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Review

Fruit and vegetable postharvest waste in Tanzania: A review of occurrence, sources, environmental impacts, and contextual utilization pathways

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Abstract: Fruit and vegetable postharvest waste (FVPW) represents a significant environmental and economic challenge in developing countries, where supply-chain inefficiencies and limited infrastructure contribute to substantial losses. While numerous technologies for FVPW utilization exist, integrated assessments that connect waste occurrence, environmental impacts, utilization pathways, and contextual feasibility within specific national settings remain limited. In this review, we synthesized evidence on the sources, environmental impacts, and valorization options of FVPW and evaluated their contextual feasibility within the Tanzanian context. A combined scoping and integrative review approach was employed using peer-reviewed literature, followed by a qualitative feasibility analysis considering technological readiness, cost, environmental benefit, infrastructure needs, and scalability potential. The findings revealed a hierarchy of implementation: High-readiness options such as composting and animal feeding provide immediate and scalable solutions, whereas medium- and low-readiness pathways, including anaerobic digestion, biochar production, bioethanol, bioactive compound extraction, and bioplastic synthesis, offer higher environmental and economic value but face infrastructural and institutional barriers. The analysis suggests that a phased transition strategy, prioritizing readily implementable technologies while progressively strengthening technical capacity and market systems, offers the most realistic pathway toward circular FVPW management. Furthermore, the study highlighted that the scalability of advanced valorization pathways is strongly dependent on access to appropriate financing mechanisms, including green finance instruments, blended finance models, and sustainability-linked investment frameworks. These insights provide practical guidance for policy, research, and investment aimed at enhancing sustainable postharvest waste utilization in Tanzania.

Keywords: Bioplastic; Circular economy; contextual feasibility; fruit waste; postharvest waste; recycling; recovery; Tanzania; vegetable waste; waste valorization

Abbreviations: AC, activated carbon; AD, anaerobic digestion; CEC, cation exchange capacity; FVPW, fruit and vegetable postharvest waste; FV, fruits and vegetables; GHG, greenhouse gas; MSMEs, Micro, Small, and Medium Enterprises; SDGs, Sustainable Development Goals; TRL, technology readiness level.

1. Introduction

Global environmental sustainability challenges, ranging from climate change to resource depletion, have intensified scholarly and policy attention toward more efficient resource management systems. The transition to circular and resource-efficient systems from linear production–consumption models has become central to sustainable development agendas worldwide. However, achieving such transitions requires more than technological solutions; it depends fundamentally on institutional capacity, governance quality, and policy coherence [1–3]. Strong institutional frameworks enable enforcement of environmental regulations, foster circular economy practices, and align economic activities with long-term sustainability objectives. Conversely, weak governance structures and fragmented regulatory systems often exacerbate environmental degradation and waste mismanagement [4].

Within this broader sustainability discourse, food loss and waste have emerged as critical concerns. Fruit and vegetable postharvest waste (FVPW) represents a significant component of global food loss, particularly in developing countries. FVPW in developing countries has emerged as a critical problem owing to inadequate waste management practices. Smallholder farmers and retail vendors incur economic losses from the spoiling of fruits and vegetables prior to reaching end consumers, which also has negative environmental impacts. Inadequately managed FVPW can severely impact water resources, air quality, and public health [5]. Moreover, the impacts of FVPW extend beyond immediate environmental consequences; they represent the forfeiture of all resources invested from cultivation to marketing, including irrigation water, fertilizer, labor, and transportation fuel [6].

In response to these losses, advances in digital agriculture have introduced complementary approaches for improving postharvest management through machine learning, computer vision, and hyperspectral imaging systems capable of detecting defects, quality deterioration, and early spoilage along supply chains. These technologies improve objective quality assessment, reduce manual bias, and support early intervention strategies that may minimize waste generation before products reach disposal stages [7,8]. While such innovations primarily focus on loss prevention and quality monitoring, they can indirectly enhance resource efficiency and reduce the volume of waste entering downstream utilization and management pathways.

