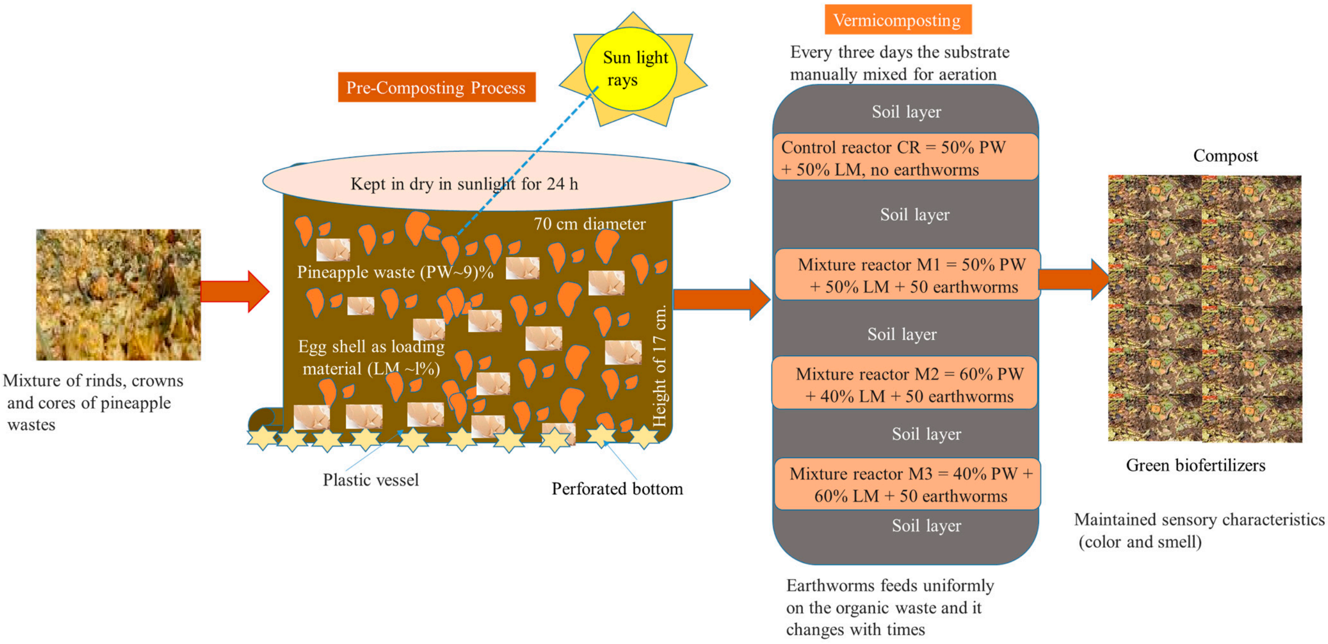

Figure 3. Composting process of pineapple waste for biofertilizer formation.

