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Integrated Zero-Waste Biorefinery of Milk Whey and Fruit-Processing Residues: Pathways for Bioenergy, Biofuels, Biofertilizers and Circular Resource Recovery

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ABSTRACT

The increasing generation of dairy and fruit-processing residues has created both an environmental challenge and an opportunity for sustainable resource recovery. Among these residues, milk whey and fruit-processing wastes are particularly attractive because of their high content of biodegradable organic matter, carbohydrates, nutrients, and other potentially recoverable compounds. This review critically examines an integrated biorefinery approach for converting these heterogeneous food-processing residues into biofuels, renewable energy, stabilized organic materials, and biofertilizers within a circular bioeconomy framework. The valorization potential of whey through anaerobic digestion and lactose-based fermentation for biogas and bioethanol production is discussed, with emphasis on substrate characteristics, microbial conversion, process stability, and major operational constraints. Fruit-processing residues are evaluated as feedstocks for biological conversion, aerobic stabilization, nutrient recovery, and production of organic fertilizer or soil amendments. Particular attention is given to cascading resource recovery, in which different fractions and residual streams are directed toward the most appropriate conversion pathway rather than relying on a single-product process. The review further considers feedstock collection, digital traceability, process integration, residual-stream management, product safety, and the challenges associated with scale-up. Environmental sustainability, techno-economic feasibility, carbon and energy balances, and life-cycle assessment are identified as essential criteria for evaluating the practical potential of integrated whey–fruit biorefineries. Overall, the integration of dairy and fruit-processing residues provides a promising pathway for shifting food-processing waste management from disposal toward resource recovery, renewable energy generation, nutrient recycling, and circular bioeconomy development, although pilot-scale validation and system-level sustainability assessment remain necessary.

Keywords: *Milk whey; Fruit-processing residues; Integrated biorefinery; Food-waste valorization; Biofuels; Biogas; Bioethanol; Biofertilizer; Nutrient recovery; Circular bioeconomy.*

1. Introduction

The increasing demand for dairy products, fruit-based beverages, and processed foods has generated substantial quantities of agro-industrial residues. Rather than being treated solely as waste, these materials are increasingly recognized as renewable feedstocks because they contain carbohydrates, proteins, lipids, minerals, fibers, and other recoverable compounds that can support the production of bioenergy, biofuels, chemicals, biomaterials, and other value-added products within a circular bioeconomy [1]. Among dairy residues, whey is particularly important due to its high content of soluble organic matter, predominantly lactose, together with proteins and minerals. Its high biochemical and chemical oxygen demand makes uncontrolled disposal environmentally problematic, while its readily biodegradable constituents make it suitable for biological valorization through anaerobic digestion, fermentation, and recovery of lactose and proteins [2,3].

Fruit-processing residues, including peels, pulp, seeds, pomace, cores, and fibrous fractions, represent another important source of renewable biomass. Although their composition varies with fruit type and processing conditions, these residues commonly contain fermentable carbohydrates, structural polysaccharides, dietary fibers, phenolic compounds, pigments, minerals, and other bioactive constituents [4].

Consequently, fruit residues have been explored for the production of biogas and bioethanol as well as the recovery of pectin, essential oils, polyphenols, pigments, and other value-added compounds [5]. This compositional diversity makes them suitable for integrated processing rather than conversion into a single product.

The biorefinery concept provides a framework for utilizing these diverse components through interconnected physical, chemical, and biological processes, thereby improving resource recovery and reducing dependence on conventional linear waste-management systems [6]. In this context, the combined consideration of whey and fruit-processing residues is particularly attractive because whey supplies readily biodegradable soluble organic matter, whereas fruit residues provide carbohydrates, structural biomass, and potentially valuable bioactive compounds. Their individual or combined utilization could therefore support complementary pathways for biofuel production, nutrient recovery, and biological stabilization. From a circular-economy perspective, this approach represents a transition from a "waste-treatment" to a "waste-to-resource" paradigm, in which organic residues are converted into useful energy and material products while minimizing residual waste.

However, the development of a zero-waste biorefinery is influenced by several factors, including feedstock variability, seasonal availability, collection and transportation, pretreatment requirements, process inhibition, downstream processing, economic feasibility, and environmental performance [5,7]. Therefore, an integrated whey–fruit residue biorefinery offers a promising framework for converting complementary food-processing residues into biofuels and biofertilizers while recovering carbon and nutrients. This review focuses on the biological conversion routes, integration strategies, and technical, economic, and environmental considerations associated with developing such a resource-efficient and circular biorefinery.