However, despite technological advances that have the potential to reduce the occurrence of FVPW through improved monitoring and early detection, the generation of such waste remains largely unavoidable in many developing countries due to low adoption rates, limited technical capacity, and infrastructure gaps. Consequently, understanding how these unavoidable waste streams can be effectively utilized becomes essential for improving sustainability outcomes. The feasibility of such utilization pathways is further influenced by structural conditions within national systems. In developing countries, managing FVPW across the supply chain remains particularly challenging due to contextual constraints distinct from those in developed economies [9]. Effective management should follow the waste hierarchy framework, prioritizing prevention, reduction, reuse, recycling, and recovery before disposal [10]. However, developing countries often face technological limitations, financial constraints, inadequate infrastructure, and insufficient regulatory enforcement mechanisms [11]. These constraints illustrate that postharvest waste is not merely a technical inefficiency but also an institutional and systemic challenge.

This governance dimension aligns closely with the global sustainability agenda, particularly Sustainable Development Goals (SDG) 12 (Responsible Consumption and Production), 13 (Climate Action), and 16 (Peace, Justice, and Strong Institutions) [12]. Circular economy approaches emphasize closing material loops and minimizing losses across supply chains, but their success depends on context-sensitive institutional frameworks and coordinated policy implementation [3]. Without robust governance systems, waste streams that have the potential to transform into productive resources instead end up as environmental burdens. Accordingly, we systematically interpret FVPW management and valorization pathways through the lens of relevant SDGs to enhance policy relevance and alignment with global sustainability frameworks.

In Tanzania, the issue of FVPW is especially pronounced. Most farming activities take place in rural regions [13], characterized by limited waste management expertise and infrastructure. Smallholder farmers, who dominate agricultural production, often lack capital to invest in improved postharvest handling technologies. Researchers report significant postharvest losses attributed to constraints along the supply chain [14–17]. According to the National Postharvest Management Strategy 2019–2029 [18], approximately 35% of cultivated food crops are lost before reaching end consumers due to insects and rodents, with an additional 16% lost during transport. When combined with inedible components, these losses translate into substantial volumes of waste requiring effective management.

Transportation of produce from rural to urban markets further increases spoilage. In rural and urban settings, inadequate solid waste management facilities [19] often result in the direct disposal of FVPW into the environment. This practice contributes to greenhouse gas emissions, land and water contamination, and public health risks while representing lost economic value. Therefore, inefficient management of FVPW in Tanzania generates a triple burden: Economic losses for producers and vendors, environmental degradation, and missed opportunities for resource recovery.

Despite increasing global attention to food waste, there remains a limited integrated synthesis of how FVPW is generated, managed, and valorized within socioeconomic and institutional contexts, such as Tanzania. Researchers tend to quantify losses [20] or focus on isolated technical solutions [21] but rarely connect occurrence patterns, environmental impacts, and contextual feasibility of utilization pathways within a unified analytical framework. This fragmentation limits evidence-based policy design and may hinder the adoption of context-appropriate waste valorization strategies.

In this review, we address that gap by synthesizing evidence on the occurrence, sources, environmental impacts, and utilization options of FVPW in Tanzania while assessing the contextual feasibility of these options within structural constraints. Rather than merely cataloging waste streams or technologies, we integrate environmental, socio-economic, and institutional considerations into a comprehensive analytical framework. Figure 1 presents the conceptual model linking FVPW sources, environmental and socio-economic impacts, and potential valorization pathways aligned with sustainability objectives.

By embedding postharvest waste management within broader sustainability and governance discussions, this review contributes to bridging the gap between technical waste solutions and the institutional realities of developing countries. In doing so, it provides an integrative foundation for future research and policy interventions aimed at reducing postharvest losses while promoting sustainable resource recovery in Tanzania.

