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Systematic Valorisation and Circular Bioeconomy Prospects from Potato Wastes: A Review

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Abstract

Potato is among the most widely cultivated and consumed food crops worldwide, with production steadily rising to meet global food demands. Alongside this growth, industrial processing of potato-based products generates substantial amounts of waste streams, including peels, mash, pulp, and process water, that are often discarded without commercial utilization. These residues are rich in carbohydrates, proteins, and bioactive compounds, making them attractive substrates for extraction and bioconversion into a wide range of value-added products. Emerging studies demonstrate their potential for producing biofuels, organic acids, enzymes, carotenoids, lipids, nutraceuticals, and pharmaceuticals, as well as fertilizers and bioenergy-related products. Valorization of potato residues not only enhances resource efficiency but also supports circular economy principles and reduces environmental burdens. This review synthesizes current advances through a bibliometric and systematic analysis of SCOPUS-indexed publications (2015–2025), complemented by keyword co-occurrence mapping using VOSviewer to capture research hotspots, technological pathways, and sustainability linkages. The findings highlight that potato waste valorization contributes significantly to Sustainable Development Goals (SDGs), particularly by promoting responsible production and consumption (SDG12), enabling clean and renewable energy generation (SDG7), and mitigating negative environmental impacts (SDGs 6, 11, 13, 14, and 15). Furthermore, integrating potato residue valorization into industrial symbiosis strengthens innovation, infrastructure, and economic growth (SDGs 8 and 9). Overall, potato waste represents a versatile feedstock for biorefinery applications, offering a holistic model that integrates circular economy strategies with sustainable development objectives.

Keywords: Potato waste, Valorization, Biorefinery, Circular economy, Sustainable Development Goals, Bibliometric analysis.

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1. Introduction

Following rice, wheat, and corn, potatoes rank as the fourth most important food crop in the world. With the global population rising, the demand for staple foods is increasing, enhancing the significance of potatoes due to their multiple advantages over rice, grains, and corn (Rahman et al., 2022). Potatoes are naturally resilient to diseases, pests, and various environmental stresses, making them a reliable crop in both temperate and tropical climates. In developing countries such as China and India, potato consumption is growing steadily, with these nations being the world's top producers and consumers of potatoes. The global potato market is projected to reach USD 111.83 billion in 2023 and USD 132.81 billion by 2028, reflecting a compound annual growth rate (CAGR) of 3.50% during this period (Mordor Intelligence, 2023). South America's Andes region is home to approximately 4,000 edible potato varieties, while over 180 wild species remain inedible due to their highly bitter flavor. Globally, more than a billion people consume potatoes, and for millions across Africa, America, and Asia, potatoes play a critical role in food security (Wubet et al., 2022).

Potatoes offer several advantages over other food crops, including high yield, ease of storage, rich nutritional content, and adaptability to a wide range of soils, particularly those with pH 6.5–7.5. Their cultivation requires relatively low input compared to other major crops, and they can be grown in diverse climatic and soil conditions, making them highly suitable for both subsistence and commercial farming. These attributes contribute to their popularity in the food processing industry, where they serve as raw material for a variety of products (Wijesinha-Bettoni & Mouillé, 2019). Despite these advantages, the potato processing industry generates substantial organic waste, including peels, pulp, and processing water. According to Khanal et al. (2023), potato peel waste is expected to reach 8,000 kilotons by 2030, potentially contributing over 5 million tonnes of CO_2-equivalent emissions. This underscores the environmental urgency of managing potato waste and highlights the untapped potential of valorizing these by-products into value-added products, in line with circular economy principles.

Potatoes are widely consumed in northern Europe, where they are a staple in traditional cuisine, and they are increasingly being adopted in countries with historically low potato consumption, such as Ireland. Globally, the potato market is primarily divided into fresh and chilled potatoes. Fresh potatoes are consumed directly, whereas chilled potatoes are primarily traded for processing purposes (Andrade-Piedra et al., 2020). Leading exporters of fresh potatoes include China, Germany, France, Canada, the United States, and the Netherlands, while China, India, Russia, and the United States were the largest producers in 2020, yielding 78.2, 51.3, 19.6, and

11.7 million metric tons, respectively (Fig. 1). Rising global demand and production indicate a growth trajectory for the potato market during the forecast period (Potatobusiness, 2023).

Potatoes serve a wide range of purposes beyond direct consumption. Approximately 50% of global potato production is consumed fresh, while the remaining 50% is processed into ingredients, starch, or animal feed (Warden, 2022). Processed potato products, including frozen potatoes, french fries, and potato crisps, have seen rising demand due to changing consumer preferences. Dehydrated products such as potato flour and flakes are widely used in the food industry as thickeners, binding agents, and instant mashed products. Potato starch, which offers higher viscosity than maize or wheat starch, is used in biscuits, doughs, ice cream, and sauces (Tijjani et al., 2021). Potatoes are also used in alcohol production, where crushed potatoes are converted into fermentable sugars for beverages like vodka and akvavit. In the United States, potato processing reached approximately 14 million metric tons in 2020, with 3 million metric tons used for chips and shoestrings and 8.6 million metric tons for frozen goods and fries. Frito Lay alone sold over USD 4.8 billion worth of potato chips during this period (FAO, 2019).

Potatoes also play a pivotal role in food security, a fact recognized by the United Nations when 2008 was designated the International Year of the Potato. Food security exists when all people have physical, social, and economic access to sufficient, safe, and nutritious food. Potatoes contribute significantly to this goal, particularly in developing countries, where enhanced processing and storage can help farmers generate high-value products, maintain livelihoods, and stimulate local economies. Historically, potatoes have been consumed in the Andes for around 8,000 years and rapidly spread across Europe after introduction by the Spanish in the sixteenth century. Today, *Solanum tuberosum* L. remains the most widely cultivated variety. On average, potatoes provide 64 kcal of energy and 2 g of protein per capita per day, though contributions vary by region, with Europe having the highest intake (FAO, 2017b). In major potato-producing countries such as Peru, Ukraine, Bangladesh, China, India, and Belarus, potatoes contribute 8%, 8%, 4%, 2%, 3%, and 10% of dietary energy per capita, respectively (FAO, 2018b). In Asia, the demand for potatoes is rising rapidly due to population growth and changing food preferences. Several Asian countries have recognized the crop's potential for food security and have implemented initiatives such as subsidies, farmer training programs, and potato research facilities to enhance production (Scharf et al., 2020).

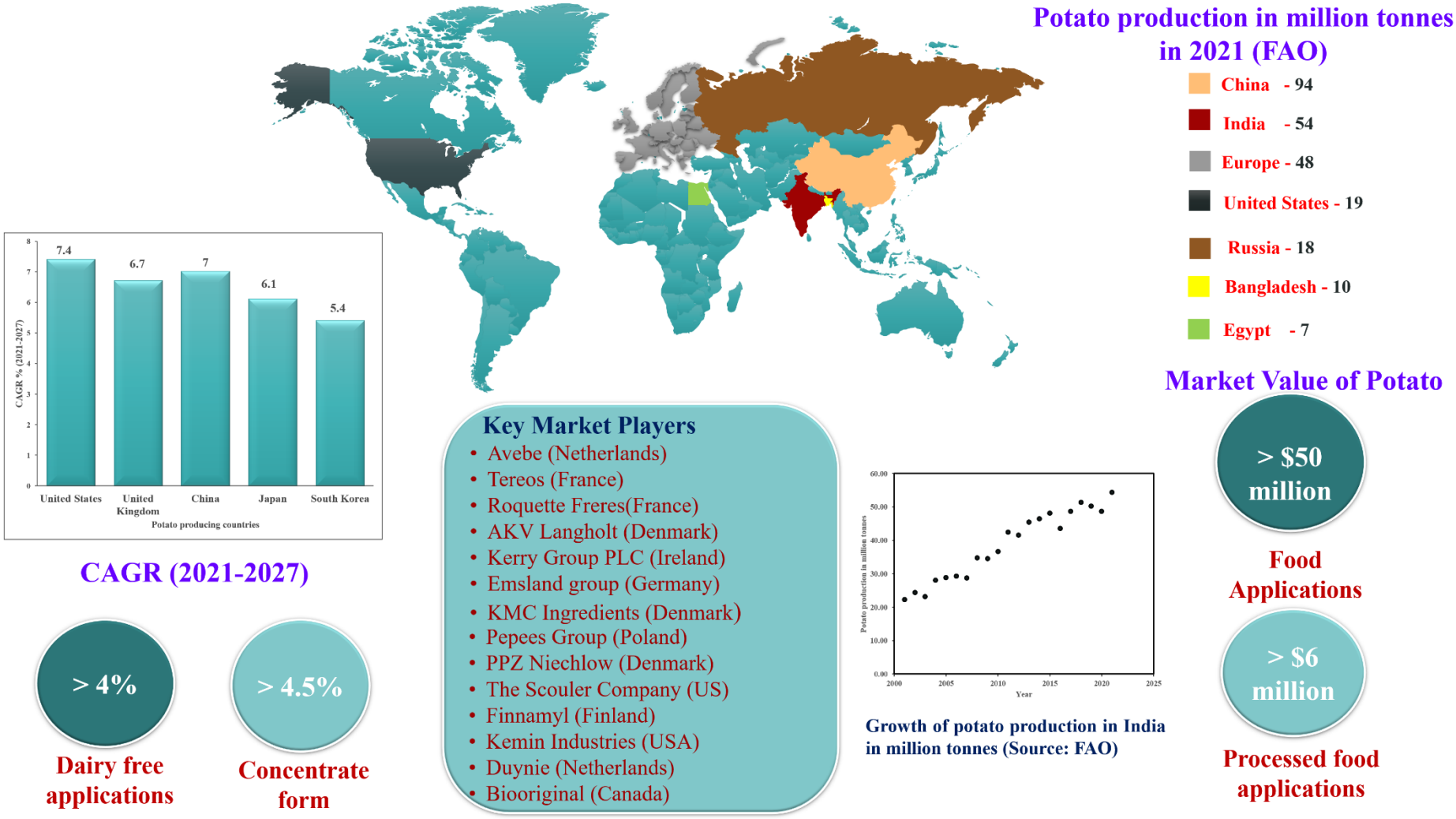

Fig. 1 An overview of Potato demand and supply with an emphasis on global production

Potatoes demonstrate remarkable adaptability, growing in climates ranging from the cold regions of northern China to the tropical temperatures of India, making them a preferred choice for farmers. Furthermore, the rise of the middle class in many Asian countries has increased demand for processed and value-added potato products, such as chips and fries. This has incentivized farmers to expand production to meet both domestic consumption and export requirements (Wijesinha-Bettoni & Mouillé, 2019).

