

Review

Biofuel Generation from Potato Peel Waste: Current State and Prospects

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Abstract: Growing environmental concerns, increased population, and the need to meet the diversification of the source of global energy have led to increased demand for biofuels. However, the high cost of raw materials for biofuels production has continued to slow down the acceptability, universal accessibility, and affordability of biofuels. The cost of feedstock and catalysts constitutes a major component of the production cost of biofuels. Potato is one of the most commonly consumed food crops among various populations due to its rich nutritional, health, and industrial benefits. In the current study, the application of potato peel waste (PPW) for biofuel production was interrogated. The present state of the conversion of PPW to bioethanol and biogas, through various techniques, to meet the ever-growing demand for renewable fuels was reviewed. To satisfy the escalating demand for biohydrogen for various applications, the prospects for the synthesis of biohydrogen from PPW were proposed. Additionally, there is the potential to convert PPW to low-cost, ecologically friendly, and biodegradable bio-based catalysts to replace commercial catalysts. The information provided in this review will enrich scholarship and open a new vista in the utilization of PPW. More focused investigations are required to unravel more avenues for the utilization of PPW as a low-cost and readily available catalyst and feedstock for biofuel synthesis. The application of PPW for biofuel application will reduce the pump price of biofuels, ensure the appropriate disposal of waste, and contribute towards environmental cleanliness.

Keywords: biogas; bioethanol; biohydrogen; biocatalyst; potato peel



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1. Introduction

The world population, which was 7.9 billion as of August 2021, is projected to become 8.6 billion, 9.8 billion, and 11.2 billion in 2030, 2050, and 2100, respectively, according to the United Nations [1]. Additionally, the Food and Agriculture Organization has predicted an increase in food and other agricultural outputs for the ever-increasing population. The increment in agricultural production is expected to be accompanied by increased land and natural resources degradation and greenhouse gas (GHG) emissions. There is, therefore, an urgent need to concentrate on producing foods with low carbon footprints, minimize food waste, and utilize the waste generated from food consumption for other purposes. For any food production system to be sustainable, the process must have a low carbon dioxide (CO₂) footprint, require less land, and have a high yield.

The dwindling global oil reserves, unpredictable oil prices, the environmental impact of fossil-based fuel exploitation, exploration, and utilization, the unsatisfactory performance of fossil-based fuel in internal combustion engines (ICEs), etc., have led to increased research into sustainable and cost-effective alternative fuel for various applications [2]. Biofuels are seen as a viable substitute for fossil-based fuels to reduce dependence on fossil-based fuels, slow down climate change, enhance fuel security, mitigate dangerous emissions, and

improve performance in ICEs [3,4]. Despite the myriad of benefits of the application of biofuels to society, the debate on the impacts of biofuels on food security, carbon stores, and land use has intensified. Additionally, with the growing global population, escalating global competition on food, land, and water, and the attendant continuous rise in the global emissions of CO₂, the demand for biofuels has continued to increase. Global biofuel production rose from 1125 million barrels of oil equivalent per day (mboe/d) in 2010 to 1444 mboe/d in 2015 and further to 1790 mboe/d in 2019 [5]. During the same period, the global CO₂ emissions grew from 33.13 Billion Metric Tons (BMT) in 2010 to 35.21 BMT and 36.44 BMT in 2015 and 2019, respectively [6] (Figure 1). The reduction in global biofuel production and CO₂ emission in 2020 can be attributed to the impact of lockdowns and restrictions of movement occasioned by the COVID-19 pandemic.

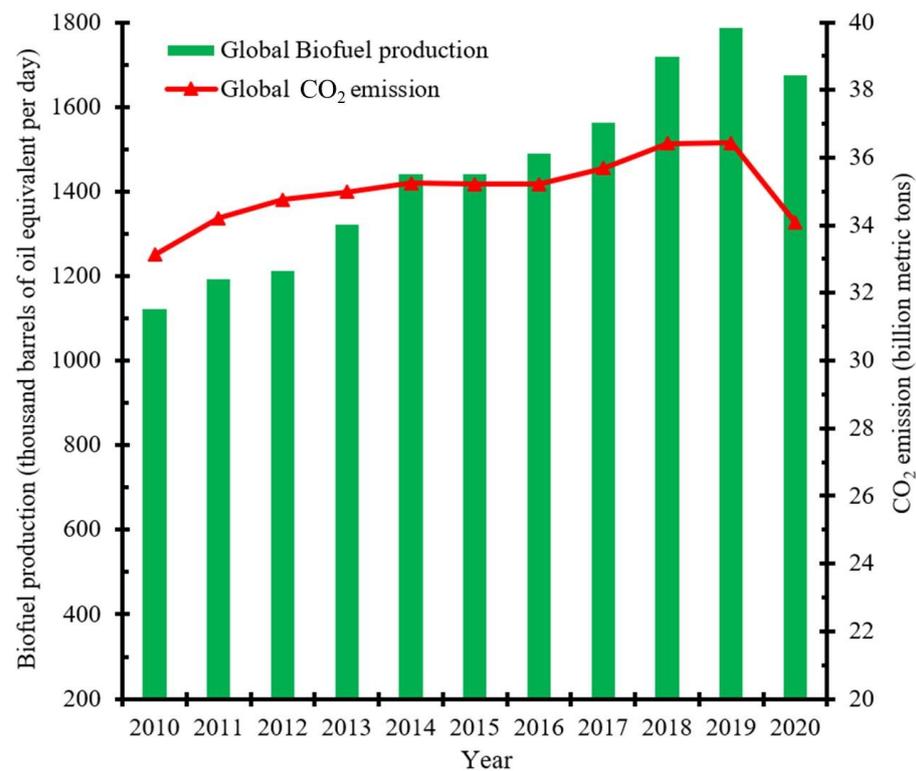


Figure 1. Global biofuel production (2010–2020) and global CO₂ emission (2010–2020). Compiled by the authors from [5,6].