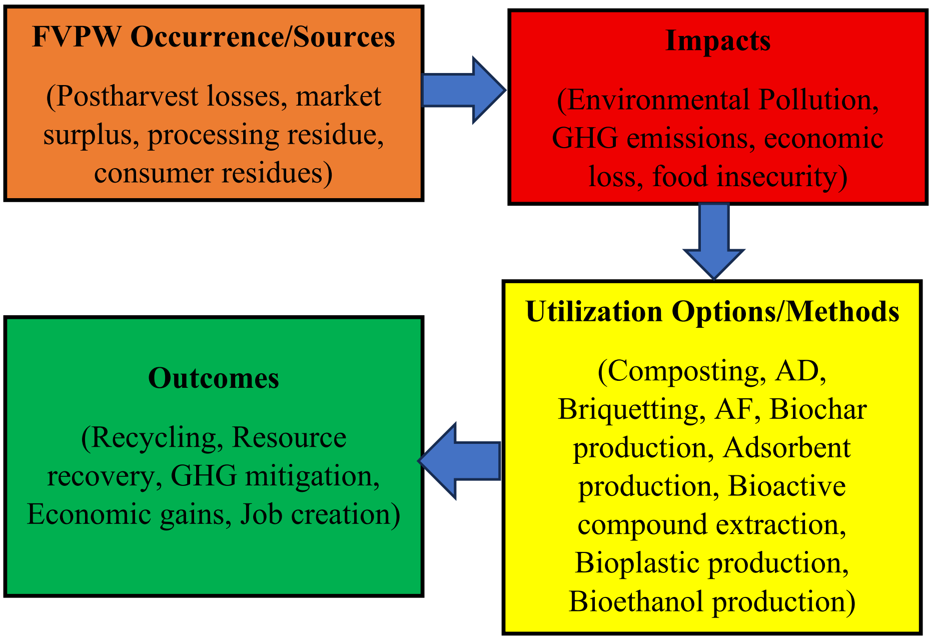

Figure 1. Conceptual framework linking FVPW occurrence/sources, impacts, and valorization pathways in Tanzania with expected sustainability outcomes.

1.1. Fruit and vegetable postharvest waste (FVPW)

FVPW refers to fruit and vegetable material generated at different stages of the supply chain, from production and processing to distribution, retail, and consumption, that is not consumed by humans. These sequential activities in the supply chain always generate waste, which may arise during the processing of fruits and vegetables to acquire valuable products, during consumption when inedible components are discarded, or due to spoiling. Spoiling of fruits/vegetables means the destruction of their value or quality and they become unfit for regular consumption by humans [22,23]. It may also involve all fruits and vegetables that are damaged, as well as those discarded for reasons such as surplus production, aesthetic imperfections, or approaching expiration dates [24]. All these generated wastes from fruits and vegetables are categorized as FVPW, encompassing inedible components of fruits and vegetables, including peels, seeds, and stems, as well as any spoilt or compromised edible portions. Efficient management of these waste streams can reduce environmental harm and protect public health [5].

2. Materials and methods

We employed a combination of scoping and integrative review approaches (Figure 2). For the scoping review phase, we aimed to map and synthesize knowledge regarding the occurrence, sources, and environmental impacts of fruit and vegetable postharvest waste (FVPW). Unlike conventional scoping reviews that often identify research gaps and formulate recommendations, the scoping component of this study was primarily intended to summarize and organize the body of evidence relevant to the review objectives [25].

The second phase consisted of an integrative review focusing on studies that reported the utilization of FVPW. Our objective of this phase was to synthesize and critically analyze evidence on conventional and emerging technologies for FVPW utilization. Following the integrative review, a contextual feasibility analysis was conducted to evaluate the applicability of the identified utilization pathways within the Tanzanian context, considering factors such as technological readiness, cost, environmental benefits, infrastructure requirements, implementation barriers, and scalability potential.