Overall, the potato remains a versatile, high-yield, and nutritionally rich crop with significant economic and food security importance globally. Its growing demand, adaptability, and potential for value-added products underscore the need for sustainable management and utilization strategies, particularly in processing and waste valorization.

2. Bibliometric analysis

A bibliometric analysis was conducted using documents sourced from the SCOPUS database (Kundu et al., 2022). The dataset reveals a prolific body of research on potatoes, with 110,663 publications overall. Narrowing this focus to potato waste, 3,704 publications were identified, of which 205 explicitly address valorization strategies. Within this subset, 82 publications explore conversion pathways such as microbial fermentation, enzymatic hydrolysis, and thermochemical conversion to produce value-added products including biofuels, biofertilizers, enzymes, and bioplastics. A notable 45 papers apply the biorefinery concept, indicating a transition from single-product recovery toward integrated, multi-product frameworks aligned with industrial symbiosis. In addition, 26 publications adopt a circular economy perspective, while only 9 explicitly map valorization to the Sustainable Development Goals (SDGs), primarily SDG 2 (Zero Hunger), SDG 7 (Affordable and Clean Energy), and SDG 12 (Responsible Consumption and Production). Despite these advancements, the literature remains fragmented, with few efforts to holistically integrate biorefinery, circular economy, and SDG dimensions into a unified sustainability framework.

A time-series analysis of 205 selected publications from 2015 to 2025 reveals consistent growth in the field. Initial activity was modest (2 publications in 2015, 6 each in 2016 and 2018, and 12 in 2019), but output increased sharply thereafter, with 23 in 2020, 24 in 2021, 27 in 2022, 32 in 2023, and 35 in 2024. Notably, 26 papers have already been published in 2025, underscoring sustained momentum and increasing recognition of potato waste valorization as a relevant research domain (Fig. 2a). Geographical distribution reflects broad international engagement. India leads with 27 publications, followed by Spain (20), Italy (18), China (15), and the United Kingdom (12). Other significant contributors include Belgium, Greece, Poland, Portugal, and the United States (11 each), as well as France (10), and Colombia and Egypt (9

each). Contributions from more than 60 countries demonstrate the global relevance and interdisciplinary scope of this research area (Fig. 2b).

In terms of document types, the analysis reveals a dominance of original research articles (148), complemented by 31 reviews, 11 book chapters, 5 conference papers, 3 conference reviews, 3 errata, and 2 books, reflecting both the maturity and the multidisciplinary nature of the field (Fig. 2c). Keyword co-occurrence analysis using VOSviewer (version 1.6.18) shows evolving research interests, with “potato” connected to 8 clusters, 243 direct links, and 321 total interactions, underscoring the growing complexity and cross-linkages of knowledge networks (Fig. 2d). Taken together, the bibliometric patterns highlight both progress and gaps. While valorization and biorefinery concepts dominate, interconnections with nutrition, health, energy, and systemic sustainability within a circular bioeconomy are limited. Few studies embed technical advances within broader sustainability or policy frameworks. This underlines the need for comprehensive reviews that consolidate technical progress, identify knowledge gaps, and explore synergies across domains, thereby offering actionable guidance for researchers, policymakers, and practitioners working toward sustainable resource management and circular economy transitions.

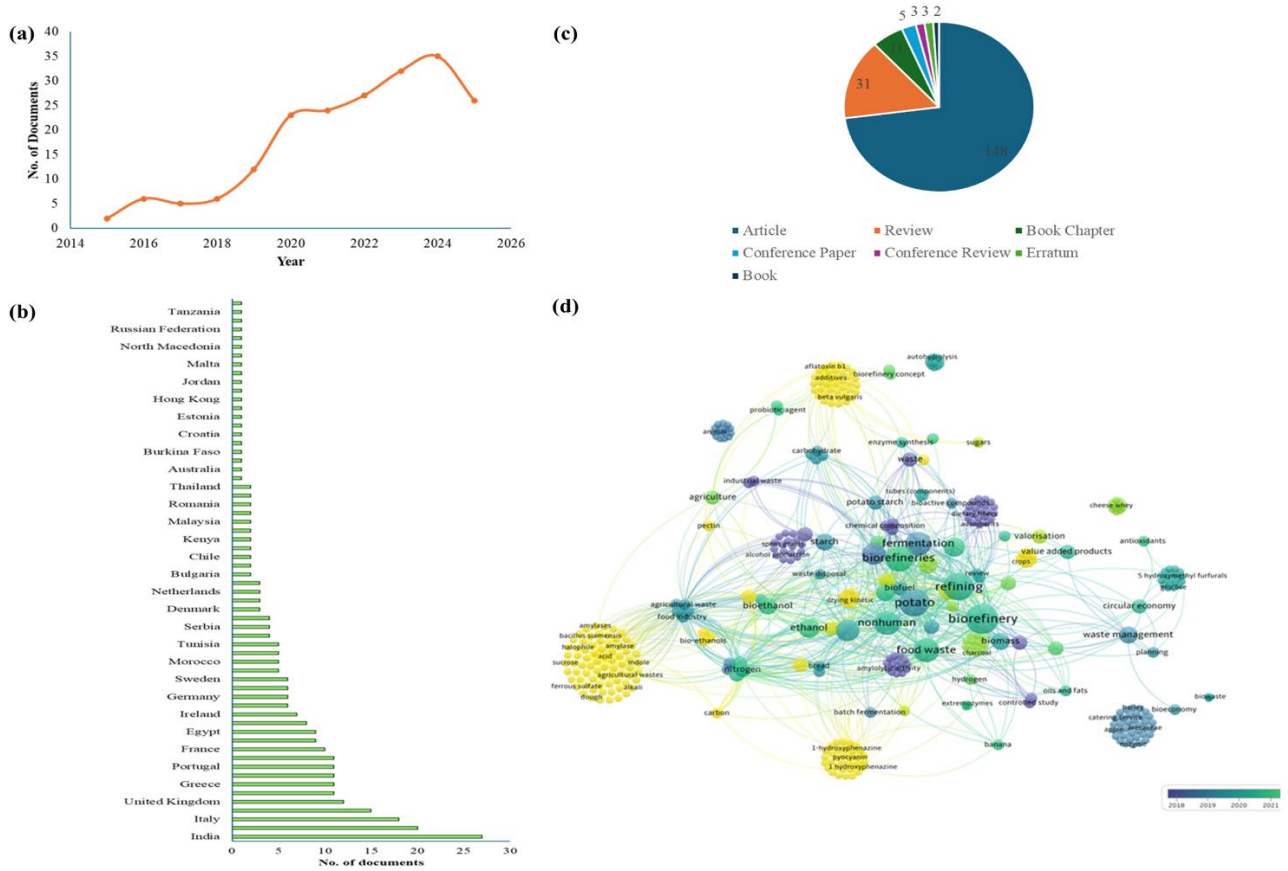

Fig. 2 Bibliometric analysis of publications on potato waste valorization and biorefinery: (a) annual publication output and growth trend; (b) distribution of publications by country; (c) document types; and (d) keyword co-occurrence network extracted from the Scopus database (2015–2025)

3. Potato from Farm to Fork: A supply chain overlooks on SDG 12

The potato supply chain involves multiple stakeholders, including seed producers, farmers, processors, suppliers of chemicals and water/irrigation, utility and power providers, telecom operators, financial institutions, logistics firms, retailers, and food service businesses (Fig. 3). Effective coordination among these stakeholders can help reduce transaction costs, minimize food losses, and lower food waste (Thiele et al., 2011).