One of the strategies to ensure household biofuel production, reduce the pump price of biofuels, and potentially avoid conflict with the food chain is to use non-food feedstocks (energy crops, food and household waste, agricultural and forestry residues, and algae) for biofuel production. Along this line, the research and development policy of biofuel production has been refocused to highlight the development of cost-competitive technologies of converting waste into fuels [3]. With the cost of feedstock accounting for about 60–80% of the total cost of biofuel generation [7], the use of food waste as feedstock and catalysts is a step towards reducing the production cost and consequently the pump price of biofuel [8,9]. Leftover kitchen waste such as waste cooking oil, recovered fats, potato peel, and maize cobs have been converted to biofuels to reduce the cost of feedstock and ensure environmental cleanliness. Previous research has confirmed the conversion of food waste to catalysts, corrosion resistance, and biofuels for ICE, biotechnological, and other applications [10–12].

2. Potato and Potato Peel

Potato (*Solanum tuberosum* L.), also known as Irish or white potato, is regarded as the fourth most significant food crop after rice, wheat, and maize, and is cultivated in practically all types of soil, except for saline and alkaline soils [13]. Although it originated from Peru, the potato is grown and consumed in more than 100 countries of the world. The global production of potatoes has increased from 328.62 Million Metric Tons (MMT) in 2010 to 361.09 MMT in 2013 and further to 370.43 MMT in 2019 (Figure 1) [14]. China is the world's greatest producer of potatoes, closely followed by India, Russia, Ukraine, and the United States of America in that order [15]. Figure 2 shows the global potato production from 2010 to 2020 and yearly potato production from China, India, Russia, and the US from 2010 to 2019.

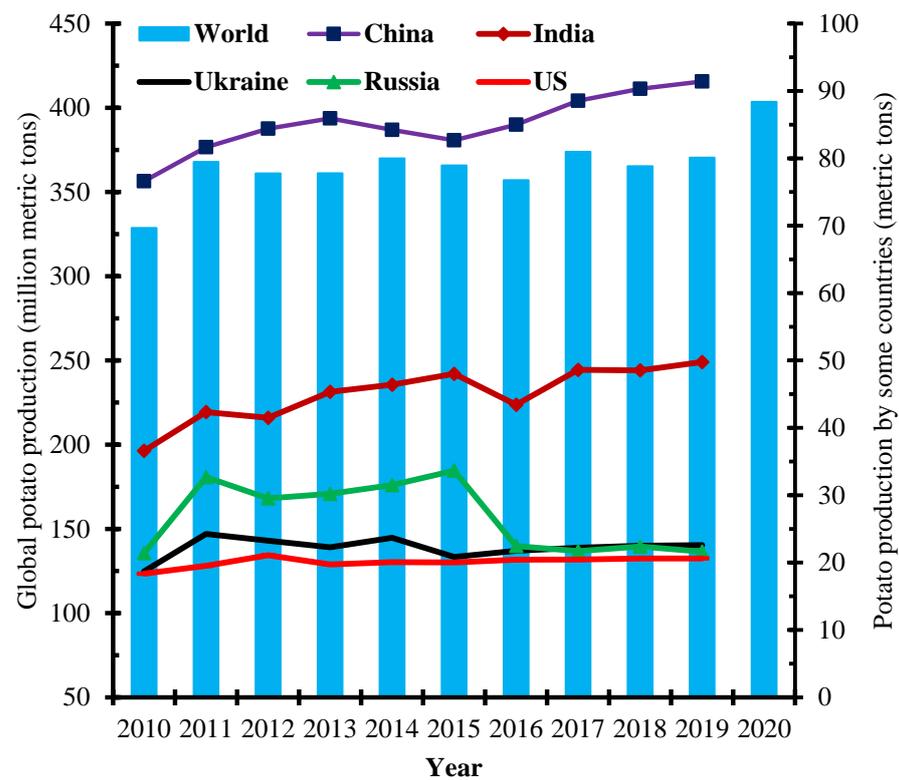


Figure 2. Global potato production (2010–2020) and potato production by top five countries (2010–2019) (secondary *y*-axis). Compiled by the authors from [14,15].

Raw potato typically contains 79% water, 17% carbohydrates, 2% protein, and the remaining percentage is fats. Because raw potato is about 88% starch, it must be boiled, fried, or baked before being consumed by humans. Potato can also be consumed in various forms including mashed potatoes, potato pancakes, potato dumplings, twice-baked potatoes, potato soup, and potato salads. Potato is rich in amino acids and other essential nutrients needed for growth and therefore has been declared the food of the future [16]. Potato has nutritional, health, and industrial benefits. For example, the consumption of potatoes helps to control blood sugar, improves the digestive system, enhances bone and heart health, prevents skin damage, helps boost immunity, and is a cheap supply of nutrients. Potatoes are naturally nutritious and rich in antioxidants such as flavonoids, carotenoids, and phenolic acids [16,17]. Other dietary contents of potatoes include potassium, phosphorous, magnesium, iron, zinc, and vitamins (Figure 3). Apart from their contributions to health and the human diet, potatoes have numerous industrial applications such as the production of alcohol, dehydrated food products, animal feed, starch production, and frozen food products.