2. Milk Whey as a Feedstock for Bioenergy

Milk whey is the major liquid by-product generated during the manufacture of cheese, paneer, and other casein-based dairy products. It contains lactose as the principal carbohydrate, along with proteins, minerals, lipids, and other soluble constituents. The high concentration of readily biodegradable organic matter, particularly lactose, makes whey a promising substrate for microbial conversion and bioenergy recovery [8]. However, the same organic richness responsible for its valorization potential also creates an environmental concern. Whey and whey-rich effluents can exhibit high biological oxygen demand (BOD) and chemical oxygen demand (COD), and their uncontrolled discharge may increase oxygen consumption in receiving water bodies and adversely affect aquatic environments [9].

The biodegradability of whey provides an opportunity to convert this organic load into useful energy rather than treating it solely as a wastewater problem. Anaerobic digestion (AD) is particularly attractive because it enables simultaneous reduction of organic matter and production of methane-rich biogas. Studies on whey permeate have demonstrated the potential of AD as a resource-recovery strategy, although process performance depends on substrate characteristics, organic loading, microbial activity, and operating conditions [10].

Beyond methane production, microbial conversion of whey lactose has also been investigated for the generation of products such as ethanol, demonstrating the broader potential of whey as a fermentation feedstock [11].

Thus, whey can serve as more than a high-strength dairy effluent; it represents a carbon-rich renewable feedstock for integrated bioenergy production. Its conversion through anaerobic digestion and other fermentation pathways can simultaneously address waste-management concerns, recover energy, and generate residual streams that may be further considered for nutrient recovery and biofertilizer production within an integrated biorefinery system.

2.1 Anaerobic Digestion and Bioenergy Valorization of Whey

Anaerobic digestion (AD) is a multistage microbial process in which organic substrates are sequentially converted through hydrolysis, acidogenesis, acetogenesis, and methanogenesis, ultimately producing methane and carbon dioxide. For lactose-rich whey, the high biodegradability of the substrate can promote rapid acid formation during the initial stages of digestion. When volatile fatty acid (VFA) production exceeds its subsequent conversion, VFA accumulation can reduce reactor pH and inhibit methanogenic microorganisms, thereby affecting process stability and methane production [12]. Thus, the rapid biodegradability of whey is both an advantage for bioenergy recovery and a potential limitation when the organic loading exceeds the capacity of the microbial community.

Efficient digestion of whey consequently depends on maintaining an appropriate balance between acid-producing and methane-producing microbial populations. pH, temperature, organic loading rate, hydraulic retention time, alkalinity, mixing, and substrate characteristics are among the major factors influencing reactor stability and methane yield [13]. In particular, adequate buffering capacity and controlled organic loading are important for preventing excessive VFA accumulation and maintaining conditions favorable for methanogens [14]. Depending on feedstock characteristics, staged digestion and co-digestion with complementary substrates may further improve process stability and substrate utilization.

2.2 Whey as a Platform for Multiple Bioenergy Products

The valorization potential of whey extends beyond methane production. Its lactose-rich composition provides a suitable substrate for different microbial conversion pathways, and whey-derived substrates have been investigated for the production of ethanol, organic acids, microbial biomass, hydrogen, and methane, among other products [15]. Earlier studies demonstrated that whey lactose could be biologically converted into methane, ethanol, and yeast biomass while simultaneously reducing the organic pollution load [16]. These findings support a broader dairy-biorefineries concept in which whey is fractionated or converted through different biological routes according to the desired product and process conditions.

2.3 Process Challenges and Research Requirements

Despite its considerable bioenergy potential, direct conversion of whey presents several technical challenges. Variations in composition, organic loading, rapid lactose degradation, VFA accumulation, and microbial inhibition can influence reactor performance, making process conditions difficult to generalize across different whey streams.

Recent research has therefore emphasized the need for improved optimization and standardization of whey-digestion systems, particularly with respect to operating conditions and process stability [17]. Co-digestion with complementary substrates offers another potential strategy by improving substrate balance and buffering capacity; however, the appropriate mixing ratio, carbon-to-nitrogen balance, organic loading, VFA dynamics, and digestate characteristics require feedstock-specific evaluation [18].