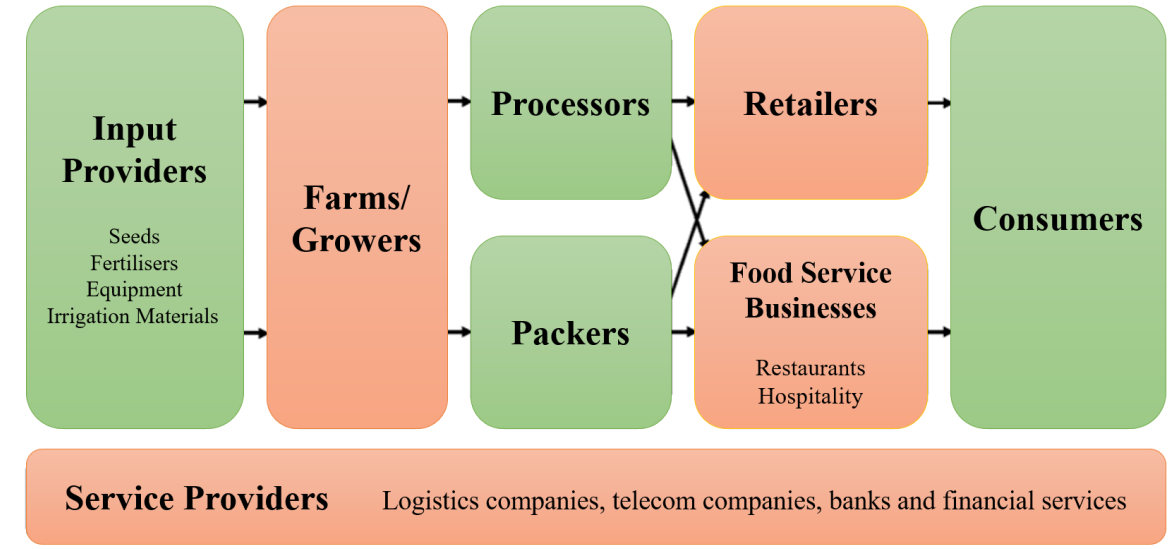

Fig. 3 Potato supply chain from input providers through farms, processors, packers, and retailers/food services to consumers, supported by service providers

The growth of potatoes can be broadly divided into seed planting, plant establishment, tuber initiation, tuber bulking, ripening, and harvesting. The overall lead time from planting to harvest is approximately 5.5 months. Once harvested, potatoes are transported to processors and packers before reaching the market, where they are sold in retail outlets or supplied to food service companies. Throughout this chain, support services such as logistics, telecommunications, and financial institutions facilitate the smooth flow of information and funds.

The supply chain is susceptible to various disruptions. For instance, extreme weather can extend delivery times by 30% to 65% (Rahman et al., 2022). Shortages of potatoes can arise from both such external disruptions and inefficiencies within the supply chain. During the COVID-19 pandemic, lockdown measures led to increased food prices and operational difficulties for retailers due to labor shortages and irregular product supplies. In India, potato prices rose by 15% during the lockdown, significantly affecting the affordability of this staple

(Narayanan & Saha, 2021). Losses and waste in the potato supply chain occur at multiple stages, largely due to processing methods, storage issues, and imbalances between supply and demand. Processing generates scraps and discards; for example, producing potato crisps involves pre-processing (sorting, destoning, washing, peeling, and dewatering), processing (slicing, washing, dewatering), and post-processing (frying, flavoring, packaging). These steps result in approximately 8% wastage by weight (Zhang et al., 2019).

Currently, by-products and waste streams are used in limited ways. Potato peel and pulp are sometimes directed to animal feed or composting, mash and other residues may be used in biogas production, while a considerable portion of wastewater remains untreated. On the consumer side, potatoes are frequently wasted due to large portion sizes. Promoting programs for redistributing surplus food can help reduce this loss, as it preserves high-value products after the stages of planting, harvesting, processing, packaging, storage, transportation, and distribution (Aktas et al., 2018). In alignment with UN SDG 12 on Responsible Consumption and Production, these waste streams can be further valorized into economically useful products or animal feed. For example, waste frying oil from chip production could be converted into biofuels, while pulp, peel, mash, solids, and wastewater can be processed in biorefineries to generate energy (biohydrogen, biodiesel, biogas), biopolymer films, or cellulose nanocrystals (Khanal et al., 2023). A detailed discussion on SDGs through potato valorisation is provided in section 8.

4. Role of potatoes in nutritional security

Food security, nutritional adequacy, and biodiversity are currently the most widely discussed global concerns in the field of nutrition since food and the lack thereof have a substantial impact on human health. Individuals who can acquire sufficient nourishment for a healthy, active life and food security are more likely to be able to make a significant economic contribution than their counterparts who are undernourished. Historically, potatoes have played an essential role in providing food security for the existing population and have always been a reliable food source during difficult times like war, famine, etc. (A hero role of potatoes in global security, 2022). Potato nutrition facts reveal that the vegetable could be a beneficial ingredient of a balanced diet when prepared properly. According to the USDA (U.S. Department of Agriculture), potatoes are enriched with phytonutrients which are plant-based substances considered to be beneficial to human health (Gordon and Szalay, 2022). Caffeic acid, flavonoids, and carotenoids are profound in potatoes. Potatoes include vitamin C, which is an antioxidant that promotes heart health, digestion, blood pressure, and even cancer prevention (Burgos et al., 2020). The fibre content in potatoes may lower cholesterol, and potassium

content functions as a vasodilator (blood pressure widener), which can help decrease blood pressure. Researchers at the Institute for Food Research have found that potatoes contain kukoamines, which are known to decrease blood pressure (Sido et al., 2017). Additionally, cardiac-healthy, the fibre content in potatoes is linked to the elimination of cholesterol from blood vessels, while carotenoids support healthy heart function whereas vitamin C and B6 help in reducing free radicals. According to a study published in the Journal of Nutritional Biochemistry, the consumption of purple potatoes may lower the risk of colon cancer as it is rich in antioxidants and anti-inflammatory agents that can lower the levels of Interleukin-6 (IL-6), a protein connected to colon cancer cell proliferation. The nutritional aspects of potatoes are represented in Fig 4(a-e).

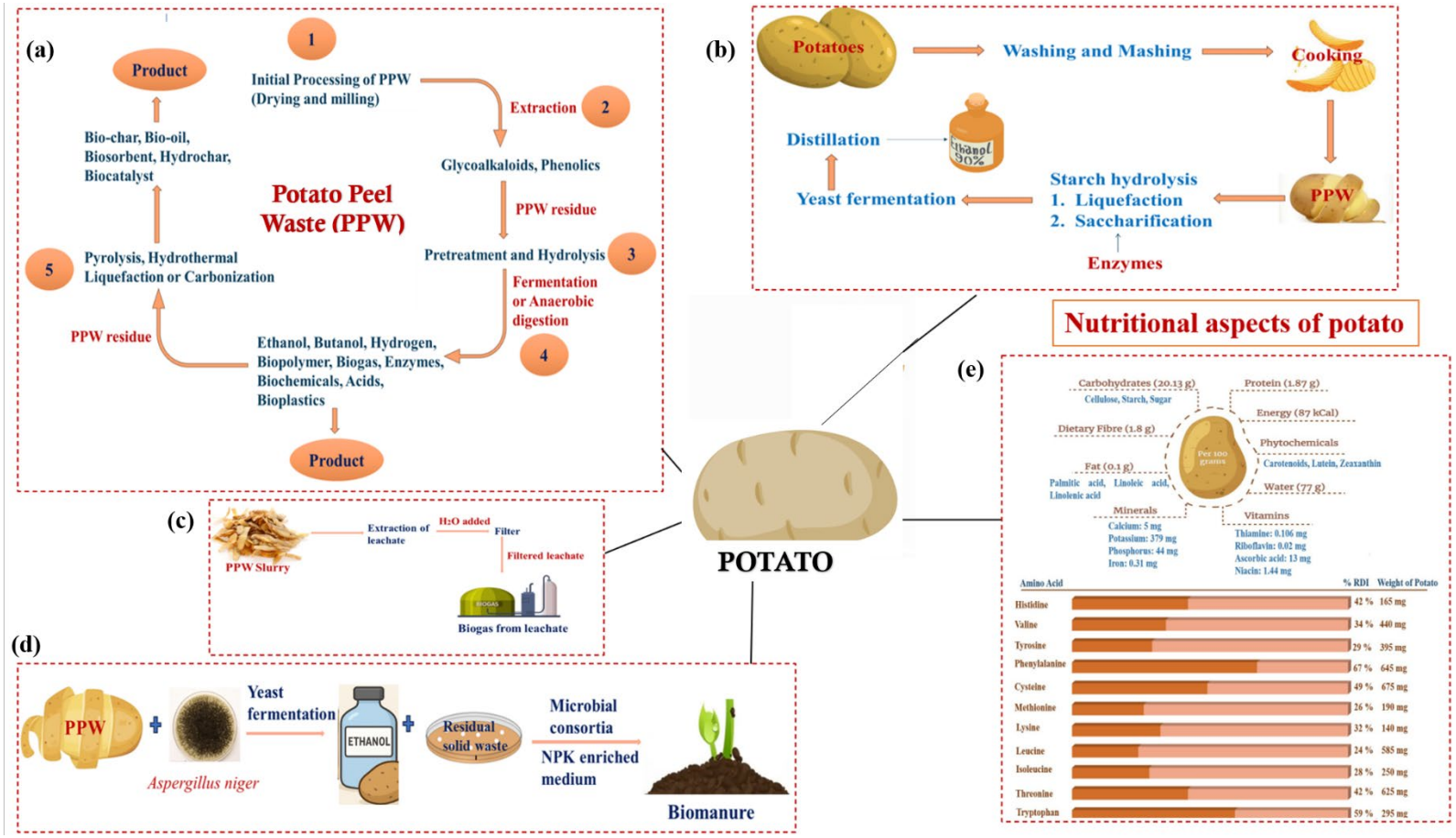

Fig. 4. Biorefinery routes for potato peel waste (PPW) valorization: (a) sequential processing for fuels, chemicals, and biomaterials; (b) ethanol production via starch hydrolysis and yeast fermentation; (c) biogas generation from PPW slurry leachate; (d) microbial conversion of PPW to ethanol and biofertilizer; and (e) nutritional profile of potato, highlighting macronutrients, micronutrients, phytochemicals, amino acids, and dietary fiber (mainly insoluble fiber such as cellulose and hemicellulose, with minor fractions of soluble fiber like pectin)

4.1 Functional foods from potato

Potatoes are the most nutrient-dense starchy food crop in the world with more vitamins, protein, and minerals than wheat, rice, corn, or sorghum, and are also a good source of phytochemicals and antioxidants. As people become more aware of the connection between nutrition, health, and diet, potato has the potential to become a significant dietary source of bioactive substances or functional foods. Consequently, potatoes may be a key component in the prevention, management, and treatment of chronic diseases like cardiovascular diseases, obesity, and Type 2 diabetes (Clinton et al., 2020). The vitamin and phytonutrient content of potatoes will have a higher dietary relevance and influence over foods consumed in sparse quantities as they are the most consumed vegetable in most of the developed world. According to market statistics, the global market for nutraceuticals and functional foods is expanding faster than the market for conventional processed foods. Functional foods containing naturally occurring bioactive substances, for example, the presence of β-glucan in oat bran for lowering the level of blood cholesterol. According to Health Canada, functional food is taken as part of a regular diet, is comparable in appearance to conventional food, and has been proved to have physiological benefits and/or reduce the risk of chronic disease beyond basic nutritional functions (Glycoalkaloids in foods, 2011).