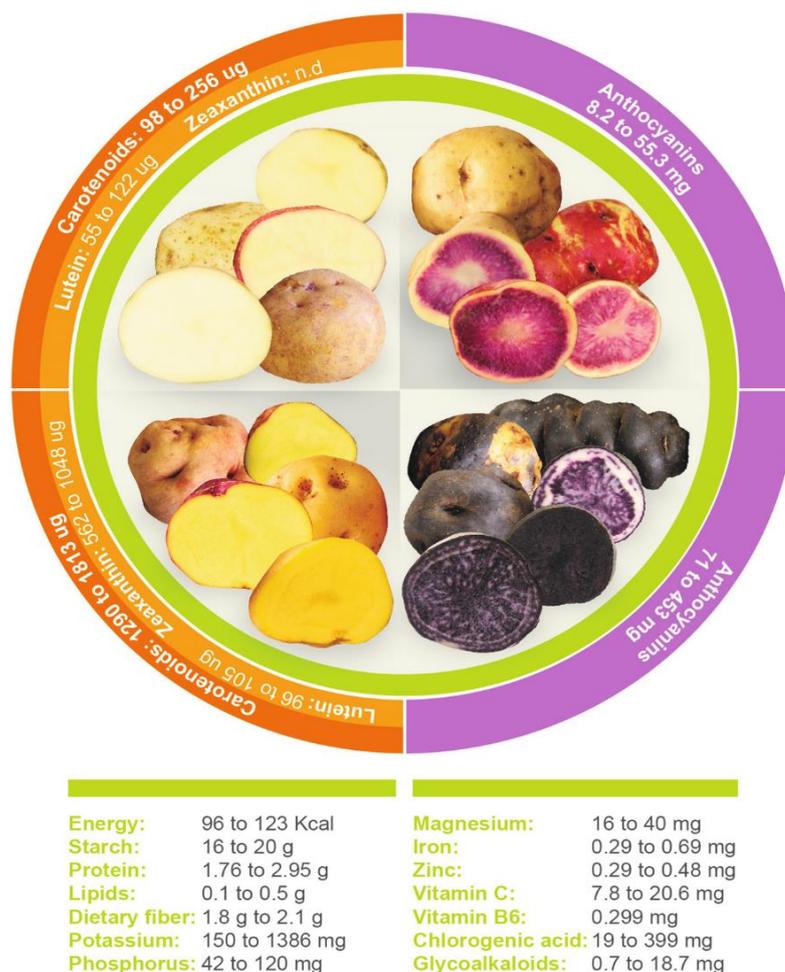


Figure 3. The nutritional composition of potato [17].

Potato peel waste (PPW) is generated in households, restaurants, and the food processing industry when the skin or outer layer of a potato tuber is removed. Peeling can be done before boiling, frying, or mashing. However, in some cases, peeling is done after boiling. Depending on the peeling technique, about 15 to 40% of a potato tuber is removed as peel and is discarded as waste [18]. Various techniques have been used to peel potato including abrasive peeling [19], steam peeling [20], extruded peeling [21], un-extruded [22], lye peeling [20], etc. Raw PPW has been reported to contain about 83 g of water, 8.7 g of total carbohydrates, 7.8 g of starch, etc., for every 100 g of potato tuber. Table 1 compares the chemical composition of PPW as reported by various researchers. PPW also contains phenols, unsaturated fatty acids, amides, and other phytochemicals. Because of the presence of glycoalkaloid compounds such as *α-solanine*, *α-chaconine*, and *solanidine*, the consumption of potato peel is toxic to humans, animals, and microorganisms [23]. Therefore, while using potato peel for nutritional purposes, the glycoalkaloid content must be kept lower than 20 mg/100 g of fresh tuber weight, which is the maximum acceptable limit [24].

The huge quantity of PPW generated annually across various jurisdictions has elicited investigations into the innovative and value-added conversion of this waste for various applications. The utilization of this carbon-rich resource will be advantageous to humankind and the environment, save the cost of raw materials, reduce the amount of waste in dumpsites, and help to avoid resource wastage. In a series of earlier research, Javed et al. [25], Wu [30], Sepelev and Galoburda [31], and Gebrechristos and Chen [32] reviewed the various applications (nutraceutical, industrial, and biotechnological) of potato peel. PPW has also been converted into by-products including bioplastic [33], biocomposites [34], nanocrystals [35], and lactic acid [27]. The application of PPW as feedstock for renewable

fuels has been evaluated. For example, Ben Atitallah et al. [36], Hijosa-Valsero et al. [28], and Dos Santos et al. [37] synthesized bioethanol, biobutanol, and biooil, respectively, from PPW.

Table 1. Chemical composition of raw potato peel waste.

Parameter	Composition				
	Dry Weight (g per 100 g) [25]	Dry Weight (%) [26]	Dry Weight (%) [27]	Dry Weight (%) [28]	Dry Weight (%) [29]
Water	83.3–85.1	85.06	ns	5.26	77.3
Protein ($N_{tot} \times 6.25$)	1.2–2.3	8	17.1 ± 0.3	10.73	13.125
Total lipids	0.1–0.4	ns	1.2 ± 0.0	ns	ns
Total carbohydrate	8.7–12.4	68.7	63.2 ± 4.2	43.2	70.3
Starch	7.8	52.14	$34.3.2 \pm 2.7$	23.01	ns
Total dietary fiber	2.5	ns	ns	ns	ns
Total soluble sugar	ns	1	ns	ns	ns
Ash	0.9–1.6	6.34	9.6 ± 0.1	7.45	5.9
Total phenolic content	1.02–2.92	ns	ns	2.5 mg/g	ns
Total flavonoids	0.51–0.96	ns	ns	ns	ns
Fat	ns	2.6	ns	2.45	ns
Nitrogen	ns	1.3	ns	ns	2.1
Lignin	ns	ns	ns	32.88	ns
Reducing sugar	ns	0.16	ns	ns	0.78
Acid soluble	ns	ns	6.2 ± 0.2	ns	ns
Acid insoluble	ns	ns	4.1 ± 0.0	ns	ns

ns = not stated.

Notwithstanding the outcome of these studies, the relevant question to pose which forms the motivation for the current study is whether the use of PPW in the biofuels sector has been fully investigated. Are there other avenues where PPW can contribute to the realization of universal access to affordable biofuel? The present intervention, therefore, is targeted at the review of recent advances in the application of PPW as feedstock for biofuel production. Specifically, the various modalities, techniques, and processes for the conversion of PPW to biogas and bioethanol published in peer review journals within the last decade are interrogated. The prospect of the generation of biohydrogen and the synthesis of bio-based catalyst from PPW to take advantage of the huge amount of waste generated from potatoes is proposed. This approach, therefore, demonstrates the feasibility, methodologies, and potentials of utilizing PPW as feedstock and a bio-based catalyst for large-scale biofuel generation towards energy security and environmental sustainability. The current effort is limited to the application of PPW in the biofuels sector and excludes the nutritional, health, and other industrial applications of PPW.