Overall, whey represents a highly biodegradable feedstock with considerable potential for renewable-energy recovery. Anaerobic digestion can simultaneously reduce the organic burden of dairy residues and generate methane-rich biogas, while alternative fermentation routes expand the range of possible products. Future development should therefore move beyond maximizing methane yield alone and focus on integrated feedstock management, process stability, energy recovery, digestate utilization, and techno-economic and environmental performance. Such integration is particularly relevant to the zero-waste biorefinery concept, where whey-derived energy and nutrient-rich digestate can contribute to both biofuel and biofertilizer production.

3. Anaerobic Digestion of Whey for Biogas Production

Anaerobic digestion (AD) is an established biological process in which biodegradable organic matter is converted into biogas in the absence of oxygen. Because whey contains a high proportion of readily biodegradable organic matter, particularly lactose, its anaerobic treatment can simultaneously reduce the organic pollution load and recover chemical energy as methane-rich biogas [19]. AD involves four interconnected stages — hydrolysis, acidogenesis, acetogenesis, and methanogenesis — that are mediated by different microbial groups [20]. In whey, much of the organic matter is already present in soluble form; therefore, extensive hydrolysis is less limiting than in structurally complex lignocellulosic substrates. During acidogenesis, rapid conversion of lactose can generate volatile fatty acids (VFAs), which are subsequently converted into acetate, hydrogen, and carbon dioxide during acetogenesis. These intermediates are finally utilized by methanogenic archaea to produce methane. Maintaining a balance among these microbial stages is essential because excessive acid production relative to methane formation can result in VFA accumulation, pH reduction, and inhibition of methanogenic activity [21].

The performance of whey digestion depends on the interaction of several operational parameters, including pH, temperature, organic loading rate (OLR), hydraulic retention time (HRT), total solids, substrate-to-inoculum ratio, nutrient availability, mixing, and VFA accumulation [22]. Mesophilic operation, generally within approximately 30–40°C, is widely used for anaerobic digestion, with temperatures around 35–37°C providing a practical operating range for many systems; however, the optimum depends on the substrate, inoculum, reactor configuration, and operating conditions [23]. Maintaining a suitable pH is particularly important because methanogens are sensitive to acidic conditions. A working range around 6.5–7.5 may be considered a practical target for stable operation, but this should be optimized for the specific microbial community and feedstock. Monitoring pH together with VFAs can therefore provide an early indication of process imbalance.

The high biodegradability of whey creates an important trade-off in reactor operation. While rapid substrate conversion can enhance biogas production, excessive organic loading may accelerate acidogenesis beyond the capacity of methanogens to consume the resulting intermediates. Substrate management, including controlled feeding or dilution, can therefore be used to moderate organic loading and reduce the risk of acidification [24]. However, dilution should be optimized carefully because excessive water addition increases reactor volume and resource requirements. Similarly, the use of co-substrates may improve substrate balance and process stability, but the appropriate mixing ratio, nutrient balance, OLR, and VFA dynamics must be established experimentally for each feedstock combination. The resulting biogas consists predominantly of methane and carbon dioxide, together with smaller quantities of hydrogen sulfide, water vapor, and other trace gases [25]. Methane provides the principal energy value of biogas, whereas carbon dioxide and contaminants such as hydrogen sulfide and moisture may need to be removed depending on the intended application. Moisture removal and hydrogen sulfide control are particularly important for protecting downstream equipment, while further carbon dioxide removal can produce biomethane with a higher methane concentration [26]. Thus, the energy value of whey is determined not only by methane generation but also by the efficiency of gas recovery, cleaning, and utilization.

Although AD provides a promising route for whey valorization, successful implementation requires feedstock-specific optimization rather than reliance on a single universal operating condition. Current research emphasizes the importance of optimizing temperature, pH, loading rate, retention time, reactor configuration, and co-digestion strategies to improve methane recovery and process stability [27]. Future studies should therefore report standardized parameters such as whey composition, inoculum characteristics, OLR, pH, temperature, HRT, methane yield and concentration, VFA levels, COD removal, and digestate characteristics. Such an approach would improve comparison among studies and support the development of reliable whey-based anaerobic-digestion systems. Overall, AD provides an effective pathway for transforming whey from an organic waste stream into a renewable energy resource, while the resulting digestate offers an additional opportunity for nutrient recovery and biofertilizer production within an integrated zero-waste biorefinery.