4.4. Pharmaceutical Sectors

In the current period, a number of research is ongoing on bioactive compounds via the use of different fruits and vegetable waste matter utilization. In the proposed task, a good example is discussed for harvesting pineapple fruits and it is discussed as tropical fruit and can be cultivated on huge land areas at a worldwide level [94]. This fruit cultivation can generate huge amounts of waste/agricultural residue in tons and then undergo burning and rotting tasks in our environment; it can create undesirable greenhouse gasses (GHGs) with other pollutants. Now, researchers are outlining the application of effective approaches/techniques to convert into high value aerogel with a clean environment and cheap cost [95]. Aerogel is the highest solid material; it can be created by combining a polymer with a solvent, which later forms a gel, and effort is exerted for the removal of liquid from the gel and replacing it with air. Now, aerogel is porous and has a low density, but it can be firm to the touch [94,95]. The aerogel product from pineapple or other waste matter can be developed with a total estimation generation/year for pineapple leaf waste amounting to nearly 76.4 million tons. In natural sources, aerogel development can help to provide options with natural source chemicals against the synthetic nature of aerogel that can release chemicals and GHGs with an influence on the environment via creating global problems [96]. In the current effort, it was detected for total waste generation and in the current context, 1 kg of pineapple fruit can generate three times more pineapple leaf waste, and it can be saddled to farmers with bulk and fibrous by-products. Then, it goes to through burning by a farmer who has some positive effort to convert it into compost matter. Some of these portions can be undergone for animals [70]. Now, waste utility is discussed for aerogel production from pineapple fruit waste. Normally, commercial aerogel can be used for heat and sound insulation and still the aerogel product cost is increased with the release of toxic carbon during the manufacturing process. So, it has been discussed for uses of pineapple leaves fiber for the creation of ultra-light and biodegradable aerogel synthesis [70,96]. This bio-based aerogel can be more effective as oils absorbent and sound/heat insulators via the exploration of the potential application of pineapple waste in the food preservation and wastewater treatment effort. Next, this effort allows us to take a big step towards sustainable agriculture and waste management via the recycling of different materials into aerogel from a few decades [97]. Figure 4 discusses the bioactive compounds in a pharmaceutical application. For a previous work, a patent was created for techniques for the creation of aerogels from old rubber tires, coffee grounds, and plastic bottles. Some of the latest works have also discussed the eco-aerogel synthesis procedure via the utilization of agricultural and food wastes and some works were reported in 2016 to be achieving promising results [70]. In the current context, some other lignocellulosic waste matters were discussed as sugarcane bagasse, coffee grounds, and okra waste. In another report, a new process was developed for the extraction of pineapple fibers from pineapple leaves using a decortication machine and mixed with cross-linker PVA (polyvinyl alcohol and cured at an 80 °C temperature for the promotion of cross-linking between the fibers and PVA). The synthesis process was reported to take 10–12 h for the production of aerogel from natural plant material, which is a faster process than the conventional process [70,97]. Fruit and vegetable processing industries have been involved in the contribution of large quantities of food waste and due to food/diet habits, the demand of production and the processing of fruit and vegetables has been increased and it can help to fulfill the rising demand for a large amount of people. Waste generation starts with the harvesting of raw materials until it is properly processed into the final product [98]. Pineapple processing industries can produce processing wastes such as the peel, core, pomace, and crown and all these are rich in various active compounds with an increased application in pharmaceutical industries. In the current context, various kinds of byproducts are utilized for their large bioactive extraction and these can provide a high quantity of nutritional and theoretical importance of the final product [99].

In current context, researchers have tried to extract the enzymes, dietary fibers, organic acid, and phenolic anti-oxidant compounds. In enzyme categories, bromelain, pectinase, xylanase, and cellulases are important enzymes that can be extracted from pineapple waste matter [98,99]. These compounds can be cheap due to the use of waste matter. In the proposed article, the bioactive compounds in pineapple wastes are discussed with their extraction techniques and potential application, such as a polymer material and in the production of bio-sorbent, bioethanol, and vanillin [100]. Bioactive compounds have shown functional and medical benefits and that they can be used independently or incorporated with other ingredients to form valorized products. Pineapple consists of both volatile and non-volatile compounds (sugars/acids) which are benefits to the human olfactory system [101]. Figure 5 discusses the pineapple-based hydrogel with an increased application.