4.2 Protein supplements from potato

Recent research highlights potato protein as a promising alternative to animal-based proteins, particularly in the context of exercise recovery. Savacool (2023) reported that potato protein supplementation supports post-exercise muscle repair with effectiveness comparable to milk protein, despite the common belief that plant proteins are less efficient due to incomplete amino acid profiles and lower digestibility. Potatoes, however, contain all essential amino acids in proportions similar to milk, making them unusual among plant-derived proteins. Since whole potatoes contain only about 1.5% protein by weight, extraction from potato juice is considered the most viable approach, and the global market for potato protein powders are projected to reach $115 billion by 2030 (Anderson and Li, 2021). Supporting this view, researchers in the Netherlands demonstrated that potato protein concentrate can stimulate muscle growth and recovery at levels equivalent to milk protein, reinforcing its potential role in human nutrition.

The physiological explanation lies in muscle protein synthesis (MPS), where amino acids are incorporated into skeletal muscle proteins, a process dependent on both protein intake and physical activity (Hoehnel et al., 2022). Potato proteins exhibit a high biological value, as indicated by their essential amino acid index (EAAI) and chemical score, which are often benchmarked against whole egg protein (Peksa et al., 2018). Nutritionally, potato protein

consists of two key fractions namely, coagulable proteins precipitated by trichloroacetic acid and free amino acids. Among these, coagulable proteins are particularly valued for their balanced amino acid composition. Importantly, protein fractions are influenced by potato variety rather than flesh colour. To expand practical applications, diverse extraction and purification strategies including salt, acid, and thermal precipitation, ammonium sulphate fractionation, ethanol precipitation, ion exchange, and peptide isolation have been employed (Waglay and Karboune, 2016), broadening the use of potato protein across food and nutraceutical industries.

4.2.1 Potato protein and its potential applications

Beyond its nutritional role, potato protein shows significant potential in functional foods and therapeutic applications. Current research suggests that bioactive peptides derived from potato proteins could be explored further for their role in managing hypertension, though limitations in fully replacing pharmaceutical interventions remain (Makinen et al., 2016). In addition to health-promoting properties, potato proteins display functional characteristics such as emulsification and foaming, which expand their applicability in food processing and formulation.

Particular attention has been given to potato protease inhibitors, which have been linked to the management of conditions such as cancer, infections, perioral dermatitis, and obesity. These inhibitors can elevate plasma cholecystokinin (CCK) levels, thereby influencing satiety and food intake. A practical example of this is the commercial weight-control ingredient Slendesta, produced by KEMIN, which contains 5% of the protease inhibitor P12. Consuming 300 mg of Slendesta (15 mg P12) prior to meals enhances CCK release, promoting fullness without reported side effects, making it a natural tool for appetite regulation.

Another promising avenue is the use of potato-derived proteins in beverage industries. Patatin, a glycoprotein recovered from potato processing residues, has been shown to act as an effective wine-fining agent. It reduces tannins, phenolics, astringency, and interactions with salivary proteins, providing a plant-based alternative for populations sensitive to animal-derived proteins (Almadiy et al., 2018). Compared with other vegetable proteins such as soy and pea, potatoes are not traditionally viewed as protein-rich. Nevertheless, their protein digestibility and amino acid score of 112 indicate that they provide complete protein. For industrial use, manufacturers employ drying techniques such as vacuum freeze-drying, spray drying, atmospheric freeze-drying, and fluid-bed drying to convert potato juice into stable protein powders (Sulli et al., 2017). The U.S. FDA (Food and Drug Administration) recognizes potato

protein as Generally Regarded as Safe (GRAS), making it a suitable candidate for everyday dietary use.

4.3 Essential amino acid and bio-active chemicals

Potato proteins and their derivatives provide not only a balanced amino acid profile but also bioactive compounds with nutritional and therapeutic value. Potato peel, though containing a modest protein content (0.7–4.6%), is considered a richer source of functional proteins than the flesh due to its favourable amino acid composition (Peksa et al., 2018). Notably, potato protein contains nine essential amino acids namely leucine, tryptophan, isoleucine, threonine, valine, methionine, lysine, histidine, and phenylalanine with valine, lysine, and leucine being predominant (5.3%, 4.5%, and 4.3% of all amino acids, respectively). Aspartic acid (23.3%) and glutamic acid (15.4%) constitute the most abundant non-essential amino acids, further enhancing nutritional value. These patterns, however, are influenced by genetic, environmental, and storage factors, with studies showing reductions in amino acid concentrations in red, purple, and yellow cultivars under low-temperature storage (Ito et al., 2017).

Free amino acids in potato peel contribute directly to nutrition while also providing distinct bioactivities. Compounds such as β-alanine enhance exercise performance, β-aminoisobutyric acid offers protection against obesity and cardiometabolic disorders, and α-aminoadipic acid has been identified as a marker of diabetes risk and glucose regulation. Additional metabolites such as phosphoserine, L-ornithine, and hydroxylysine have been linked to bone health, stress relief, and neuroprotection, including prevention of Alzheimer's disease (Peksa et al., 2021; Sato et al., 2019). These findings highlight the dual nutritional and therapeutic potential of potato amino acid derivatives.

In addition to proteins and amino acids, potato peel is rich in polyphenols and glycoalkaloids that contribute to bioactivity. Approximately 50% of phenolic compounds are concentrated in the peel, with chlorogenic acid representing the major component, followed by caffeic, gallic, and protocatechuic acids (Akyol et al., 2016). Flavonoids, particularly flavonols and anthocyanins, are also abundant in pigmented potato cultivars, conferring antioxidant, anti-inflammatory, and anticarcinogenic effects (Benavides-Guerrero et al., 2020; Cerón-Lasso et al., 2018). Chlorogenic acid, for instance, is associated with modulation of lipid and glucose metabolism, supporting its role in preventing diabetes, cardiovascular disease, and obesity (Naveed et al., 2018). Similarly, caffeic acid and rutin provide antimicrobial, antifungal, and anticarcinogenic properties. The strong antioxidant capacity of these phenolics is thought to be responsible for many of the reported health benefits.

Glycoalkaloids, primarily α-solanine and α-chaconine, have also attracted interest due to their anticancer and anti-inflammatory activities (Alves-Filho et al., 2018). Although their toxicity limits direct use, structural modifications could enhance therapeutic potential while minimizing adverse effects. In pharmaceutical contexts, these compounds are being investigated as building blocks for antibiotics, hormone synthesis, and dermatological treatments. Collectively, the diverse amino acids, polyphenols, flavonoids, and glycoalkaloids in potatoes demonstrate significant nutritional value while also offering promising avenues for nutraceutical and pharmaceutical applications.

5. Tapping for health benefits

5.1 Paediatric and geriatric formulations from potato

Starchy carbohydrates from potatoes provide an important energy source and support healthy growth in children. Beyond energy, potatoes contribute to functional nutrition by offering prebiotic and antioxidant properties. When cooked and subsequently cooled, potatoes form resistant starch (RS3) through retrogradation, which resists digestion, lowers glycaemic response, and promotes beneficial gut microbiota activity (Robertson et al., 2018). Potatoes are also a natural source of phenolic antioxidants such as chlorogenic and caffeic acids, which contribute to reducing oxidative stress (Han et al., 2023).

For older adults, the soft texture and high digestibility of potatoes make them suitable for individuals with chewing or swallowing difficulties. Their dietary fiber, mainly insoluble (cellulose, hemicellulose, lignin) with smaller soluble fractions (pectin), enhances bowel regularity, while resistant starch fermentation in the colon generates short-chain fatty acids (SCFAs) that support gut health (Bushell, 2022).

5.2 Edible vaccines from potato

Potato has been widely explored as a platform for edible vaccine production, given its global availability and ease of consumption. Early work demonstrated that transgenic potatoes expressing the cholera toxin B subunit (CTB) accumulated up to 0.3% of total soluble protein in tubers and leaves. Similarly, potatoes engineered with the Norwalk virus (NV) capsid protein successfully triggered serum IgG antibodies in mice, confirming the feasibility of inducing immune responses through oral delivery. A subsequent human trial further validated this approach, where 95% of participants consuming NV-expressing potatoes developed an immune response, although antibody levels varied (Siamalube et al., 2025).