4. Bioethanol Production from Whey

In addition to methane production through anaerobic digestion, the lactose-rich composition of milk whey makes it a promising substrate for microbial bioethanol production. Lactose is the principal fermentable carbohydrate in whey; however, conventional *Saccharomyces cerevisiae* is generally unable to efficiently ferment lactose. Consequently, whey-to-ethanol research has focused on lactose-utilizing yeasts, particularly *Kluyveromyces marxianus* and other *Kluyveromyces* species [28]. In *K. marxianus*, lactose is hydrolyzed into glucose and galactose through β-galactosidase activity and subsequently metabolized through fermentative pathways to produce ethanol and CO_2. Therefore, the selection of an appropriate microorganism is a major determinant of whey fermentation efficiency [29].

Experimental studies have demonstrated ethanol production from both crude whey and whey permeate using *K. marxianus*. Zafar and Owais reported that *K. marxianus* MTCC 1288 utilized most of the lactose in crude whey within 22 h and produced approximately 2.10 g L^{-1} ethanol under their experimental conditions [30].

In contrast, fermentation of ricotta cheese whey containing approximately 44 g L^{-1} lactose has produced ethanol concentrations of about 22 g L^{-1}, corresponding to up to 95% of the theoretical yield within 15 h [31]. The considerable variation between these results highlights the influence of substrate composition, microbial strain, fermentation mode, and operating conditions on ethanol productivity.

Microorganism selection, substrate concentration, fermentation time, temperature, and pH are therefore important determinants of whey-to-ethanol conversion. *K. marxianus* has received particular attention because of its lactose utilization capability, relatively rapid growth, and thermotolerance, and recent research has identified it as a promising platform for whey-permeate valorization [32]. Increasing lactose concentration can enhance ethanol titre up to a certain level, whereas excessive substrate concentrations may impose osmotic stress and reduce fermentation efficiency; adapted *K. marxianus* strains have shown efficient ethanol production at lactose concentrations of approximately 150 g L^{-1} [33]. Fermentation duration must also be optimized because prolonged operation can lead to ethanol accumulation and reduced yeast activity. Continuous fermentation studies have demonstrated the influence of hydraulic retention time on ethanol yield, while batch studies have similarly reported reduced microbial growth at extended fermentation times [34,35].

Temperature and pH further affect yeast growth, lactose metabolism, enzyme activity, and ethanol formation. However, the optimum conditions are not universal and depend on the microorganism, substrate, and fermentation configuration. For example, a fed-batch fermentation with *K. marxianus* investigated temperatures of 30, 35, and 40°C and reported the highest biomass and ethanol concentration at 30°C under the tested conditions [36]. In contrast, another study using organic whey reported high ethanol yields at both 30 and 40°C under low-pH conditions, demonstrating the influence of strain and process configuration on the apparent optimum [37]. Thus, process conditions should be optimized experimentally rather than applying a single temperature or pH value to all whey-based fermentation systems.

Following fermentation, ethanol must be separated from the aqueous broth, with distillation being a conventional recovery method. However, downstream separation can impose substantial energy requirements, particularly when processing dilute whey streams. Therefore, assessment of whey bioethanol production should extend beyond fermentation yield to include ethanol titre, productivity, lactose conversion, downstream recovery, energy consumption, water requirements, and process economics. More importantly, bioethanol production can be integrated into a broader whey biorefinery in which valuable components are recovered before the lactose-rich fraction is directed toward fermentation or anaerobic digestion. Recent systematic evaluation of cheese-whey-permeate valorization has highlighted *K. marxianus*-based ethanol production as a promising fermentation pathway [38]. Nevertheless, substantial variation among reported yields indicates the need for improved strain robustness, process optimization, low-energy ethanol recovery, and techno-economic and life-cycle assessment before large-scale implementation. Such integration could allow whey to contribute simultaneously to renewable fuel production and nutrient recovery, supporting the broader zero-waste biorefinery concept.

5. Fruit-Processing Residues as a Resource

Fruit-processing industries generate substantial quantities of solid residues during juice extraction and other processing operations. These residues commonly include peels, pulp, pomace, seeds, cores, and fibrous fractions, with their composition varying according to fruit species, processing technology, and the fraction generated. Rather than being regarded solely as disposal materials, fruit-processing wastes (FPW) are increasingly recognized as renewable biomass resources for the production of bioenergy, biofuels, biochemicals, bioactive compounds, and agricultural products [39]. Their valorization potential is largely associated with their heterogeneous composition, which may include soluble sugars, pectin, cellulose, hemicellulose, lignin, dietary fiber, minerals, phenolic compounds, pigments, and other bioactive constituents. This diversity provides opportunities for cascading utilization, in which high-value compounds are recovered before the remaining carbohydrate-rich fraction is subjected to biological conversion [40].