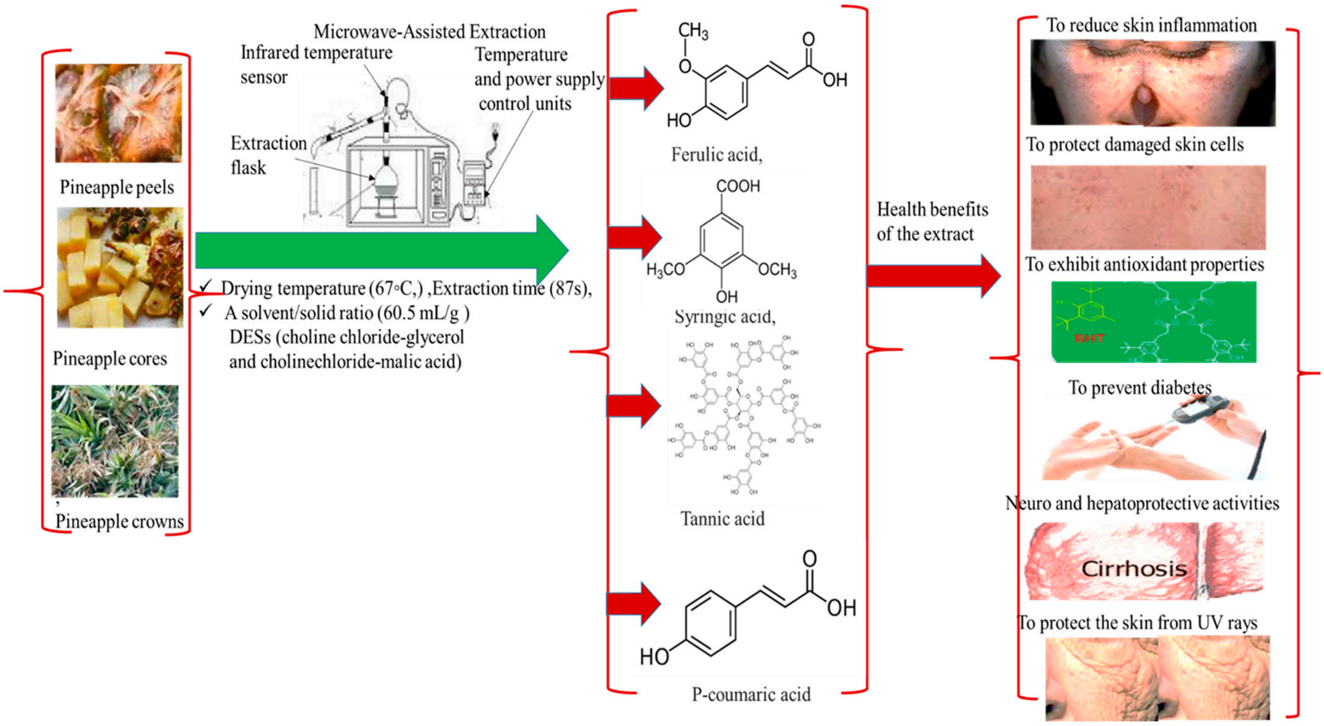

Figure 4. Pineapple biomass utilization via application of extraction technology for bioactive compound with health benefits.

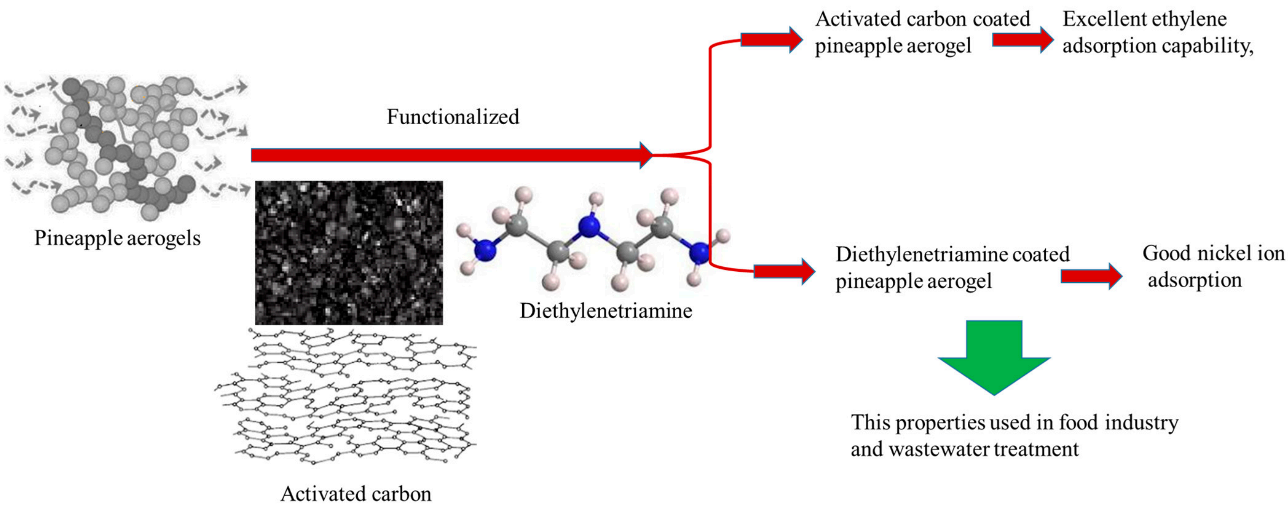

Figure 5. Pineapple based hydrogel preparation having applications in food industrial sectors.