3. Application of PPW for Biogas Production

Biogas is produced during anaerobic digestion (AD) when microorganism methanogen or anaerobic microorganisms break down feedstocks in the absence of oxygen. The anaerobic digestion of biomass to generate biogas occurs in an airtight reactor called a digester. Basically, biogas contains 55% to 75% methane, 24% to 45% CO₂, by volume, and other trace gases such as hydrogen sulfide, ammonia, nitrogen, and moisture. The leftover, after the generation of biogas, is rich in organic matter and nutrients such as nitrogen, phosphate, and potash, which are used as organic fertilizers [38].

AD contributes to the circular economy, reduces dependence on fossil-based fuel, helps in climate change mitigation, improves urban air quality, and contributes towards improved health and sanitation through better solid waste management [39]. Since the turn of the century, global biogas production has been escalated considerably from a meager 0.28 exajoules (EJ) in 2000 to 0.84 EJ, 1.27 EJ, and 1.36 EJ in 2010, 2017, and 2018, respectively (Figure 4) [40]. The global biogas market size which was USD 6.9 billion has been predicted

to become USD 60 billion in 2021 [41]. Although information on the global production of biogas from PPW is not available, it is believed that more researchers are adopting PPW as feedstock for biogas generation.

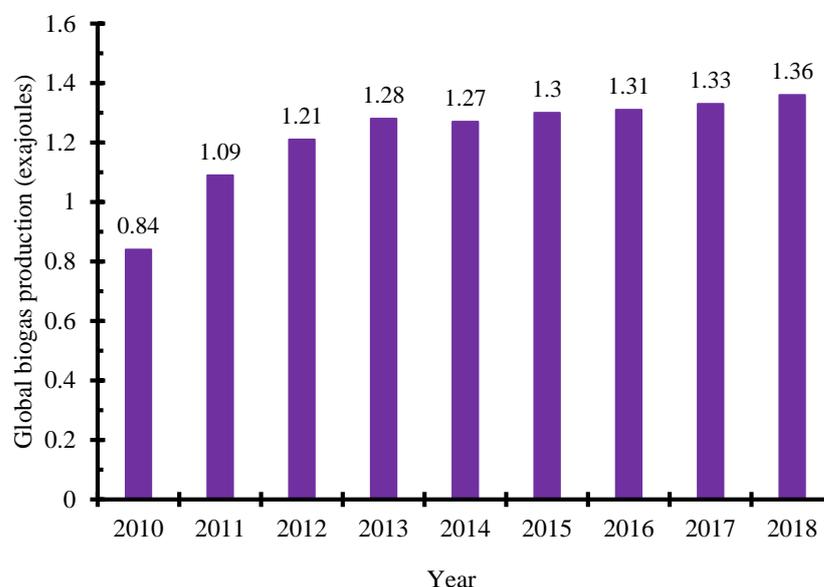


Figure 4. Global biogas production from 2010 to 2018 (exajoules). Adapted by the authors from [40].

Researchers have experimented with various feedstock, digesters, and production parameters (Table 2). The PPW, which is the major feedstock, is first washed thoroughly in running water to remove all the dirt adhering to the body of the peel. The PPW is thereafter drained and sun-dried before further drying in an oven at between 80 °C and 100 °C for about 60 min. The dried PPW is pulverized into a powdered form to increase the surface area for reaction and increase product yield [9,42]. In an earlier experiment, Suntikunaporn et al. [42] investigated the application of PPW for biogas production in a 20 L floating drum digester. They attributed the impressive yield of 3500 mL per day to the high carbohydrate content of PPW. Similar results were obtained when Sheikh and Sandeep [43] and S. Liang and McDonald [44] synthesized biomethane from PPW through AD but with better CH₄ content. In a study demonstrating the impact of pretreatment of feedstock on biogas yield, it was reported that biogas yield increased from 383.7 mL/g VS_{added} for untreated feedstock to 453.2 mL/g VS_{added} and 485.4 mL/g VS_{added} for feedstock subjected to pulverization and acid hydrolysis, respectively, with marginal improvement in CH₄ content [45].

In recent research, Lu et al. [46] examined the effect of pH during the AD of PPW and reported that PPW substrate maintained at a pH of 7.0 produced 41.9 g of COD/L and 632.2 mg COD/g VS_{fed} when compared with 21.6 g COD/L and 309.5 mg COD/g VS_{fed}, 18.1 g COD/L and 272.6 mg COD/g VS_{fed}, and 58.0 g COD/L and 31.4 mg COD/g VS_{fed} recorded for uncontrolled pH, pH 5.0, and pH 11.0, respectively [46]. Similarly, Lahbab et al. [47], Awosusi et al. [48], and Sanaei-Moghadam [49], at various times and locations, co-digested PPW with cow dung for methane generation. While reiterating the potency of PPW for biogas generation, they reported that the addition of cow dung substrate improves the efficiency and rate of biogas generation.

Going forward, while the suitability of PPW as a viable substrate for biogas production owing to its chemical composition, oxidation state, and pH, is not in doubt, various pretreatment techniques and co-digestion techniques are necessary to improve biogas yield and enhance the concentration of CH₄ [50]. The statistical parametric optimization studies of process conditions such as reactor type, operating temperature, pH, mixing ratio, and pretreatment methods deserve further investigation. The application of modeling tools in methane generation needs to be further studied to achieve better cumulative biogas synthesis.

Table 2. Some of the reported productions of biogas from PPW.

Type of Digester	CH ₄ Content	Yield	Remark	Ref.
20 L plastic floating drum tank	40–50%	3500 mL/d	PPW is a viable feedstock for AD	[42]
ns	65%	High methane yield	Addition of PPW led to a 112% increase in biomethane yield	[43]
1 L glass batch reactor	60–70%	273 L/kg VS	PPW exhibited good performance and biogas yield	[44]
500 mL glass bottles	56%	383.7 mL/g VS _{added}	Good biogas yield	[45]
500 mL glass bottles	57.5%	453.2 mL/g VS _{added}	Grinding of PPW feedstock led to improved biogas yield and CH ₄ concentration	[45]
500 mL glass bottles	58.3%	485.4 mL/g VS _{added}	Acid hydrolysis pretreatment of PPW led to improved biogas yield and CH ₄ concentration	[45]
5 L reactor	ns	41.9 g COD/L and 632.2 mg COD/g VS _{fed}	PPW substrate maintained at pH of 7.0 achieved highest VFA	[46]
1 L glass bottle	ns	170 mL (CH ₄)/g VS	Improved biogas production	[47]
600 L polyethylene	66%	1.6 m ³	Co-digestion improved the biogas yield and CH ₄ concentration	[48]
5 L double-wall glass cylinder	ns	375 L _N (kg VS) ⁻¹	Addition of cow dung substrate improve the efficiency of biogas production	[49]

ns = not stated, COD/L = chemical oxygen demand per liter, COD/g = chemical oxygen demand per gram, VFA = volatile fatty acid, vs. = volatile solids.