In addition, potato plants expressing the hepatitis B surface antigen (HBsAg) induced antigen-specific antibodies in mice, indicating the potential for oral immunization against hepatitis B. These outcomes suggest that potatoes could serve as an affordable and practical vehicle for

vaccine administration, with significant relevance for underserved populations. Nonetheless, challenges such as achieving stable antigen expression, consistent immunogenicity, and controlled dosage must be addressed before potato-based edible vaccines can be considered for large-scale medical use (Vo and Trinh, 2025). Potato is an appropriate model for producing various vaccines against different antigens and viruses.

5.3 Alternate meat products

The utilization of potato-derived proteins as meat substitutes represents an innovative approach that supports the growing demand for sustainable and plant-based foods. Raw potato contains approximately 2.7% protein (Rajewska et al., 2023), while by-products such as potato peel (18%), pulp (4%), and wastewater after coagulation (0.93–1.57%) also serve as significant protein sources (Kot et al., 2020). Recognizing this potential, Branston Ltd., in partnership with B-hive Innovatives, is developing a process to convert potato waste into a clean-label functional protein suitable for meat analogues (FoodNavigator, 2021). Moreover, leading companies like Impossible Foods Inc. incorporate potato protein into their formulations for plant-based meat products. Their products combine six key ingredients such as heme, potato protein, soy protein, a cellulose-based binder, sunflower oil, coconut oil, and water to achieve the desired texture and nutritional value (Ahmad et al., 2022). These developments emphasize the value of potato proteins not only in waste valorization but also in advancing sustainable food innovations.

6. Biorefinery loom from potato and its wastes

Beyond its dietary and health contributions, potato serves as a raw material for diverse industrial applications, including dehydrated and frozen food products, starch and alcohol production, and animal feed (Sepelev et al., 2015). A major by-product of processing is potato peel waste (PPW), generated during peeling in households, restaurants, and the food industry, which can account for 15-40% of the tuber mass depending on the method (steam, abrasive, lye, extruded, or unextruded peeling) (Martin et al., 2021). PPW is unsuitable for direct consumption by humans, animals, or microbes due to its toxic glycoalkaloids such as solanidine, α-solanine, and α-chaconine (Joshi et al., 2020).

Valorizing this carbon-rich residue offers both environmental and economic benefits by lowering raw material costs, reducing landfill waste, and supporting resource recovery (Fig. 4). PPW has been successfully converted into a range of bioproducts including lactic acid, bioplastics, biocomposites, and nanocrystals, highlighting its versatility as a renewable feedstock (Hijosa-Valsero et al., 2018). In bioenergy, PPW extends beyond conventional biogas and bioethanol to serve as a feedstock and catalyst in advanced biofuel synthesis and as

an adsorbent in wastewater treatment, with pyrolyzed PPW-derived activated carbon shown to remove heavy metals such as copper, cadmium, nickel, and lead from aqueous systems (Hossain et al., 2018). The global availability of potato peel, derived from over 400 million metric tonnes of potato production in 2020, presents a significant opportunity for biofuel generation and other agro-industrial applications (Arikan and Bilgen, 2019). Realizing this potential aligns with zero-waste and circular economy strategies, emphasizing the transformation of agro-waste into value-added products (Ben Atitallah et al., 2019).

6.1 Biofuel

6.1.1 Ethanol

Bioethanol remains the most widely produced biofuel from potato processing residues. PPW is particularly suitable for ethanol production due to its rich content of starch, hemicellulose, cellulose, and fermentable sugars. Multiple conversion strategies are employed, including simultaneous saccharification and fermentation (SSF), conventional hydrolysis followed by fermentation, and consolidated bioprocessing (CBP) (Ebrahimian et al., 2022) (Table 1). Using hydrolysis and fermentation, 235.4 mg/g ethanol has been reported from potato waste (Chatterjee & Mohan, 2021). In CBP, saccharification and fermentation occur in a single step using microorganisms such as *Bacillus subtilis*, offering a simplified and efficient route (Maleki et al., 2021).

Recent advances highlight the potential of integrated and nano-assisted processes to improve bioethanol yields from potato waste. For example, co-valorization with black liquor from pulp and paper mills has enhanced ethanol recovery, while Zondi et al. (2025) demonstrated a CuO nanoparticle-assisted pretreatment that simultaneously detoxified inhibitors and improved sugar recovery from starchy potato waste (SPW). This process resulted in a 1.68-fold increase in ethanol yield while achieving a 100% freshwater-free pretreatment, marking significant progress toward cost-effective and sustainable biofuel production. Such approaches support circular bioeconomy principles by maximizing waste valorization, minimizing water use, and reducing environmental burdens.

6.1.2 Methane

Biogas production through anaerobic digestion proceeds in four stages such as hydrolysis, acidogenesis, acetogenesis, and methanogenesis. The resulting biogas typically contains 65-75% methane, 35-45% carbon dioxide, and trace amounts of gases such as nitrogen, ammonia, and hydrogen sulphide. The digestate left after biogas generation is nutrient-rich, containing potash, nitrogen, and phosphate, and can serve as an effective organic fertilizer (Kreidenweis

et al., 2021). Owing to its diverse nutrient composition and high carbon content, potato waste is considered a suitable substrate for biogas production (Achinas et al., 2019).

Several studies have demonstrated the potential of potato residues, either alone or in co-digestion with other organic wastes, for enhanced methane recovery (Table 2). For instance, a methane yield of 170 mL/g TS was achieved during the anaerobic digestion of PPW. Co-digestion strategies, such as combining potato waste with cabbage waste (Mu et al., 2017), pig manure (Adeleye et al., 2022), or microalgae (Zhang et al., 2020), have further improved gas yields and process stability. Thus, the valorization of potato waste for biogas production not only provides a renewable energy source but also offers a sustainable waste management solution contributing to environmental cleanliness.

6.1.3 Butanol

Biobutanol is commonly produced through acetone-butanol-ethanol (ABE) fermentation, primarily mediated by *Clostridium* spp., which generate acetone, butanol, and ethanol in a ratio of 3:6:1. Compared to ethanol, butanol is a superior biofuel due to its low water solubility, high energy density, and low vapor pressure, making it highly compatible with existing transportation infrastructure (Pinto et al., 2021). The biobutanol production process generally involves five stages namely feedstock selection, pretreatment and detoxification, fermentation, downstream processing, and ABE product recovery (Veza et al., 2021). PPW presents a promising substrate however, its glycoalkaloid content inhibits microbial activity and hampers ABE fermentation. To overcome this, detoxification is necessary prior to fermentation. The techniques such as ultrasonic and solvent extraction are applied, while detoxification with XAD-4 resin has been shown to enhance butanol yields significantly, from 3.8 g/L to 8.0 g/L using pretreated sweet potato residues (Jin et al., 2021). Since potato starch can also be directed toward ethanol production through enzymatic hydrolysis, and anaerobic digestion of potato organic matter can yield methane for energy applications, the choice between butanol, ethanol, or biogas production depends largely on waste type, technological feasibility, and market demand.

6.2 Platform Chemicals

6.2.1 Organic acid

Potato waste is used to generate several organic acids such as lactate, acetate, formate, and ethanol. Lactic acid is an organic acid that has various applications in the food industry (flavour, food preservation, acidifier), pharmaceuticals (antifungal, antiviral, antifungal), and cosmetics (moisturizers). Recently, potato peels were brought to focus for lactic acid production by anaerobic fermentation. *Geobacillus stearothermophilus* was used for lactic acid

production from potato peel which uses 50 g/L of raw potato starch to produce 37 g/L of 98 % optically pure lactic acid (Smerilli et al., 2015). Thai and Dutch cow rumen samples were utilised to produce organic acid from potato waste. The microorganism present in the rumen converts organic waste into organic acids such as lactate, formate, acetate, and ethanol (Palakawong Na Ayudthaya et al., 2018). In a recent study, Zondi et al. (2025) demonstrated the feasibility of utilizing potato peel waste as an inexpensive and sustainable substrate for gluconic acid production. Through microbial screening and enrichment techniques, fungal isolate VDF 11, identified as *Penicillium oxalicum*, produced a maximum yield of 72.13 g/L gluconic acid. This reinforces the value of potato waste not only as a carbon source but also as a promising candidate for organic acid biorefineries, especially for applications in food, pharmaceutical, and chemical industries. The study highlights how agro-industrial byproducts can serve as cost-effective feedstocks for microbial bioconversion, supporting circular economy and waste-to-resource strategies.