The volatile aromatic compounds in pineapple waster can be found as ester, lactone, acids, and hydrocarbon and sulfur-containing and carbonyl compounds. Pineapple waste can contribute to the development of flavor [102]. This can be dependent on the cultivar, processing conditions, ethylene control, chemical treatment, and maturity as well as post-harvest factors such as light, the temperature, the carbon supply, and water [103]. In pineapple residues, the main volatile compound is ester (35%) and the volatile compounds have characteristics such as methyl hexanoate, ethyl hexanoate ethyl decanoate, methyl octanoate, and a terpineol/nonanal compound. These compounds' presence in pineapple waste can be made to have more potential with an effective extraction and the utilization of natural essence compounds [104]. Esters are synthesized by reacting carboxylic acid and alcohol in a condensation reaction. Some esters are responsible for pineapple flavors. These are methyl-2-methyl butanoate, ethyl-2-methyl butanoate, ethyl acetate, and ethyl butanoate and methyl butanoate. Hydrocarbons are simple aliphatic molecules, terpenes, and benzene rings [98,105]. The recovery of various bioactive compounds from pineapple waste is shown is Table 3.

Table 3. Bioactive compounds development from pineapple waste resources utilization generating zero-waste.

Bioactive Compounds	Sources of Wastes	Technique Used	Reference
Fabrication of pineapple leaf fibers (PALF) is done in sustainably mode.	The pineapple leaves were further processed in Malaysia and this occurred during more pineapple production/cultivation and waste generation.	We extract valuable fiber from pineapple leaves and it turns into useful goods. A number of projects have been undertaken there.	[1]
Higher impactful polystyrene composites may use PALFs and their mechanical characteristics as reinforcement agents.	The impacts of NaOH treatments are shown on PALF, and it has applied with zero, two, and four percent NaOH solutions.	Short PALFs have been studied for their best mechanical characteristics, including their tensile strength, tensile modulus, etc. They can be found as the best reinforcement agents.	[3]
The tensile and impact strength of moldable cellulose fiber-reinforced polylactide (PLA) composites is developed from waste biomass.	Lyocell/PLA composites' performance is affected by many factors, including fiber loading, fiber fineness, as well as processing parameters such as compression molding (CM) as well as injection molding (IM). It impacts the final products' quality and performances.	The fiber aspect ratio as well as void distribution are primarily factors, responsible or the variable mechanical properties of CM and IM samples.	[4]
Pectin, lipids, etc., are only some of the bioactive chemicals that may be extracted from food processing waste (FPWs) peels, pomace, as well as seed fractions.	Greater than half a billion tons of garbage of waste are produced annually by the fruit processing industry.	Most extraction procedures are discussed that leave behind byproducts and these might be utilized renewable resources in the generation of bioenergy.	[22]
The carotenoids in pomegranate peels and seeds were recovered using ultrasound assisted approaches.	Applied approach was discovered a novel way to use pomegranate peels in the food industry, and then it has extracted the sufficient quantity of carotenoid.	Applied extraction conditions has resulted in maximum production of pomegranate peel carotenoids. It was as follows: 51.5 °C; peels/solvent ratio of 0.10; amplitude level of 58.8%; sunflower oil as solvent; extraction time of 30 min.	[32]
Natural compounds produced from plants waste matter that are used in the treatment of cancer.	Natural products derived from plants are applied the extraction process to anticancer products.	Information on the origins, extraction, anticancer mechanisms is done with clinical investigations, and pharmaceutical preparation of the substance is presented.	[57]
Catechin, quercetin, and gallic acid are just some of the polyphenolic chemicals that may be found in abundance quantity in waste plant extract.	*Ananas comosus* peels (AcP) are a kind of agro-industrial biomass that contribute to a considerable amount of garbage in Malaysia, and then it is processed to obtain value-added products.	The optimized AcPE nano cream showed no signs of coalescence during the accelerated testing, but it did undergo Ostwald ripening after being stored at 4 degrees Celsius for a period of six weeks.	[58]
Bromelain is a cysteine protease that may be discovered in the tissue of pineapples.	Bromelain was purified from its crude extracts by the use of ultrafiltration, chromatography, etc.	Bromelain has been shown to be effective in the treatment of a variety of medical conditions due to its anti-inflammatory and anti-cancer properties, as well as its capacity to promote apoptotic cell death.	[59]
Compounds with biological activity include, but are not limited to, carotenoids; polyphenols; dietary fibers; vitamins; enzymes; oils; and others.	When compared to other horticultural crops, fruits and vegetables have the highest market value as commodity markets.	The waste consists mostly of the seed, skin, rind, and pomace, all of which are rich in potentially important bioactive components and make up the majority of the trash.	[74]
Pineapple fruit waste contains important nutrients, vitamins, and even certain medicinal properties.	According to the source, fresh and juice are used when pineapples are fully ripe.	Pineapple has qualities that vary depending on the growth location and type. Accelerating the ripening process using ripening chemicals decreases the fruit's nutritional value.	[88]