4. Application of PPW for Bioethanol Production

There has been a consistent increment in the yearly global ethanol production over the past decade. According to the available data [51], the global ethanol production moved from 13 123 Million Gallons (MG) in 2007 to 21 812 MG, 26 583 MG, and 29 026 MG in 2012, 2016, and 2019, respectively (Figure 5). The reduced production volume of 26 059 MG recorded in 2020 can be attributed to the lockdowns and restrictions occasioned by the spate of the COVID-19 pandemic. In terms of the market share, the global ethanol market size that amounted to (United State Dollar) USD 89.1 billion in 2019 became USD 93.7 billion in 2020 and is anticipated to grow at 5.2% from 2021 to 2030 [52]. The anticipated increment is propelled by the increased application of ethanol as fuel. It is believed that no less than 73% of the global ethanol production is applied as fuel, while the remaining percentage is used for beverages and industrial ethanol [26].

As with other liquid biofuels, the commercial production of bioethanol has been hampered by the high cost of feedstock and interference with the food chain. With a production cost estimated at USD 0.40/l [26] and the use of edible feedstocks, it is not surprising that the widespread use of bioethanol as an alternative fuel for ICEs has not been achieved. The use of PPW as a raw material for the synthesis of bioethanol is an avenue for the democratization of sustainable bioethanol production and utilization. Table 3 compiles the outcomes of some of the studies on the conversion of PPW to bioethanol. Hijosa-Valsero et al. [28], Meenakshi et al. [53], and Soltaninejad et al. [54] reported that PPW was first washed with distilled water, dried in the sun for 2–3 days, dried in an oven at 45 °C, crushed with a ball mill, and sieved to a particle size of 0.5–1.0 mm as physical pretreatment measures. Other chemical, biological, and ultrasonic pretreatment techniques with the use of acids, alkaline, wet oxidation, ozonolysis, and hydrogen peroxide with metal salts were employed. These pretreatment processes have been found to ensure the improvement of product yield by increasing the surface areas of the reactants [9]. The conversion of PPW to ethanol [26,55], bioethanol [56,57], or biobutanol [28] was demonstrated using various techniques including hydrolysis, saccharification, and fermentation. The production rate varied from 7.6 g/L to 40 g/L. The aggregate of the outcomes of these investigations is a pointer to the suitability and the impressive performance of PPW as a cost-effective and readily available feedstock.

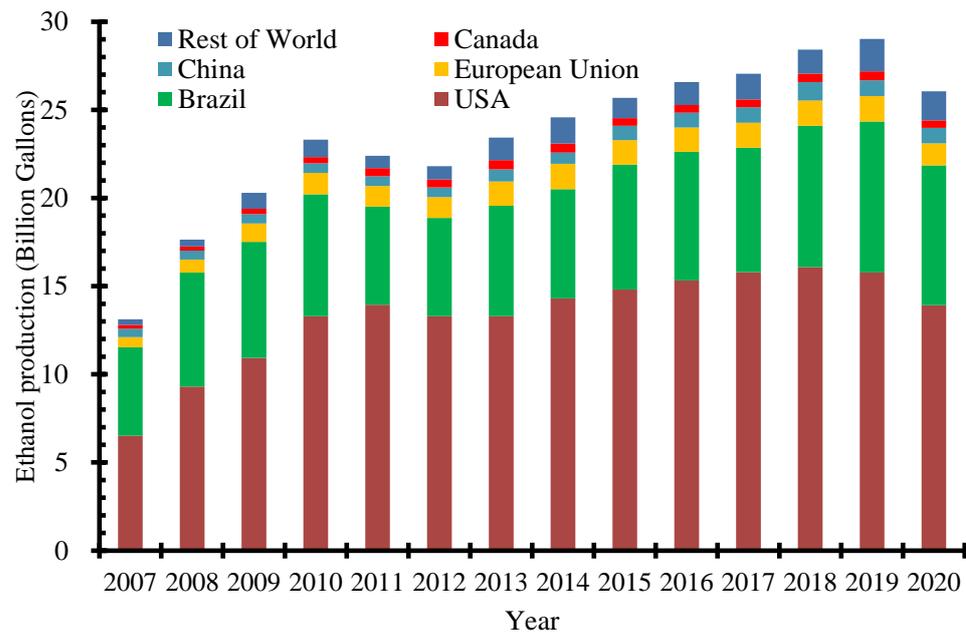


Figure 5. Global ethanol production (Billion Gallons) from 2007 to 2020.

Table 3. Application of PPW for bioethanol.

Production Techniques	Enzymes	Production Rate (g/L)	Yield (%)	Remark	Ref.
Fermentation	<i>Saccharomyces cerevisiae var. bayanus</i>	7.6	91.6	Efficient conversion of PPW to ethanol	[26]
Autohydrolysis and enzymatic hydrolysis	<i>Clostridium</i>	40	ns	Production of biobutanol at industrial scale	[28]
Fermentation	<i>Saccharomyces cerevisiae</i>	48.76	80.62	Low-cost ethanol production	[55]
Saccharification and fermentation	<i>Saccharomyces cerevisiae</i> BY4743	22.54	ns	Effective bioethanol production	[56]
Enzymatic hydrolysis and fermentation	<i>Saccharomyces cerevisiae</i>	30	ns	Improved yield of bioethanol	[57]
Enzymatic hydrolysis, saccharification and fermentation	<i>Saccharomyces cerevisiae</i>	ns	5.8	Low-cost bioethanolProduction at moderate conditions	[58]
Enzymatic hydrolysis and fermentation	<i>Alpha amylase and cellulase</i>	11.9	ns	Bioethanol production from varieties of PPW	[59]
Fermentation	<i>Termamyl and amyloglucosidase</i>	21	ns	Effective production of bioethanol from PPW	[60]
Fermentation	<i>Clostridium acetobutylicum</i> MTCC 11274	ns	96	Improved yield of biobutanol	[61]
Fermentation	<i>Clostridium acetobutylicum</i>	24.8	75	Low-cost and eco-friendly production of biobutanol	[62]
Pyrolysis	ns	ns	47.5	Effective biooil production	[63]
Pyrolysis	ns	ns	29.18	Novel conversion of PPW to biofuel	[64]

ns = not stated.