Table 1. Applications of potato wastes in different sectors

Potato wastes	**Strategies**	**Microorganisms**	**Results**	**References**
Biogas production				
Potato peel	Anaerobic digestion	Effluent of mesophilic anaerobic digestion from wastewater treatment plant	239 L/kg VS_{fed} CH_4	Liang & McDonald, 2015
Potato peel	Anaerobic digestion	From a mesophilic operating anaerobic bioreactor from the wastewater treatment plant	217.80 mL CH_4/g VS	Achinas et al., 2019
Potato processing waste	Anaerobic digestion	*Chlorella vulgaris* + Glycerol + Potato Peel	62-74% enhanced CH_4	Zhang et al., 2020
		Chlorella vulgaris + Glycerol + Potato discarded waste	53-128% enhanced CH_4	
Potato waste	Semi-continuous co-digestion of potato and	Anaerobic granular sludge from carbohydrate wastewater treatment plant	360 mL/g VS CH_4	Mu et al., 2017

	cabbage waste (1:1) ratio			
Potato peel	Anaerobic digestion	From mesophilic operating anaerobic bioreactor from the wastewater treatment plant	57.90 L/ kg of dry PPW CH_4	Soltaninejad et al., 2022
Ethanol production				
Potato peel	Saccharification	*Wickerhamomyces anomalus*	0.49 $g/g_{consumed\ sugars}$	Ben Atitallah et al., 2019
Potato peel	Plackett-Burman design and Response Surface Modelling	*Wickerhamia* sp	21.70 g/L	Hossain et al., 2018
Potato mash	Statistical optimization using CCD	*Aspergillus niger* and *S. cerevisiae* co-culture	35.19 g/L	Izmirlioglu & Demirci, 2016
Potato peel	Solid state fermentation	*A. niger* and *S. cerevisiae* co-culture	6.18 % (v/v)	Chintagunta et al., 2016
Potato mash	Solid state fermentation	*A. niger* and *S. cerevisiae* co-culture	9.30 % (v/v)	Chintagunta et al., 2016
Potato peel	Saccharification and fermentation	*S. cerevisiae* BY4743	22.54 g/L	Chohan et al., 2020
Potato peel	Enzymatic hydrolysis	*Saccharomyces cerevisae var. bayanus*	7.60 g/L	Arapoglou et al., 2010
Potato peel	Enzymatic hydrolysis	*Aspergillus niger* and *Trichoderma reesei*	30 g/L	Ben Taher et al., 2017
Butanol production				

Potato peel	Autohydrolysis and enzymatic hydrolysis	*C. saccharoperbutylacetonicum* DSM 2152	8.10 g/L	Hijosa-Valsero et al., 2018
Potato peel	Fermentation	*Clostridium beijerinckii* ASU10	10.98 g/L	Abd-Alla et al., 2017
		C. chauvoei ASU12	5.50 g/L	
Potato peel waste	Fermentation	*Clostridium acetobutylicum* MTCC 11274	0.35 g/g	Kamboj & Ms, 2021
Organic acids production				
Potato peel	Anaerobic fermentation	Undefined mixed culture from a municipal wastewater treatment plant	Lactic acid yield 0.25 g/g	Liang et al., 2015
Potato peel	Fermentation	Mixed cultures from wastewater treatment plant sludge	Lactic acid 0.22 g/g, acetic acid 0.06 g/g, and ethanol 0.05 g/g	Liang et al., 2014
Potato starch	Direct fermentation	*Geobacillus stearothermophilus*	Lactic acid 37 g/L	Smerilli et al., 2015
Potato peel	CCD based RSM	Methanogenic granular sludge	Acetic acid 513.70 mg/g COD and butyric acid 491.90 mg/g COD	Ribeiro & Silva 2022
Solid potato waste	Sludge from the wastewater treatment plant	Anaerobic digestion	Acetic acid 420, butyric acid 310, propionic acid 140, and caproic acid 90 mg/g total VFAs	Zondi et al., 2025

6.2.2 Alternative sweeteners

Overconsumption of sugar leads to various health problems such as cardiovascular disease, diabetes, and weight gain. Therefore, different alternatives are used to overcome the sugar side

effects such as aspartame, sucralose, and stevia. Potato is a good source of monosaccharides including glucose (3.25 to 255 mg/100 g fresh weight (FW), fructose (2.5 to 153.7 mg/100 g FW), and disaccharides including sucrose (43 to 159.7 mg/100 g FW), which can be extracted and used as a sweetening agent. Potato is also a good source of starch (16.5 to 20.0 g/100 g FW) (Burgos et al., 2020), resulting in sugar formation during breakdown. This sugar can be used as an artificial sweetener. However, potato is not used for sweetener production, as they contain low starch content as compared to other crops, such as sugarcane, sweet potato, and corn, thus, producing a low amount of sugar. Creating a commercially viable sweetener from potatoes would require refining and processing techniques to extract and purify these sugars efficiently (Fig. 5(a-j)).

6.2.3 Polymer/Plastic precursors

Potatoes, being a rich source of starch, provide a sustainable feedstock for the development of biodegradable films and polymer precursors within a biorefinery framework. Starch-based biofilms derived from potato peel have shown promising functional properties, including reduced water solubility, lower swelling capacity, and decreased vapor permeability. Films produced from low-starch potato peel demonstrated stability at high temperatures, high transparency, accelerated soil biodegradation, and favorable mechanical properties, highlighting their suitability for packaging and coating applications (Charles et al., 2022). Similarly, potato processing residues can serve as substrates for the microbial production of poly-β-hydroxybutyrate (PHB), a biodegradable polymer synthesized by *Alcaligenes eutrophus* following enzymatic hydrolysis.

Blends of potato peel powder with sweet lime pomace have also been explored to enhance biofilm characteristics. Films prepared under optimized ultrasound conditions exhibited improved moisture absorption, tensile strength, and water vapor permeability, confirming the potential of potato biomass valorization for bioplastic development (Borah & Badwaik, 2017). In addition, starch nanoparticles (SNPs) derived from potato starch have been incorporated into nanocomposite starch films, resulting in significantly reduced water vapor transmission rates and enhanced biodegradability compared to conventional starch films (Gujral et al., 2021). Beyond laboratory studies, potato waste has also been utilized in pilot-scale innovations. For example, compostable cling films have been commercialized using potato peel starch in combination with other plant-derived components, offering a practical alternative to petroleum-based plastics (Finney, 2022). Furthermore, precision fermentation initiatives are exploring potato waste as a substrate for biopolymer production, contributing to circular

economy strategies by converting residual starch into valuable polymeric intermediates (Nielsen, 2023).

6.2.4 Bio-solvents and Nanomaterials

Potato waste can serve as a feedstock for the production of various bio-solvents such as ethanol, methanol, butanol, biofuels, and organic acids, as summarized in Table 2. For instance, Changchun Daheng Industrial Group utilizes starch in integrated biological and thermochemical processes to produce ethylene glycol, propylene glycol, and 2,3-butanediol, with an annual output of approximately 10,000 tons of 2,3-butanediol (Oklu et al., 2020).

In addition, potato- and potato-waste-derived nanoparticles are being explored for diverse applications in food, medicine, and material science (Table 2). Silver nanoparticles synthesized from potato peel exhibit antimicrobial activity, suggesting potential use in food preservation and industrial wastewater treatment (Sharma et al., 2023). Similarly, zinc oxide nanoparticles have been prepared using potato extract and zinc nitrate (Buazar et al., 2016), while gold nanoparticles ranging from 17.5 to 23.5 nm have been obtained using potato extract in aqueous systems (Castillo-López & Pal, 2014). Copper-based nanoparticles (Tyr-Cu (II)-AEEA NPs), synthesized from copper (II)-tyrosinase isolated from potato peel powder, demonstrated cytotoxic activity, indicating possible applications in cancer therapy (Idhayadhulla et al., 2021). Furthermore, hollow selenium nanoparticles (hSeNPs, ~115 nm) derived from potato starch have shown antimicrobial properties. Magnetic nanoparticles (MNPs) have also been synthesized from potato extract and were effectively applied for the degradation of Rhodamine B dye (Sharma et al., 2019). Furthermore, potato alkaloids have been used to produce silver nanoparticles (AgNPs) with diameters ranging between 39.5 and 80.3 nm, which demonstrated antifungal activity against phytopathogenic fungi (Almadiy & Nenaah, 2018). Overall, the production of bio-solvents and nanomaterials from potato waste underscores its potential not only as a low-cost resource for industrial and biomedical applications but also as a key contributor to circular bioeconomy strategies that emphasize value addition and waste minimization.