5. Future Perspectives

Pineapple biomass as a waste matter is reported in different forms, such as pineapple leaves, the crown, and pomace and other waste juicy parts. The waste biomass from fruit industry processing has shown potential values with the recovery of biofuels, biofertilizer/compost development, and many phenolic antioxidant compounds. Researchers have applied zero-waste technology for the conversion of pineapple biomass/its waste matters into value-added products [106]. These bio-based products with bioactive components are applied in different sectors for human health benefits. Now, researchers are using many techniques for the extraction of value-added products. The impact of pineapple waste accumulation (via reports for significant parts, disposed in landfill, releases greenhouse gasses) is more demanded for pineapple fruits and with its products in the world [107]. These trends of waste fruit are responsible for a huge generation with the accumulation and increased availability of pineapple waste with disposal issues and its techniques is a critical issue/concern [106,107]. Figure 6 shows the utility of pineapple waste as potential raw sources for industrial products synthesis. A number of techniques have been exploited for pineapple waste conversion into valuable products such as bioenergy, bioactive compounds, and reinforcement agents, as discussed in the previous section. These conversion technologies need to be employed in a sustainable way of managing these waste residues with a proper understanding of the useful properties and compositions. Some methods have been concentrated for the production of useful products from on-farm pineapple waste and processing wastes [108]. In the current context, bioenergy generation from this waste utilization is reported to be one of the best options for green energy sources via encountering the increasing demand of fuel sources with the promotion of sustainable development goals for agricultural wastes. From pineapple waste residues, extraction approaches of the protease enzyme, such as bromelain, for an industrial application are also necessitated as far as an application if food industries are concerned. In the current context, the bromelain production from these wastes is exploited with suitable recovery methods [109]. Additionally, pineapple waste is a good source of a high cellulose content and it is a promising raw material with a good potential for the production of cellulose nanocrystals, biodegradable packaging, and biosorbent agent/compounds. These bioproducts from plant waste can be potentially applied for the development of polymers and the food and textile industries. A few more applications of pineapple waste are discussed as being potential and suitable for wine, vinegar, and organic acid biosynthesis, and this is due to containing a high sugar content in waste such as the peel or pomace parts of pineapple fruit [108,109].

In some reports, various fruit waste potentials are explored for suitable substrates for bioenergy production with good sources of biofuels (such as bioethanol, biobutanol, and biodiesel) and biogas (such as biomethane and biohydrogen). Pineapple waste used at a commercial scale can be obtained for the proper processing of the generation of enzyme, antioxidant, and bioenergy sources. These products from this waste matter showed the best opportunity for a systematic utilization to obtain zero-waste synthesis. The future perspectives and challenges are also discussed, concerning pineapple waste utilization for the generation of value-added products [110]. Sustainable conversion technologies can help in the best/efficient way for the conversion of pineapple waste into valuable products with good efforts in the reduction in waste generation and accumulation. It can find the best option for obtaining products with the support of the waste of the wealth concept. In these efforts, additional procedures, such as a pretreatment and purification with a systematic implementation for such waste matter, are needed [111]. It is necessary to select a method that can depend on environmental concerns and technical costs in the future research into additional process tasks for such waste matter. These techniques can ensure the production of the extraction of high efficiency valuable products and their purification, and then it can achieve the level of the market standard and production [110,111].