Sujeeta et al. [58], Chavez et al. [59], and Khawla et al. [60] utilized PPW for the production of bioethanol using *Alpha amylase* and *cellulase*, *termamyl* and *amyloglucosidase*, and *Clostridium acetobutylicum* MTCC 11274, respectively. The outcome of their investigations gave credence to the practicality of the conversion of PPW to bioethanol. In research,

Kamboj and Ms [61] applied powdered orange peel (*Citrus sinensis*) extract to improve the conversion of PPW to Acetone butanol and ethanol via fermentation using *Clostridium acetobutylicum* MTCC 11274. It was reported that the generation of butanol increased with the addition of orange peel extract. Using a similar technique, Abedini et al. [62] used *clostridium acetobutylicum* for the conversion of PPW to biobutanol via fermentation. In both situations, PPW was effectively used as low-cost and eco-friendly feedstock under a mild production process.

PPW has been pyrolyzed for the production of various grades of biooil with encouraging outcomes. Önal et al. [63] and da Silva Batista [64] produced biooil by pyrolyzing PPW powder in a reactor maintained at 400–700 °C, with a heating rate of ~ 100 °C/min for 3 min. The process yielded a combination of solid, liquid, and gaseous fuels at various percentages depending on the process parameters. PPW has been successfully pyrolyzed into biochar, biooil, and syngas for various applications. For example, Daimary et al. [65] pyrolyzed PPW at 500 °C for 30 min to obtain biochar (29.50%) and biooil (23.60%) for catalytic biodiesel production, while Liang et al. [66] reported a yield of 30.5% biochar, 22.7% biooil, and 46% syngas from pyrolyzed PPW. Kim et al. [67] and Frantzi and Zabaniotou [68] cataloged the types, composition, properties, and applications of various products from the pyrolysis of PPW and other food wastes. The authors reported that PPW was converted into biofuel without the use of an enzyme or catalyst. The aggregate of opinions from the various researchers indicates that PPW is a low-cost, readily available, and effective feedstock for bioethanol production.

5. Prospect of PPW in the Biofuel Sector

Apart from the production of biogas and bioethanol, there is great potential for more applications of PPW in the biofuel sector. From the compositional and economic points of view, PPW has the potential to be used in other areas of biofuel synthesis both as feedstocks and catalysts.

5.1. Potential of PPW as Feedstock for Biohydrogen Production

Hydrogen can be used as a fuel and as a raw material for industries. As a fuel, hydrogen is an integral part of the global energy mix, a key pillar of decarbonization for industry, and an alleviator of the impacts of global warming. Hydrogen can be used as a fuel, chemical, and industrial feedstock. Because of its multi-faceted applications, the global demand for hydrogen has continued to increase from 18.2 million metric tons (MMT) in 1975 to 39.8 MMT, 62.4 MMT, and 74.5 MMT in 1995, 2010, and 2018, respectively (Figure 6). The reduction in global demand recorded in 2020 is a result of the impact of the global lockdowns occasioned by the COVID-19 pandemic. Global hydrogen demand has been projected to become 88.3 MMT, 415.2 MMT, and 519 MMT in 2030, 2060, and 2070, respectively [69]. In terms of market share, the global hydrogen generation market that was USD 130 billion in 2020 has been predicted to become USD 201 billion in 2025 [70].

The major driver for the favorable growth in hydrogen generation is the advent of new hydrogen separation techniques, the increased utilization of hydrogen, and government policy on desulfurization and greenhouse gas emissions. However, huge amount of CO₂ emissions from hydrogen production and cost storage has continued to limit its application. Currently, about 95% of hydrogen is synthesized from fossil-based fuels sources, including coal, oil, and natural gas, emitting about 830 million tons CO_{2eq} per year globally (equivalent to the CO₂ emission of the United Kingdom and Indonesia) [71–73]. Producing hydrogen from renewable feedstocks and low-carbon footprint technologies (biohydrogen) will contribute to the decarbonization of the energy system, slow down the impacts of the GHG, reduce energy consumption during production, and democratize utilization. The production of biohydrogen is more environmentally friendly, safer, cheaper, and less energy-intensive when compared with hydrogen production from fossil-based sources [72,74].