The effective utilization of FPW begins with appropriate collection, segregation, and feedstock characterization. Contamination with soil, plastics, metals, packaging materials, or other non-biodegradable materials can interfere with subsequent biological processing, while variations in fruit variety, maturity, season, processing method, and residue fraction can substantially alter substrate characteristics [41]. Basic parameters such as moisture, total and volatile solids, pH, organic carbon, carbohydrate content, and COD can therefore provide useful information for selecting suitable conversion pathways. Physical pretreatment, including sorting, washing where necessary, size reduction, and homogenization, can improve substrate accessibility. Particle-size reduction may enhance the surface area available for microbial action, although the associated energy requirement must be considered when determining the optimum degree of grinding [42]. Similarly, moisture content and structural characteristics influence biodegradability, and the need for additional physical, thermal, chemical, or biological pretreatment depends on the composition of the individual residue [43].

Following appropriate preparation, FPW can be directed toward several biological conversion pathways. Their carbohydrate-rich fractions can serve as substrates for anaerobic digestion and fermentation, while selected fractions may be processed for recovery of higher-value compounds. Anaerobic digestion can convert biodegradable organic matter into methane-rich biogas while generating a nutrient-containing digestate, and reviews of fruit and vegetable residues have identified their potential for producing methane, hydrogen, volatile fatty acids, and other biorefinery products [44]. Similarly, fermentable sugars released from fruit residues can support ethanol production, although the resulting yield depends on feedstock composition, pretreatment, hydrolysis efficiency, microorganism, and fermentation conditions. This flexibility makes FPW particularly suitable for a multi-product biorefinery rather than a single-product conversion system.

An integrated approach can therefore direct different fractions of fruit residues toward the most appropriate valorization pathway, potentially combining recovery of bioactive compounds with production of biofuels and stabilization of residual organic matter. Such cascading utilization can improve overall resource recovery compared with treating the entire residue as a homogeneous waste stream, and multi-product fruit-waste biorefineries have been proposed as a means of integrating higher-value products with bioenergy generation [45]. However, the conversion strategy must remain feedstock-specific. Seasonal availability, high moisture content, storage instability, contamination, compositional variability, and the presence of potentially inhibitory compounds can influence biological conversion. For example, certain citrus residues contain essential oils and related compounds that may interfere with microbial processes, limiting the direct transfer of digestion or fermentation conditions between different fruit wastes [46].

Pretreatment represents an additional consideration because improvements in conversion efficiency do not necessarily translate into improved overall sustainability. Energy consumption, chemical requirements, capital investment, waste generation, and environmental impacts associated with pretreatment must be evaluated alongside biofuel or bioproduct yields [47]. Consequently, the development of a fruit-residue biorefinery should be based on systematic feedstock characterization followed by process-specific optimization rather than assuming a uniform conversion strategy for all FPW. Within the proposed zero-waste biorefinery, fruit-processing residues can therefore complement milk whey by supplying carbohydrate-rich biomass and potentially valuable bioactive fractions, while their biodegradable residues may be further directed toward bioenergy recovery and nutrient recycling. Such integration could contribute to a circular system in which fruit-processing residues are transformed from disposal liabilities into sources of biofuels, bio-based products, and biofertilizer, provided that technical, economic, and environmental feasibility can be demonstrated.

6. Biological Processing and Biofertilizer Production from Fruit Residues

Fruit-processing residues such as peels, pulp, seeds, and pomace contain substantial amounts of biodegradable organic matter and can therefore be valorized through controlled biological processing. Aerobic composting is particularly relevant when the objective is to stabilize the organic fraction and recover nutrients as an agricultural product. Size reduction can improve substrate accessibility, while the addition of suitable bulking materials may improve porosity, moisture balance, and aeration [48]. During composting, aerobic microorganisms utilize readily degradable carbohydrates, proteins, lipids, and other organic constituents, progressively converting them into more stable organic matter, with carbon dioxide, water, heat, and stabilized organic compounds as major products. The process generally progresses through mesophilic, thermophilic, cooling, and maturation phases, with adequate oxygen availability being essential for maintaining efficient aerobic degradation [49].