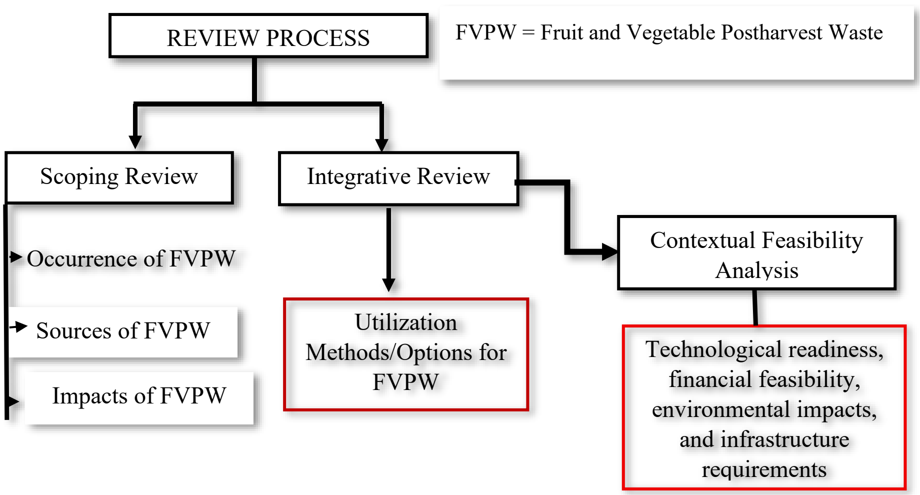

Figure 2. Overall methodological framework illustrating the scoping review, integrative review, and contextual feasibility analysis used in this study.

2.1. Data sources, search strategy, and screening

We employed a combination of Scopus, ScienceDirect, and Google Scholar to identify literature relevant to the study objectives. For the integrative review, Scopus was used as the primary database due to its extensive coverage of peer-reviewed literature, while ScienceDirect served as a supplementary database for targeted retrieval of relevant studies. Google Scholar was used exclusively for the scoping review and iterative backward snowballing to identify additional relevant studies from the reference lists of included articles. Specifically, reference lists of eligible articles were examined to identify further studies for potential inclusion. This process was repeated iteratively until no additional relevant records were identified.

The literature search was conducted using combinations of keywords related to fruit and vegetable postharvest waste (FVPW), its occurrence, sources, environmental impacts, prevention strategies, and utilization pathways. For the scoping review, Google Scholar searches were performed using combinations of terms such as: ("Source" OR "Occurrence" OR "Reduction Techniques" OR "Prevention Methods" OR "Impacts" OR "Challenges") AND ("Food Waste" OR "Fruit Waste" OR "Vegetable Waste").