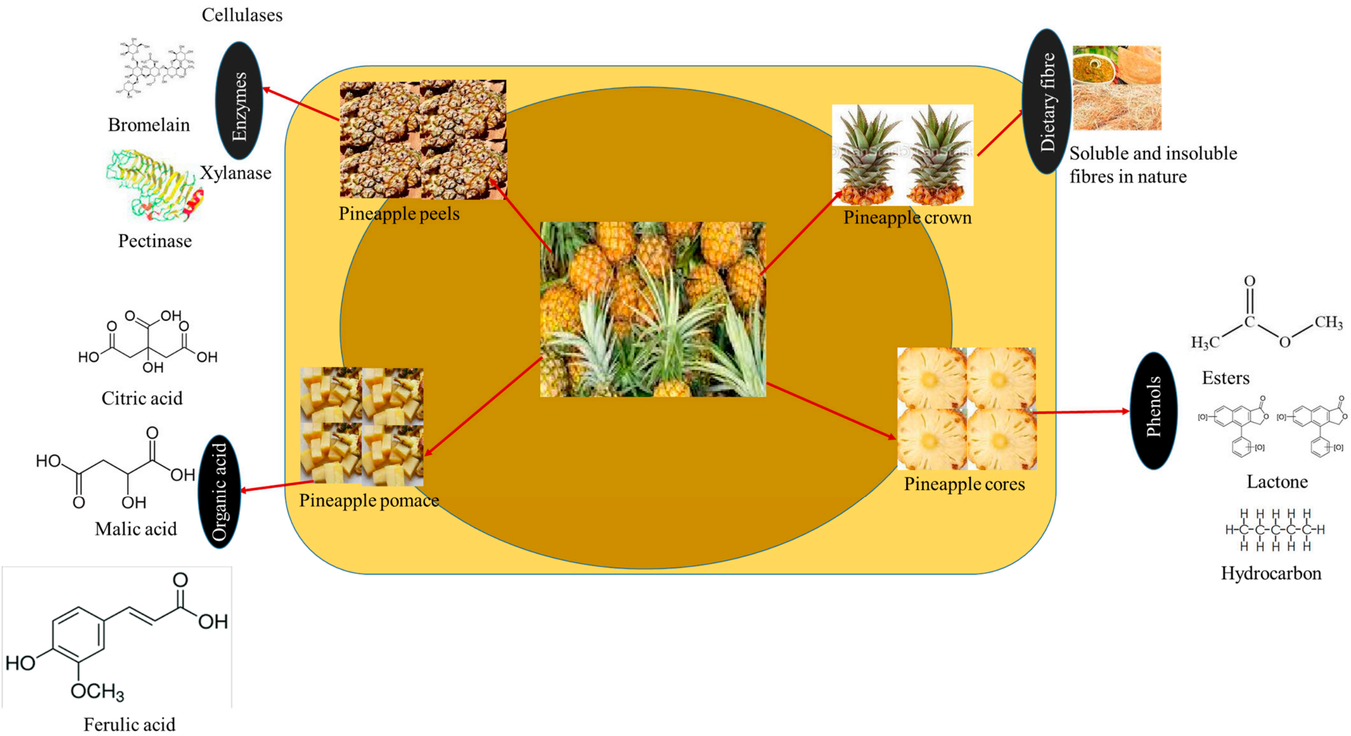

Figure 6. Present and future scope of pineapple waste matter processing with sustainable products generation leading to zero-waste generation.

Researchers have been involved in the advanced conversion approaches for pineapple waste into different types for the development of valuable products. Some reports are discussed regarding the worldwide pineapple fruit production capacity; this is due to the increased demand of pineapple fruit and its fruit-based product [106,108]. In product development, a huge quantity of pineapple fruit waste is reported with a global pineapple production and it needs to process in a well-planned way for the development of more valuable products with least/zero-waste generation. Some places in the world contribute due to increase in the waste matter availability; this can be undergone for the landfill task and then releases of GHGs [112]. The life cycle assessment task for the conversion of pineapple waste matter into the development of value-added products can be applied. This can help to minimize the amount of solid waste which prevents minimizing the economic and environmental impact needed to achieve the SDGs. The exploitation for pineapple waste is done as raw materials for the production of value-added products in a sustainable nature via the utilization of the different available conversion technologies [111,112]. Massive opportunities for conversion into energy generation is reported, with more security of sustainable fuel sources such as biogas and biofuels. Different parts of pineapple fruits waste matter can be characterized with a different composition, and these can make them have a greater potential for bromelain, bioactive compounds, and cellulose nanocarbon (CNC) feedstock [107,109]. Some intensive research is shown on the pineapple waste utilization potential as an adsorbent for the removal of dye and heavy metals. Still, the high sugar content in pineapple pulp, peel, and core waste together with pineapple juices with some waste matter can play a critical and significant role as a potential feedstock for biofuel, especially second-generation biofuels [106,110,112].