The efficiency of composting is strongly influenced by moisture, aeration, carbon-to-nitrogen ratio, pH, temperature, oxygen availability, and porosity. Excessive moisture can restrict oxygen diffusion, whereas insufficient moisture may limit microbial activity; therefore, moisture must be adjusted according to the physical characteristics of the feedstock and bulking material [50]. Aeration can be maintained through periodic turning or forced-air systems, while appropriate carbon and nitrogen availability supports microbial growth and decomposition. During the thermophilic phase, elevated temperatures contribute to rapid organic-matter degradation and can assist in reducing undesirable microorganisms when adequate temperature exposure is achieved [51]. As readily biodegradable compounds are depleted, microbial activity and temperature decline, followed by a cooling and maturation phase in which remaining organic compounds undergo further transformation and humification [52].

Maturation is particularly important for producing a stable agricultural product because immature compost may contain phytotoxic compounds, readily degradable organic matter, or unstable microbial activity that can adversely affect plant growth. Compost maturity should therefore be evaluated using appropriate physicochemical and biological indicators rather than being inferred solely from appearance or composting duration [53]. The resulting stabilized material can be assessed for its suitability as an organic fertilizer or soil amendment using parameters such as pH, electrical conductivity, organic matter, total organic carbon, C/N ratio, total nitrogen, available phosphorus, potassium, moisture content, stability, maturity, and microbiological quality [54]. The agronomic value of the final product depends not only on its total nutrient content but also on nutrient availability and the stability of the organic fraction.

A seed-germination or phytotoxicity assay provides an additional means of evaluating compost maturity. Germination index (GI), which combines seed germination and root elongation relative to an untreated control, is widely used as an indicator of phytotoxicity and compost maturity [55]. Microbiological safety is equally important before agricultural application. The elevated temperatures and extended microbial activity associated with well-managed composting can reduce populations of several undesirable microorganisms; however, pathogen reduction depends on the actual temperature profile, exposure time, aeration, moisture, and overall process management [56]. Consequently, microbiological assessment of the finished material remains important rather than assuming complete pathogen elimination solely from the occurrence of a thermophilic phase.

From a zero-waste biorefinery perspective, aerobic composting should be clearly distinguished from anaerobic biofuel production. Under oxygen-rich conditions, the dominant pathway is aerobic oxidation and stabilization of organic matter, whereas methane production occurs primarily under anaerobic conditions. Therefore, fruit-residue composting should not be presented as a direct methane-producing pathway unless a separate anaerobic process is experimentally demonstrated. Instead, the principal outcome of this stage is the generation of a stabilized, nutrient-containing organic fertilizer or soil amendment, while biofuel production can be achieved through separately validated anaerobic digestion or fermentation routes [57]. Integrating these pathways provides a more scientifically defensible strategy in which readily convertible fractions can be directed toward biofuel production and the remaining stabilized organic fraction can contribute to nutrient recycling and soil fertility.

7. Integrated Zero-Waste Biorefinery Model

An integrated zero-waste biorefinery aims to convert different food-processing residues into multiple useful products rather than treating them as conventional waste. Milk whey and fruit-processing residues have complementary characteristics: whey is rich in readily biodegradable lactose and is suitable for bioenergy and fermentation processes, whereas fruit residues contain carbohydrates, structural polysaccharides, organic matter, and bioactive compounds that can support biofuel production and nutrient recovery. Integrating these streams can therefore improve overall resource utilization and reduce the environmental burden associated with their disposal [58–60].

The major strength of this approach is cascading resource recovery, in which different fractions are directed toward the most suitable conversion pathway. Whey can be utilized for biogas or bioethanol production, while fruit residues can be subjected to biological stabilization and recovery of nutrient-rich organic material. Such multi-product integration can increase the value obtained from heterogeneous waste streams and reduce dependence on a single conversion technology [61,62]. However, the concept of "zero waste" should be understood as minimizing residual waste and maximizing resource recovery rather than achieving complete elimination of all residues.