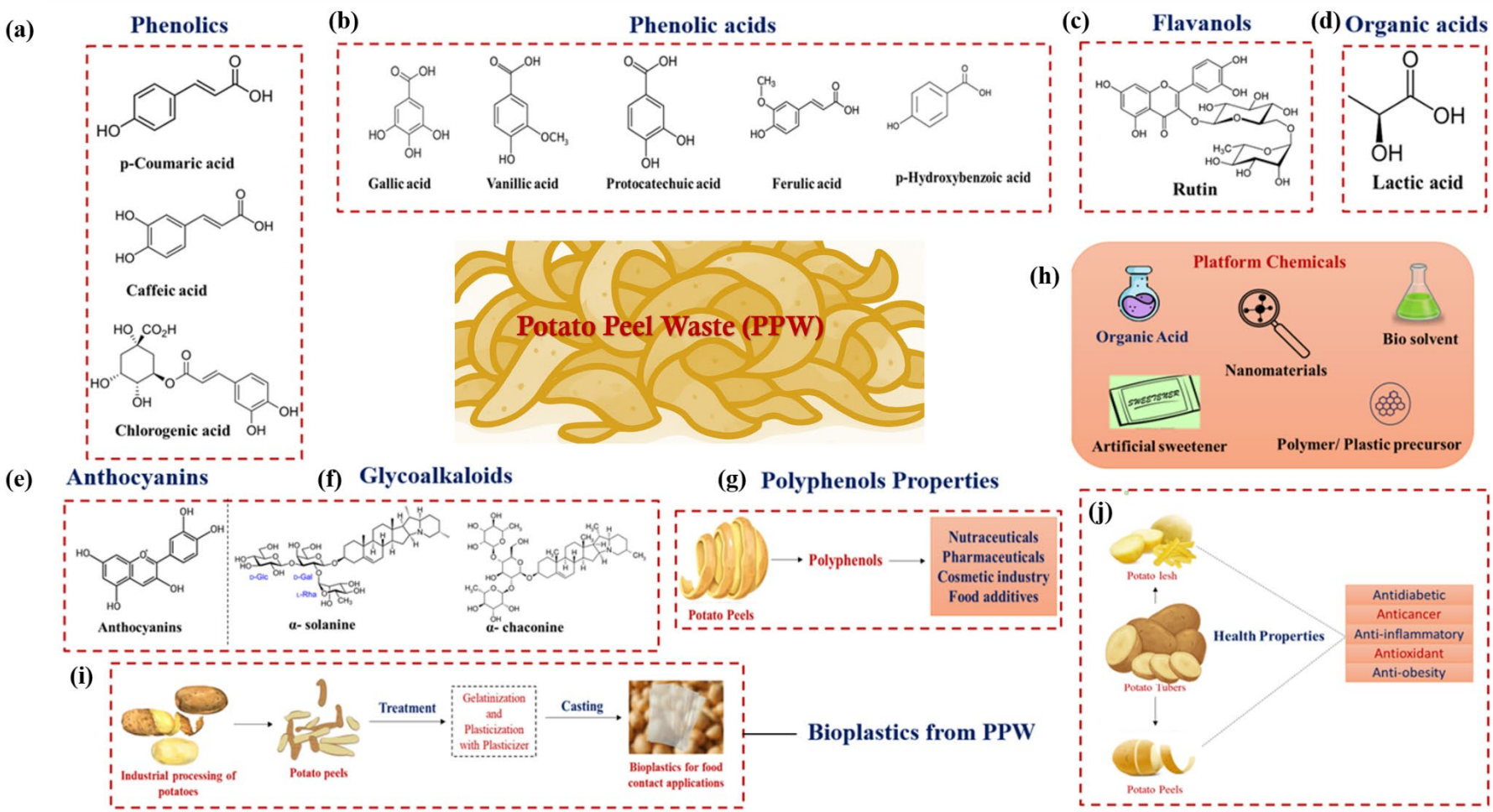

Fig. 5. Potato peel waste (PPW) as a source of bioactive compounds and biopolymers: (a–f) phenolics, phenolic acids, flavanols, organic acids, anthocyanins, and glycoalkaloids; (g) polyphenol applications; (h) platform chemicals; (i) bioplastics production; and (j) health-promoting properties

Table 2. Different kinds of nanoparticles produced from potatoes and their waste

Potato source	Nanoparticles	Size (nm)	Applications	References
Potato peel	Silver	20-60	Antibacterial activity against *E. coli* and *Staphylococcus aureus*; wastewater treatment	Sharma et al., 2023
Potato peel powder	Copper	Average size 110	Anticancer activity	Idhayadhulla et al., 2021
Potato extract	Magnetic	20-30	Use in degradation of rhodamine B dye	Sharma et al., 2019
Potato alkaloids	Silver	39.50-80.30	Antifungal activity against phytopathogenic fungi	Almadiy & Nenaah, 2018
Potato extract	Zinc oxide	20 ± 1.20	NR	Buazar et al., 2016
Potato extract	Gold	17.50-23.5	NR	Castillo-López & Pal, 2014

NR= Not reported.

6.3 Agricultural chemicals and inputs

Bio-clean is a sustainable project that uses the waste residue of potato starch and cow manure for the production of biofertilizers and biogas. It can produce more energy by including yeast and potato waste in a bioreactor through the process of yeast fermentation that turns sugar-derived potato waste into methanol. Additionally, as it contains microelements that plants require, such as potassium or phosphate, the waste recovered from the bioreactor after energy production can be used as a high-quality biofertilizer. The solid residue left over after ethanol production still contains certain nutrients, being further enhanced and can be used to make biomanure which is an effective method of reducing the quantity of solid waste that builds up in the environment. The enriched residue is an essential organic manure that contains all the necessary nutrients for plant growth as well as humus to build the structure of the soil. The addition of chemical fertilizers to the soil results in a nitrogen shortfall that leads to the degradation of soil and other environmental problems. The study reported by Chintangunta et al. (2016) utilized blue-green algae to enrich the potato waste that can fix nitrogen, a necessary component for plant growth. The hormones like gibberellin and auxin are excreted by algae that are involved in encouraging plant growth. In addition to being a more affordable method

of enriching the soil, the use of biomanure is a better way to address environmental issues caused by the usage of chemical fertilizers. The peel and water of potatoes can act as natural plant fertilizers (Chauhan et al., 2023). However, the potato water, which is the water left over after boiling potatoes, contains valuable nutrients such as phosphorus, potassium, and nitrogen. The potassium content in potato water is necessary for plant growth and helps to promote the development of strong root and disease resistance, while phosphorus is necessary for seed formation, root development, and photosynthesis (Savacool, 2023). Potato peels are a good source of nutrients are high in organic matter and help in the improvement of soil structure and fertility making it easier for plants to take up water and nutrients. Potato peel has been successfully employed in the manufacturing of biofertilizers as it is rich in starch and proteins that produce fertilizers with a high nitrogen content after degradation by soil microorganisms. The bacterial count in vermicompost made from potato peel earthworms (*Pheretima elongata*) was higher than in the surrounding soil. Therefore, the slurry obtained from the potato peel biogas plant (anaerobic digester) is a suitable biofertilizer for land application and these substitute nutrients in the soil could improve an overall rise in vegetative growth (Tijjani et al., 2021). Comparable valorization strategies have also been explored for sweet potato processing residues, which like potato peel are rich in starch, polyphenols, and essential micronutrients. Sweet potato bagasse, generated during starch extraction, contains valuable bioactives and fibers, and has been successfully utilized for the development of biofertilizers, feed, and biostimulants through biorefinery approaches (Chakraborty et al., 2024). These insights reinforce the versatility of root and tuber crop waste as sustainable agricultural inputs, opening pathways for broader cross-crop innovations in soil fertility and plant health management.

7. Potato wastes valorization and circular economy

The intensification of food production has led to increased waste generation, prompting circular economy models to prioritize waste recovery and minimization. Potato processing waste, especially peels, has gained renewed interest as a valuable bioresource, due to its richness in hydroxycinnamate polyphenols, including chlorogenic acid, with promising applications in food, pharmaceutical, and biorefinery sectors (Makris, 2025). In the broader context of sustainable development, utilizing renewable resources and embracing circular economy principles are paramount (Lizundia et al., 2022). Integrating waste utilization into circular and bio-based economies represents a shift towards resource-efficient and sustainable production and consumption. By converting organic waste, agricultural biomass, and forest residues into valuable biomaterials and biochemicals, circular economy principles promote resource reutilization and waste reduction (Cristóbal et al., 2018).

The circular economy emphasizes closed-loop networks and biorefining processes, offering pathways toward sustainable economic growth (Teigiserova et al., 2020). By substituting primary resources with secondary ones, these systems enhance market competitiveness while minimizing environmental impacts. Moreover, resource reutilization, waste reduction, and renewable energy production stimulate the development of new technologies, economies of scale, job creation, and rural development.

Practically, transforming potato waste into high-value bioproducts through biological and thermochemical techniques holds immense promise (Ebrahimian et al., 2022). A comprehensive potato waste biorefinery could involve the extraction of inhibitory compounds, biological conversion into biofuels, biopolymers, or biochemicals, and thermochemical conversion into bio-char, bio-oil, or biosorbents. This multi-step valorization approach maximizes value recovery from potato waste while minimizing environmental impact. The conceptualized closed-loop approach for harmonizing the circular economy scheme in potato waste biorefinery is depicted in Fig. 6 (a-c). This scheme enhances the value of potato waste, generates multiple high-value products, and substantially reduces waste creation (Priyadarshini et al., 2020). Valorizing potato waste within the circular economy framework not only addresses environmental concerns but also unlocks economic opportunities and promotes sustainable development.

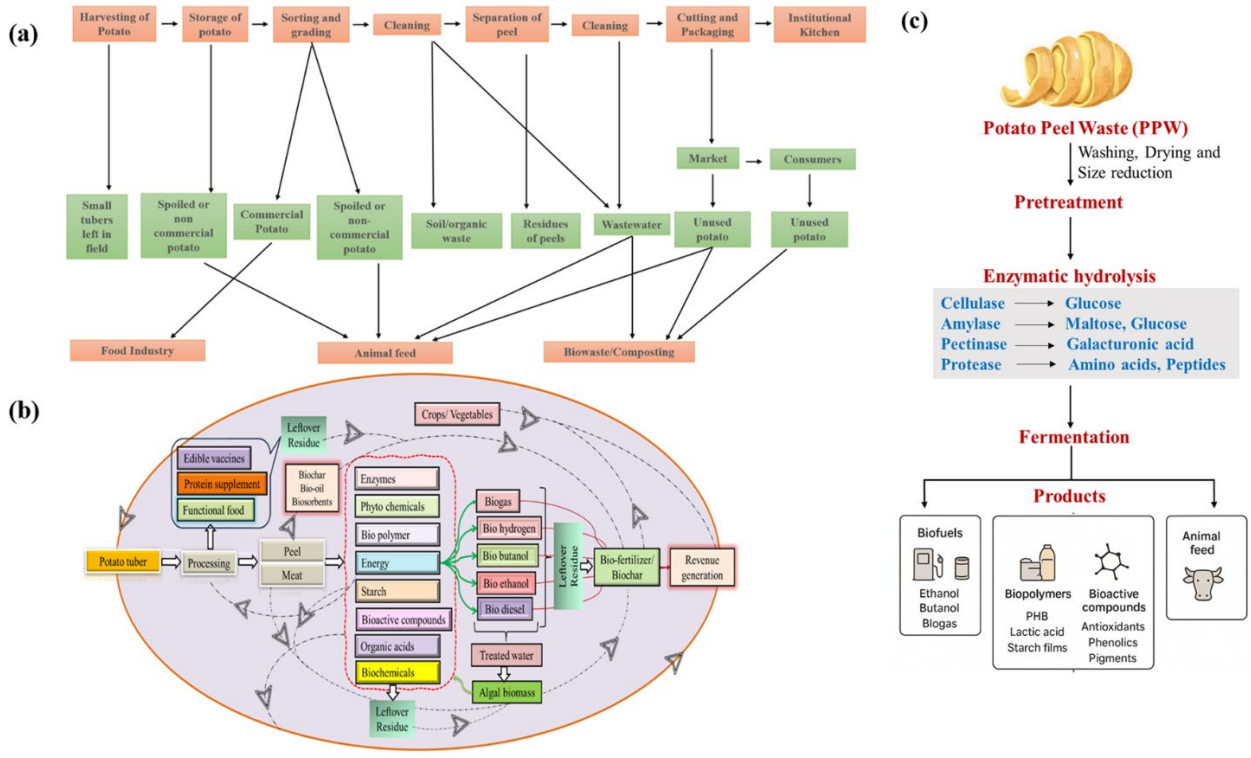

Fig. 6 (a) An overall process flow of potatoes from Farm to Fork with an emphasis on waste generation; (b) Conceptualize valorization approaches of potato waste adopting circular economy model; (c) Valorization of potato peel waste through enzymatic hydrolysis and fermentation for the production of biofuels, biopolymers, bioactive compounds, and animal feed