Recently, scientists discussed the potential of discarded fruits with other waste matters, including pineapple, for industrial applications, such as the extraction of functional ingredients, the extracting of bioactive compounds, and also the fermentation process for fuel sources development [113]. From these approaches, there are more chances for utilizing the abundant availability, simplicity, and safe handling, with the good biodegradability of pineapple waste which can be best utilized in more extensive ways for the recovery of valuable-added products with extensive research into the work performance. Now, researchers are applying waste resources for an economic development via cheap product synthesis [104]. Vast agro-industrial waste can be investigated as a low-cost material for the production of a variety of high-value goods and product development. In recent years, more researchers have placed increased concentration on the exploitation of pineapple waste for the development of enzymes and also the extraction of prebiotics oligosaccharide with biogas, organic acid, the low cost of fibers, phenolic antioxidant, and ethanol [113,114]. Multiple efforts are shown which place emphasis on pineapple waste valorization approaches and the extraction of bioactive and functional ingredients together with disclosed advantages in many areas [115]. Pineapple waste utilization from the socioeconomic perspective is discussed as a new raw material source to industries and it can potentially replace the current expensive and non-renewable material sources. Various approaches are discussed for using the pineapple waste processing potential for the development of several important value-added products that gained some contribution towards healthy food and the sustainable environment [113,115].

The extraction of bromelain from pineapple waste is a widely published on research area, as is the topic of some other bio-based products, such as dietary fibers and phenolic antioxidant compounds from various waste extractions, or their generation; this is also of critical concern with a future perspective and they can be applied as nutraceutical resources by offering a significant low-cost nutritional dietary supplement for low-income communities [116]. Now, the market of functional food is also reported to create a vast vista for the utilization of natural resources. In this context, cheap substrates such as pineapple waste can be found to be a promising prospect [117]. The environmentally polluting by-products can be converted into valuable products in eco-friendly ways and in a manner with more economic value than the main product [116,117]. The sustainable utilization of pineapple waste and with its application, with the help of novel scientific approaches and technological methods for valuable products, is focused on as far as environmental, food, and energy sectors are concerned [114,118–120]. The application of zero-waste concepts in terms of environmental sustainability can be achieved, leading to the development of ecotourism [121–125].

6. Conclusions

The current review discusses the different sources of fruit-processing industries with a huge capacity for pineapple-based waste matter generation. Plant-based products can provide increased nutritional benefits with a health/medical value to humans. This proposed review is focused on zero-waste generation technologies for pineapple that can produce high yielding final products with industrial importance. In this context, green extraction approaches and solvent utilization are discussed for the generation of bioactive compounds. A fermentation technique is applied for fuel development from pineapple wastes. This review also focused on bromelain recovery and purification by HPLC techniques and the desalting approach. This review also discussed the hydrothermal techniques and enzyme pretreatment for the extraction of value-added product development that can achieve zero-waste generation with the recycling task of bio-based byproducts. This paper described the compost material from the composting of fruit waste matter under controlled conditions, with a potential benefit to the environment. Further, pineapple waste has been utilized for the conversion of different fuel sources such as ethanol, biodiesel, and biogas. These energy sources are sustainable fuel sources and these can be utilized in the transport sector with zero-waste generation or no GHGs/particulate matter. A further section also discussed the waste matter utilization for different bioactive compounds that can provide potential benefits. Pineapple leaf fiber is discussed with a potential application in the enhancement of material strength as a reinforcement agent. Finally, readers will obtain a crucial concept for zero-waste generation via the exploration of the pineapple waste potential.

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