The practical feasibility of an integrated whey–fruit biorefinery depends on feedstock variability, process stability, collection and transportation, energy requirements, downstream recovery, product quality, and economic viability. Therefore, future studies should combine mass-balance analysis with techno-economic assessment (TEA), life-cycle assessment (LCA), and environmental evaluation before claiming large-scale feasibility [63]. Overall, integration of whey and fruit-processing residues represents a promising circular strategy for simultaneous recovery of biofuels, bioenergy, organic matter, and nutrients, providing a potential pathway toward more sustainable food-processing waste management.

8. Digital Vendor Network for Waste Collection

An effective food-waste biorefinery requires a reliable supply of segregated, traceable, and consistently available feedstock. In decentralized systems, whey and fruit residues may originate from numerous dairy shops, paneer and cheese units, juice centers, fruit vendors, and food-service establishments, making collection and quality control challenging. A digital vendor network could provide a structured interface between these waste generators and the biorefinery by recording information such as waste type, approximate quantity, collection frequency, location, and collection history. Digital technologies have increasingly been explored for improving waste-management logistics, traceability, and resource recovery within circular-economy systems [64].

A simple QR-based identification system could be used to link each participating vendor with a digital profile. Collection requests and batch information could then be recorded and connected with subsequent measurements of quantity and feedstock quality. Such traceability would be particularly useful for a biorefinery because the composition of whey and fruit residues can vary considerably and directly influence biological conversion efficiency. The collected data could also support collection scheduling and route optimization by considering vendor location, waste quantity, collection frequency, and transportation capacity. These functions could potentially reduce unnecessary transportation and improve the reliability of feedstock supply [65].

However, the digital network should initially be regarded as a supporting and pilot-stage component rather than an established technological solution. Its effectiveness should be evaluated using measurable indicators such as vendor participation, quantity collected, contamination rate, collection reliability, transportation distance, collection cost, and the proportion of feedstock successfully utilized.

Integration of digital coordination with source segregation, feedstock characterization, and biological conversion could ultimately establish a more traceable and organized supply chain for decentralized food-waste valorization. Its environmental and economic benefits, however, require validation through pilot-scale studies, logistics assessment, techno-economic analysis, and life-cycle assessment.

9. Environmental Significance

The proposed whey–fruit residue biorefinery offers an integrated approach to organic-waste reduction, renewable-energy recovery, and nutrient recycling. Instead of treating dairy and fruit-processing residues solely as disposal burdens, the system considers their biodegradable carbon and nutrient fractions as resources for productive recovery. Whey can be directed toward anaerobic conversion for biogas production, while fruit residues can be stabilized and converted into nutrient-containing organic materials. Such integrated valorization of food-processing residues is increasingly recognized as an important component of circular bioeconomy systems [66,67].

The environmental benefits, however, depend on the efficiency of the selected conversion pathways and the resources required for collection, transportation, preprocessing, conversion, and downstream recovery. The recovery of methane, organic matter, nitrogen, phosphorus, and potassium can contribute to resource conservation and reduce dependence on conventional waste-disposal practices. Nevertheless, waste valorization should not automatically be considered environmentally superior, as energy consumption, transportation, residual-stream management, and process inputs may offset some of the potential benefits. Therefore, mass and energy balances, greenhouse-gas assessment, nutrient recovery, COD/BOD reduction, and life-cycle assessment (LCA) should be incorporated when evaluating the overall environmental performance of the proposed system [67,68].

Overall, the environmental significance of the whey–fruit residue biorefinery lies in its potential to transform heterogeneous food-processing residues into biofuels, renewable energy, stabilized organic matter, and recoverable nutrients while reducing dependence on conventional disposal. Fruit-waste valorization studies further support the potential of integrated biorefinery approaches for renewable energy, biofuels, bioactive compounds, and agricultural applications [66]. However, pilot-scale validation and quantitative sustainability assessment will be necessary to establish whether the proposed framework can deliver measurable environmental advantages and contribute to a genuinely circular food-processing system [68].

10. Challenges and Limitations

The practical realization of an integrated whey–fruit residue biorefinery is constrained by feedstock variability, biological instability, process integration, and downstream product quality. Whey and fruit residues can vary considerably with source, processing conditions, season, and storage, directly affecting microbial conversion and product yields. Consequently, routine physicochemical characterization and reliable feedstock traceability are important for maintaining consistent process performance. Feedstock heterogeneity is widely recognized as a major challenge in the development and scale-up of food-waste biorefineries [69].