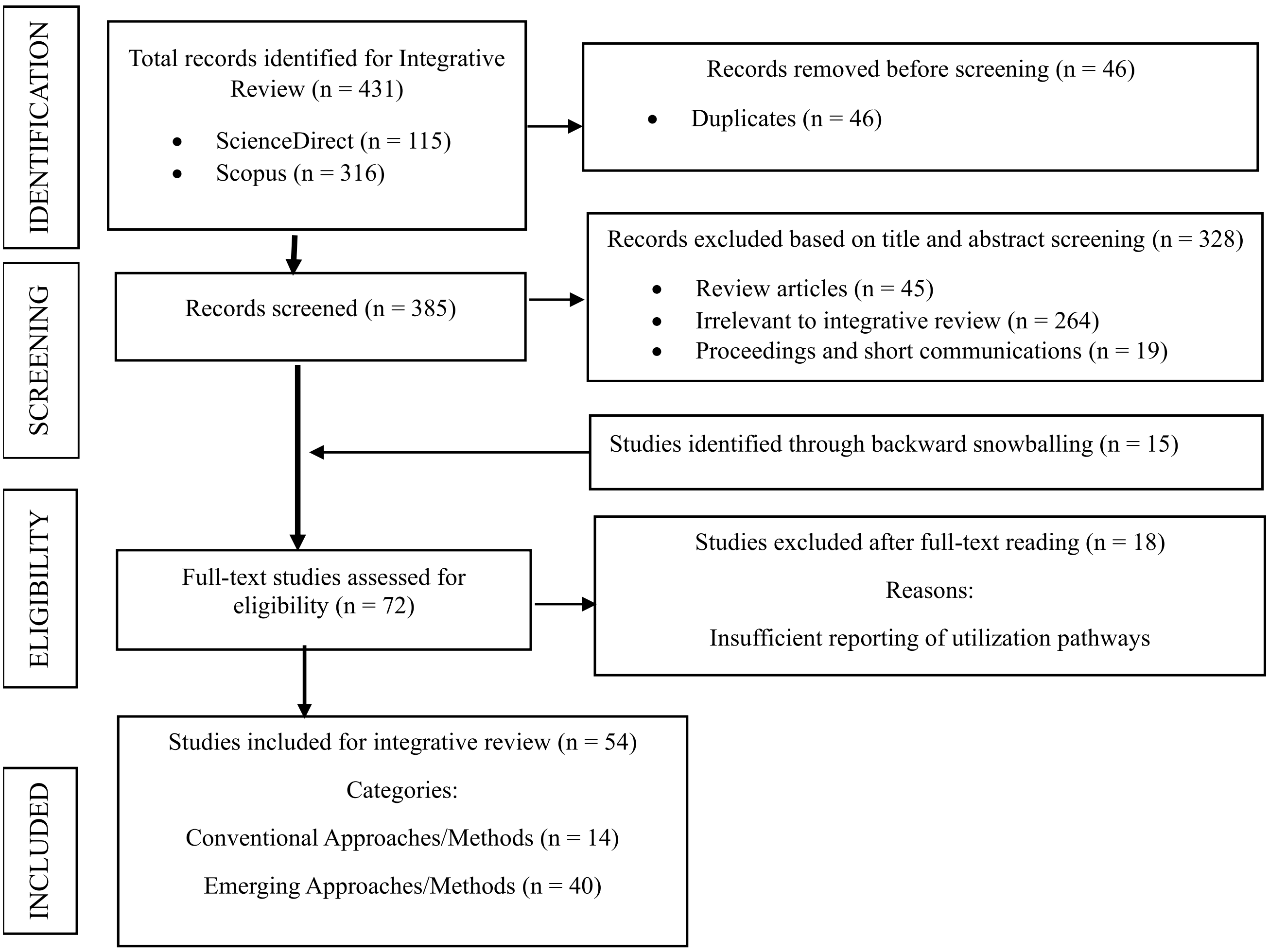

Figure 3. Flow diagram illustrating the identification, screening, eligibility assessment, and inclusion of studies used in the integrative review of fruit and vegetable postharvest waste (FVPW) utilization pathways.

For the integrative review, systematic searches were conducted in Scopus and ScienceDirect. The search strategy was structured into two broad categories: (i) Conventional utilization approaches and (ii) emerging utilization approaches. Additional studies were identified through backward snowballing of the reference lists of eligible articles. The complete search strings used for Scopus and ScienceDirect are presented in Table S1. In ScienceDirect, search terms were occasionally separated and searched in combinations within relevant subject areas because the platform has limitations regarding the length of search strings. The literature search across all databases was conducted between November 2024 and December 2024. The identification, screening, eligibility assessment, and inclusion process used for the integrative review is presented in Figure 3. Screening and full text assessment were conducted collaboratively by all three authors. Records were assessed based on relevance to FVPW utilization pathways, article type, and availability of sufficient information for the integrative review. Inclusion and exclusion decisions were discussed jointly, and any differences were resolved through consensus.

2.2. Selection and inclusion criteria

The selection of studies was guided by their relevance to the review objectives and the availability of sufficient information to support data extraction and synthesis. For the scoping review, publications were included if they provided descriptive, theoretical, empirical, or policy-related information relevant to the occurrence, sources, environmental impacts, prevention strategies, or utilization pathways of fruit and vegetable postharvest waste.