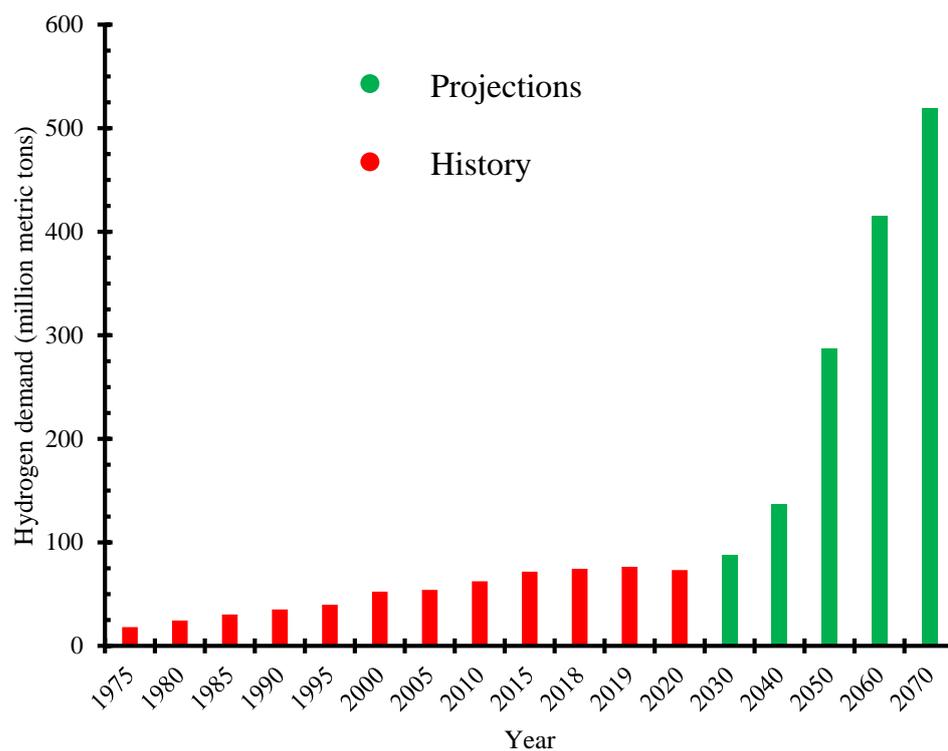


Figure 6. Global demand for hydrogen (Million Metric Tons) from 1975–2020 and 2030–2070 projections. Compiled and adapted by the authors from [69,71].

Among the technologies for hydrogen generation such as coal gasification [75], steam methane reforming [76], thermochemical water splitting [77], water electrolysis [78], and methane pyrolysis, biomass gasification has a low production cost and minimum carbon footprint [79]. This has popularized the production of biohydrogen from various biomass and waste. Feedstocks such as substrates (glucose, starch, sucrose, and lactose) and waste carbohydrates (bagasse, molasses, waste biomass, cyanobacterial) have been used to generate biohydrogen through dark fermentation [80]. Carbohydrate and starch have been identified as the two major substrates needed in any feedstock for the synthesis of biohydrogen through a dark fermentation process. Waste foods, wastewater, waste vegetables, and biomasses with high sugar and complex carbohydrates contents are easily fermented to generate biohydrogen. Taking these facts, Islam et al. [74], Zhang et al. [81], Rezaeitavabe et al. [82] Srivastava et al. [83], Sivaramakrishnan et al. [84], and Reaño [85] synthesized biohydrogen from wastewater, corn stover, food wastes, sugarcane bagasse, rice bran waste, and rice husk, respectively, and reported that by using appropriate bioprocess technologies, the identified wastes served as sustainable, low-cost, and low-energy-intensive raw materials for biohydrogen generation.

To corroborate these facts, Sinha and Pandey [80] and Marone et al. [86] used various waste vegetables and biomasses for the effective generation of biohydrogen. They relied on the high carbohydrate, total lipids, glucose, sucrose, and starch content of various feedstocks to produce biohydrogen. The work of Mars et al. [87], who synthesized biohydrogen from untreated and hydrolyzed potato peels, can be further stretched and explored to include the use of PPW. Similarly, Ferreira et al. [88] synthesized biohydrogen from PPW for use to complement Portuguese transportation fuel. From the foregoing, it is safe to conclude that apart from the composition of the potential feedstocks, availability, cost-effectiveness, substrate purity, and the ease of hydrolysis and biodegradation are among the major requirements for biohydrogen production. Based on this, innovative investigations are needed to utilize the compositional advantage, availability, and purity to meet the increasing demand for biohydrogen.

5.2. Potential of PPW as Biocatalyst for Biofuel Production

One of the problems militating against the universal and commercial adoption of biofuels for various applications is the high financial outlay of production. The high price of raw materials, mainly feedstock, and catalysts account for 60–80% of the total cost of production [89]. Apart from the exorbitant cost of some catalysts, the use of commercial catalysts not only instigates disposal challenges but also impacts the environment negatively, as many of them are not eco-friendly and biodegradable. The application of heterogeneous catalysts derived from waste not only reduces the cost of raw materials by more than 13% but also promotes waste utilization, controls pollution, ensures availability, non-toxicity, and engenders less destructive ecological impacts [90]. There is a large gap for the conversion of more food and agricultural wastes to biocatalysts for various biofuel applications.

To convert PPW into heterogeneous catalysts, waste materials must be collected from households and restaurants and transported to laboratories. The PPW must be separated from any other waste and any unwanted objects. The PPW is washed under running warm iodized water to remove any dirt and impurities on the body of the peels. The water in the washed peel is drained into a sieve, and the peel is dried in the sun. The PPW is exposed to further drying in an oven kept at 100 °C for 6 h. The dried PPW is subjected to further processing, as depicted in Figure 7. The PPW powder is subjected to any of the established modification processes, including physical mixing, high-temperature calcination, calcination–hydration–dehydration, wet impregnation, bifunctional, co-precipitation, and sol gel [91,92]. The potential bio-waste catalyst is subjected to thermal, compositional, and spectroscopic characterization to determine the suitability of the powder for catalytic applications. Among other techniques, X-ray diffraction is used to identify and determine the sample's composition, phase, or structure, while *Brunauer–Emmett–Teller*, thermogravimetric analysis, scanning electron microscopy, and differential scanning calorimetry will reveal the structural and specific surface area, thermal stability, structural analysis, and heat flow, and heat capacity, respectively [93–95].

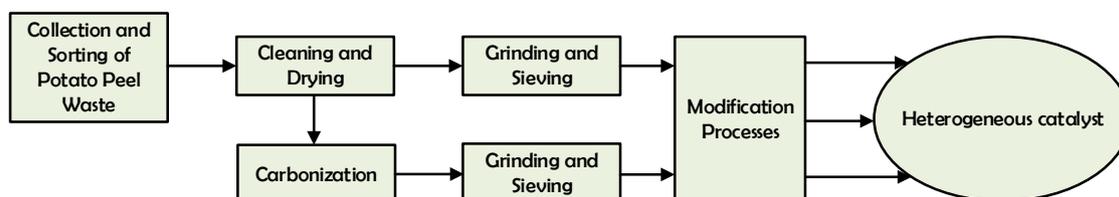


Figure 7. Flowchart for the proposed procedure for the development of catalyst from PPW.