Another important challenge is the optimization and integration of biological conversion pathways. Anaerobic digestion and fermentation are influenced by substrate loading, pH, temperature, microbial activity, retention time, and inhibition. In particular, the rapid biodegradability of whey may promote acidification under excessive loading, affecting methane production. Moreover, directing the same biodegradable carbon toward ethanol or methane production requires careful process selection. Separate, sequential, or fractionated configurations should therefore be compared using overall carbon recovery, energy efficiency, product yield, and process stability rather than considering individual products in isolation [70].

Residual-stream management, product safety, scale-up, and economic feasibility also remain significant limitations. Digestate, fermentation residues, liquid effluents, and stabilized fruit residues require appropriate characterization before agricultural or other applications, including assessment of nutrient composition, maturity, phytotoxicity, contaminants, salinity, and microbiological safety. At larger scales, transportation of dispersed feedstocks, preprocessing, process-energy requirements, downstream product recovery, and gas purification may substantially influence both economics and environmental performance. Therefore, pilot-scale validation supported by techno-economic analysis (TEA), life-cycle assessment (LCA), and comprehensive mass, carbon, and energy balances is essential before commercial implementation [71].

Overall, the proposed system should be regarded as a conceptual circular biorefinery framework rather than a fully validated zero-waste process. Its successful development will depend on demonstrating reproducible conversion, efficient resource recovery, safe and consistent products, economic viability, and a measurable net environmental benefit.

11. Future Perspectives

Future research should move beyond optimization of individual conversion processes toward integrated validation of whey–fruit residue biorefineries. Particular attention should be given to feedstock variability, microbial performance, organic loading, process stability, co-digestion, and microbial-community dynamics to improve the reliability of anaerobic digestion and fermentation under variable substrate conditions [72]. Greater emphasis is also required on the valorization and safety assessment of secondary streams. Digestate, fermentation residues, stabilized fruit residues, and liquid effluents should be incorporated into comprehensive mass and nutrient balances, while their potential use as biofertilizers or soil amendments should be validated through physicochemical, phytotoxicity, microbiological, and plant-growth assessments.

The proposed digital vendor network also warrants pilot-scale evaluation to determine whether digital traceability, source segregation, collection scheduling, and logistics optimization can provide a reliable and economically viable feedstock supply. Integration of digital monitoring with process data and predictive approaches could further support feedstock forecasting and system-level optimization. Such digitalization may become particularly valuable in decentralized biorefineries where feedstock availability and composition fluctuate over time [73].

Finally, life-cycle assessment (LCA), techno-economic analysis (TEA), and comprehensive carbon and energy balances should become integral components of future research. These assessments should consider collection and transportation, preprocessing, biological conversion, downstream recovery, residual-stream management, greenhouse-gas emissions, energy consumption, and revenues from recovered products. A combined technical, economic, and environmental assessment will be essential for identifying the conditions under which integrated whey–fruit residue valorization can provide genuine advantages over conventional waste-management practices [74].

12. Conclusion

The integrated valorization of milk whey and fruit-processing residues provides a promising pathway for transforming food-processing wastes into useful resources within a circular bioeconomy. Whey, owing to its lactose-rich and readily biodegradable nature, can support biological routes such as anaerobic digestion and bioethanol fermentation, while fruit-processing residues offer carbohydrates, organic matter, and nutrients suitable for bioenergy production, aerobic stabilization, and recovery of fertilizer resources. The proposed biorefinery therefore moves beyond single-product conversion by adopting a cascading resource-recovery approach, in which energy, organic matter, and nutrients are recovered through complementary pathways. Integration of feedstock collection, digital traceability, biological conversion, and residual-stream utilization could further improve the efficiency and sustainability of decentralized food-processing waste management.

Nevertheless, the concept of a zero-waste biorefinery should be understood as a goal of maximizing resource recovery and minimizing residual waste rather than achieving complete elimination of waste. Feedstock variability, process instability, collection logistics, downstream recovery, product safety, energy requirements, and economic feasibility remain important challenges that must be addressed before large-scale implementation. Future research should therefore focus on pilot-scale validation, process integration, reliable feedstock management, and comprehensive techno-economic and environmental assessment. Overall, the whey–fruit residue biorefinery represents a potentially scalable strategy for converting heterogeneous food-processing residues into biofuels, renewable energy, stabilized organic resources, and nutrient-rich agricultural products, thereby supporting a transition from conventional waste disposal toward a more sustainable and circular food-processing system.

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