For the integrative review, only peer-reviewed journal articles published between 2000 and 2024 were considered. This time frame was selected to capture developments in waste management and resource recovery practices that emerged during the period of increasing global emphasis on sustainable development and waste minimization initiatives [26]. Studies were included if they reported conventional or emerging utilization pathways for fruit and vegetable postharvest waste and provided sufficient methodological and outcome information to support comparative analysis. Review articles, conference proceedings, short communications, and studies lacking adequate information on utilization pathways were excluded during the screening and full text assessment.

2.3. Research works included for integrative review

Following the application of the inclusion and exclusion criteria and the screening of studies reporting fruit and vegetable postharvest waste (FVPW) utilization pathways, a total of 54 peer-reviewed articles published between 2000 and 2024 were included in the integrative review (Figure 3). These studies were selected from an initial pool of 431 records identified through database searches, supplemented by records obtained through backward snowballing.

The temporal distribution of the included studies indicated a growing research interest in FVPW utilization pathways over the past two decades, with a marked increase in publications after 2015 (Figure 4). This trend reflected increasing global attention toward waste valorization, circular economy approaches, and sustainable resource recovery from organic residues.

Among the included studies, bioactive compound extraction was the most frequently reported utilization pathway (n = 14), followed by bioethanol production (n = 9), animal feed production (n = 7), biochar production (n = 6), adsorbent production (n = 6), bioplastic film production (n = 5), anaerobic digestion (n = 4), and briquette production (n = 3). These studies formed the basis for the comparative synthesis of conventional and emerging FVPW utilization pathways presented in this review.

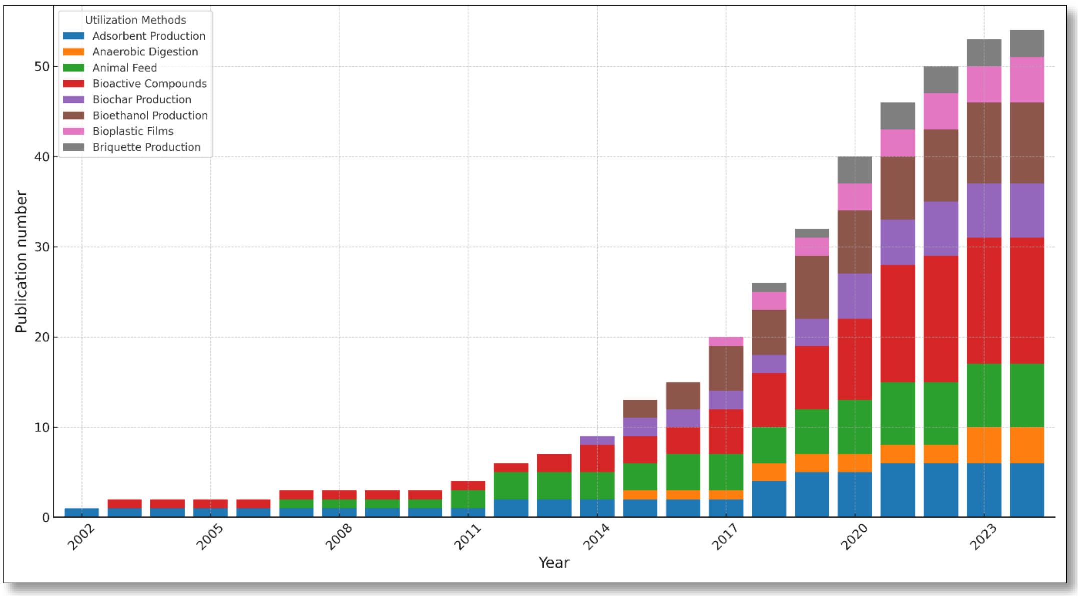

Figure 4. Temporal distribution of published studies on fruit and vegetable postharvest waste (FVPW) utilization pathways included in the integrative review.