In a study, Hussein et al. [96] synthesized a sulfonated carbon (SO₃H-PPAC) catalyst from PPW for the conversion production of biodiesel from several low-grade, highly acidic feedstocks. This was achieved by mixing the PPW with ZnCl₂. The outcome was then activated at 450 °C for 1 h to obtain a porous carbon (PPAC) material. The PPAC was later sulfonated through concentrated sulfuric acid treatment. The generated catalyst was characterized and found to possess a high surface area of 827.7 m²/g and a high concentration of acidic active sites of 1.6 mmol/g. During usage, a high oleic acid conversion efficiency of 97.2% was achieved at a catalyst dose, reaction temperature, and time of 5 wt.% SO₃H-PPAC, 80 °C, and 2.5 h, respectively. With activation energy of 32.9 kJ/mol and reusability of five runs, the PPW-derived heterogeneous catalyst showed impressive catalytic performance. Biochar obtained from the pyrolysis of PPW was calcinated at 700 °C was used as a heterogeneous catalyst for the conversion of soybean waste cooking oil into biodiesel [65].

5.3. Other Applications of PPW

PPW has also been utilized for adsorption purposes. In another application, activated carbon obtained from pyrolyzed PPW was used as a natural and green adsorbent

for the removal of cobalt, copper, nickel, cadmium, iron, lead, and other heavy metals from wastewater and other aqueous solutions [97–99]. Quisperima et al. [100], El-Nahas et al. [101], and Maleki et al. [102] successfully produced active adsorbents for the effective removal of phosphorus, nitrate, and dye, respectively, from domestic wastewater, industrially contaminated water, and aqueous solutions. Modified activated carbon generated from the valorization of PPW was used as an eco-friendly adsorbent for the effective removal of dorzolamide and pramipexole from synthetic aqueous pharmaceutical effluents [103].

Wesley et al. [104] and Durairaj et al. [105] synthesized biochar from PPW to produce a copper(II)Phthalocyanine compound for the novel production of appropriate electrode material for electrochemical supercapacitors for energy storage applications. The biochar was generated through hydrothermal carbonization and activated with a potassium hydroxide solution. Similarly, porous carbon materials doped with heteroatoms were derived from PPW for the development of eco-friendly, efficient, and low-cost supercapacitor electrode materials for improved energy storage applications [106]. In another application, Andreas Arie et al. [107] synthesized a carbon–sulfur composite as a cost-effective cathode material for lithium–sulfur battery capabilities. These applications further demonstrate the wide applications of PPW for various purposes. PPW offers effective, efficient, low-cost, environmentally friendly, and readily available raw materials.

6. Implications

The utilization of PPW for biofuel applications is a step to meeting the global renewable energy quota. The peel derived from the over 400 MMT of the potato produced in 2020 can be utilized to meet the global biofuel production. Apart from the production of biogas and bioethanol from PPW, there are more utilization pathways for the huge amount of waste generated from potatoes. The implication, therefore, is to explore more avenues for the utilization of PPW for various applications in the biofuel sector. The conversion of waste to useful products is a major component of waste utilization, zero waste, and the circular economy.

The high moisture content of PPW is one of the major challenges militating against its conversion, development, and utilization. The collection, processing, handling, storage, shelf life, and transportation of PPW are greatly impacted by the high moisture content. The application of PPW for catalytic applications will be greatly impacted by the high moisture content of PPW. The high water content of PPW requires an effective dryer, drying time, and additional drying cost for its conversion to a heterogeneous catalyst [108]. The high moisture content of PPW is a major drawback and reduces the effectiveness of pyrolysis as a conversion technique. Additionally, the rapid decomposition of PPW commences almost immediately after peeling, with an unpleasant odor [109]. This makes the sourcing and storage of PPW as a feedstock challenging. Additionally, the viability and sustainability of PPW as a starting raw material for activated charcoal needs to be improved and made less challenging. Despite the huge quantity of PPW generated, the actual collection of an adequate quantity for various applications is doubtful.

At the household level, generated PPW is often mixed with other food waste and is difficult to be separated before disposal. However, industries and restaurants that deal in potatoes as their major raw materials generate, separate, and collect the generated PPW at the peeling section. When compared with PPW, Panahi et al. [110], Neto et al. [111], and Karmee [112] reported that waste such as food waste, fruit and vegetable waste, as well as other kitchen waste can be converted to bioethanol, biogas, and other biofuels, respectively. The conversion yield of food waste to biodiesel was reported to be between 95% and 97%, while the conversion yield of between 92% and 96% was recorded with bioethanol. Most food waste, fruit and vegetable waste, crop residue, and animal manure have strong potential as feedstocks for biofuels and other value-added products. The deciding factors are the selected valorization strategies, production parameters, and the chemical composition, particularly the concentration of carbohydrate, in the different waste deployed as feedstocks.

7. Conclusions

Potato is one of the most popular and essential foods in the world. The huge quantity of PPW generated globally has been a source of concern to waste managers and environmentalists over the years. The huge amount of PPW generated and collected every year has widespread applications in various sectors and industries. Currently, efforts are being made regarding the conversion of PPW to a form of biofuel including biogas and bioethanol. The conversion of PPW into biogas and bioethanol is influenced by its availability and chemical composition. The high content of water, carbohydrate, starch, and ash influence its conversion to biogas and bioethanol. There are economic, sanitary, and environmental advantages in the conversion of PPW to biofuel that are too numerous to be ignored.

The potential of utilizing PPW for biohydrogen production is very promising and economically viable. This is not only from a waste conversion point of view but also to meet the huge demand for biohydrogen as a renewable fuel. The conversion of PPW to a biobased heterogeneous catalyst for possible biofuel is a research gap that needs further investigation. Going forward, further investigations are needed to optimize PPW generation, cost outlay, energy consumption, conversion efficiency, and yield of the current conversion process. An adequate and seamless PPW collection infrastructure should be established and maintained to ensure an unbroken supply of waste for biofuel applications. The use of appropriate techniques and technologies such as cloud computing, the internet of things, and other fourth industrial revolution technologies should be incorporated into the mapping, collection, and conversion of PPW into valuable products.

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