8. Potato Waste Valorization and the Sustainable Development Goals (SDGs)

The SDGs constitute a global framework introduced by the United Nations General Assembly under the 2030 Agenda for Sustainable Development. Encompassing 17 goals, the SDGs are anchored in the principle of "leaving no one behind" and aim to improve societal well-being while ensuring environmental protection and economic resilience across both developed and developing nations. National and regional governments, industries, and research communities are increasingly aligning policies and practices with these goals, making them a universal action plan for advancing "people, planet, and prosperity" by 2030 (Kundu et al., 2022). Within this framework, waste valorization has emerged as a critical pathway, not only offering resource efficiency but also addressing pressing challenges of food security, climate change, and environmental degradation. By promoting circular economy practices rooted in the principles of reduce, reuse, and recycle, valorization approaches create measurable impacts on SDG progress while offering scalable and context-specific solutions (Bharathi et al., 2022). Although climate change impacts are already evident, effective integration of valorization within sustainable production systems can mitigate their severity, though adaptation capacities may vary across regions (Venkatesh, 2023).

Potato waste valorization exemplifies how biorefinery concepts can be operationalized within the SDG framework, contributing simultaneously to multiple targets through diverse product streams. The conversion of potato residues into value-added outputs such as nutraceuticals, biofuels, functional proteins, and biogas establishes direct linkages to SDG2 (Zero Hunger) through enhanced food and nutrition options, SDG7 (Affordable and Clean Energy) via renewable energy generation, and SDG12 (Responsible consumption and production) by reducing waste burdens. Furthermore, integrating potato waste valorization into industrial symbiosis strengthens SDG8 (Decent work and economic growth) and SDG9 (Industry, innovation, and infrastructure), while co-benefits extend to environmental goals such as SDG13 (Climate action), SDG14 (Life below water), and SDG15 (Life on land). At the urban level, valorization supports SDG6 (Clean water and sanitation) and SDG11 (Sustainable cities and communities) by reducing landfill loads and mitigating water contamination risks (Fig. 7). Taken together, potato waste valorization offers a holistic model that integrates biorefinery

principles with circular economy strategies to advance SDGs in a synergistic and system-wide manner.

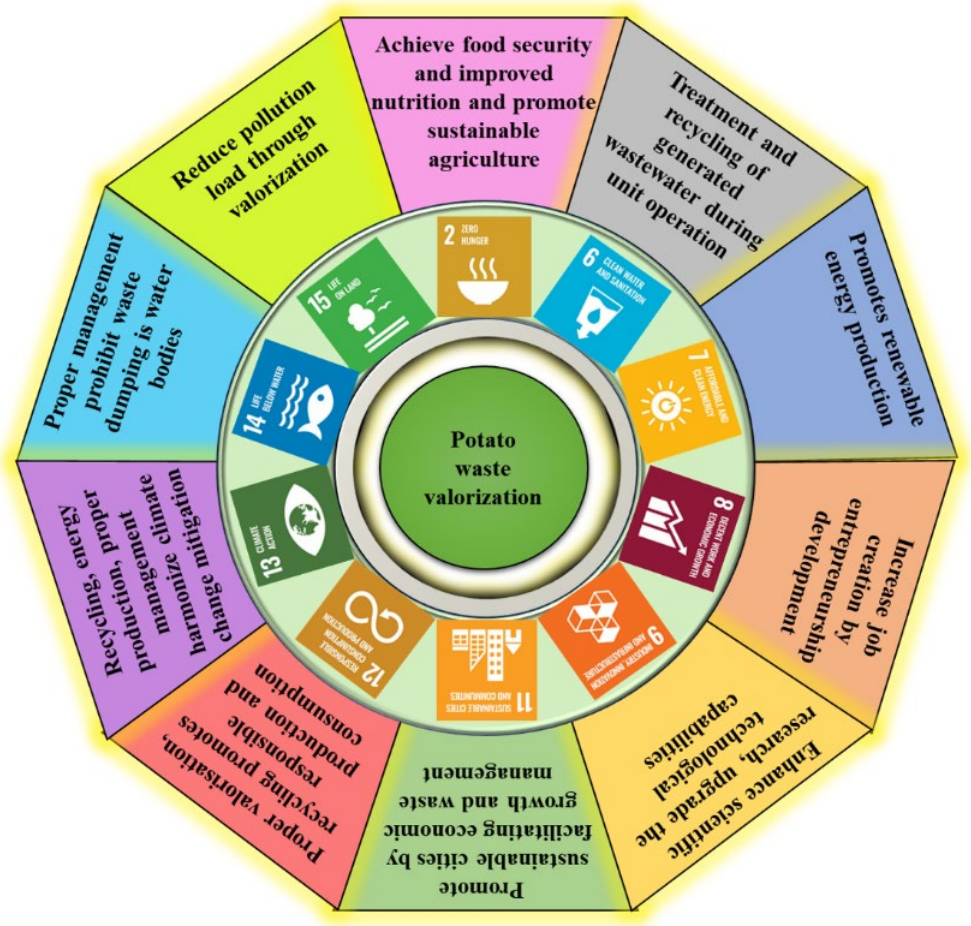

Fig. 7 SDGs alignment with potato waste valorization approaches

Potato waste valorization directly advances several UN SDGs by integrating circular economy principles into food, energy, and environmental systems. For instance, the reuse of potato residues supports SDG2 by enhancing smallholder incomes and resilient farming practices (Targets 2.3 and 2.4), while efficient treatment and recycling of wastewater from potato industries contribute to SDG6 by improving water quality, reducing pollution, and expanding safe reuse (Target 6.3) (Sarker et al., 2024; Kundu et al., 2022). Converting potato waste into bioenergy through biorefinery approaches strengthens SDG7 by promoting universal access to affordable and sustainable energy, while industrial symbiosis fosters inclusive growth under SDG8 through job creation, entrepreneurship, and innovation (Targets 8.3 and 8.5). Moreover, valorization initiatives enhance technological capacity and domestic innovation (Targets 9.3, 9.5, and 9.b), embedding waste valorization into industrial infrastructure development and national research agendas (Leong et al., 2021; Rehan et al., 2023).

At the community and regional level, valorization projects reinforce SDG11 by promoting sustainable cities, peri-urban, and rural linkages, reducing per capita environmental burdens (Targets 11.1 and 11.6) while securing livelihoods and services. They also enable responsible consumption and production (SDG12), particularly through efficient resource use (Target 12.2), reducing food losses across the supply chain (Target 12.3), and minimizing waste generation via recycling and reuse (Target 12.5) (Tsegaye et al., 2021; Sarker et al., 2024). These actions simultaneously strengthen climate mitigation efforts under SDG13, discourage marine and land pollution under SDG14, and promote terrestrial ecosystem conservation under SDG15 (Rehan et al., 2023; Nguyen et al., 2022). Collectively, potato waste valorization exemplifies a systems-level approach where biorefinery innovations generate interconnected social, economic, and ecological benefits, demonstrating how localized circular practices can accelerate progress toward global SDG commitments.

9. Conclusion and Future Prospects

Potato cultivation and processing generate considerable amounts of wastes such as peels, pulp, mash, and downgraded tubers, which, if left untreated, create serious environmental and economic challenges. This review emphasizes that these residues, rich in starch, proteins, fibers, and bioactive compounds, can be effectively valorized into diverse products including biofuels, bioplastics, nutraceuticals, and biomaterials. Such strategies not only mitigate waste disposal issues but also strengthen circular bioeconomy frameworks and contribute to the SDGs by promoting responsible resource utilization and sustainable production pathways.

Significant research gaps remain, particularly in the areas of standardized pretreatment methods, cost-effective downstream recovery, and comprehensive techno-economic and life-cycle assessments. Addressing these gaps is essential to ensure scalability and industrial adoption. Maximizing this potential requires greater efforts to integrate waste valorization into potato processing industries as parallel production streams. Standardized methods for pretreatment, microbial fermentation, and product recovery, supported by techno-economic and life-cycle analyses, would be critical for industrial scalability. Looking forward, advances in synthetic biology, metabolic engineering, and nanotechnology are expected to unlock new opportunities and improve process efficiency. Interdisciplinary collaborations, coupled with supportive policies and pilot-scale demonstrations, would play a decisive role in translating research into practice. Ultimately, valorizing potato waste provides an avenue to reduce environmental burdens while simultaneously fostering economic growth and sustainable development.

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