2.4. Contextual feasibility analysis

A contextual feasibility analysis evaluated the viability of a project, option, or technology within a specific operational, socio-economic, environmental, and institutional context. In this review, we primarily aimed to align global evidence with local requirements. The contextual feasibility analysis involved an analysis of several factors: i) technology readiness, ii) cost, iii) environmental benefits, iv) infrastructural requirements, v) key barriers, and vi) scalability potential. The selection of factors for inclusion was based on the baseline information pertaining to the contextual feasibility study in other fields [27]. Scoring was derived from a qualitative synthesis of peer-reviewed literature, case studies, and additional resources, validated against the authors' expertise in the Tanzanian context. The contextual feasibility assessment was conducted independently by all three authors. Each author evaluated the identified FVPW utilization pathways against the six assessment criteria using evidence extracted from the reviewed literature and contextual knowledge of Tanzania. The individual assessments were then compared and discussed to reach a consensus classification. Moreover, where differences in interpretation or scoring emerged, additional literature was consulted and re-evaluated collectively until agreement was achieved.

Technological readiness was assessed using a scale from 1 to 10, with 1 indicating poor readiness and 10 representing strong readiness, supported by evidence of adoption in similar circumstances. Costs were distributed based on the specific conditions of implementing the methods or technologies within the Tanzanian setting. The classification was low, moderate, or high, indicating corresponding capital, operational, and monitoring expenditures [28]. Environmental impacts were evaluated using a three-tier scale (low, moderate, and high), taking into account reported emissions, waste diversion potential, and co-benefits [29-31]. The infrastructure requirements were assessed based on the needs for the installation and operation of the technology, encompassing land, materials, and tools. The assessment of essential barriers was qualitatively analyzed according to several factors, including training prerequisites, regulatory structures, and technical obstacles. Scalability was evaluated qualitatively by considering each technology's potential for replication and expansion across regions of Tanzania.

2.5. Methodological potential and limitations

The combined use of scoping and integrative review methodologies was appropriate for addressing the broad and multidisciplinary nature of fruit and vegetable postharvest waste (FVPW) management. The scoping review enabled the mapping of evidence on the occurrence, sources, and environmental impacts of FVPW, while the integrative review enabled a deeper synthesis and comparison of utilization technologies reported across contexts. By combining these approaches, the study moved beyond descriptive evidence mapping and provided a structured basis for evaluating technological options relevant to Tanzania. This integration supported the contextual feasibility analysis by linking scientific evidence with local technological, economic, institutional, and infrastructural conditions.

However, limitations must be recognized. We did not adhere to a full systematic review or meta-analysis protocol; hence, quantitative effect size comparisons were unfeasible. Dependence on published material may engender publication bias and restrict the incorporation of unpublished local experiences. The feasibility analysis involved qualitative synthesis and authors' evaluation, potentially introducing a level of subjectivity despite adherence to set criteria and supporting research. Ultimately, the selection of databases, temporal constraints, and language limitations may have prevented the inclusion of certain relevant studies. We must acknowledge these limitations when analyzing the results and implementing them in policy or practice.

3. Findings and discussion

3.1. Occurrence of FVPW

To manage FVPW effectively, it is essential to understand the critical stages in the supply chain where postharvest waste occurs [32,33]. Figure 5 shows the conventional logistics and supply chain of fruits and vegetables (FV) in Tanzania, emphasizing the distinct steps and processes that contribute to waste production at various stages. Retailers, middlemen, or wholesalers directly purchase the harvested FV for further distribution. The wholesalers obtain the FV from middlemen [34] or directly from farmers, or occasionally acquire processed FV from industries or middlemen, which they subsequently sell to retailers who sell to final consumers. The participation of numerous intermediaries, although economically significant for market access, may elevate handling frequency and transportation time, thereby exacerbating the danger of physical damage and quality degradation noted in comparable regional supply-chain analyzes [35].

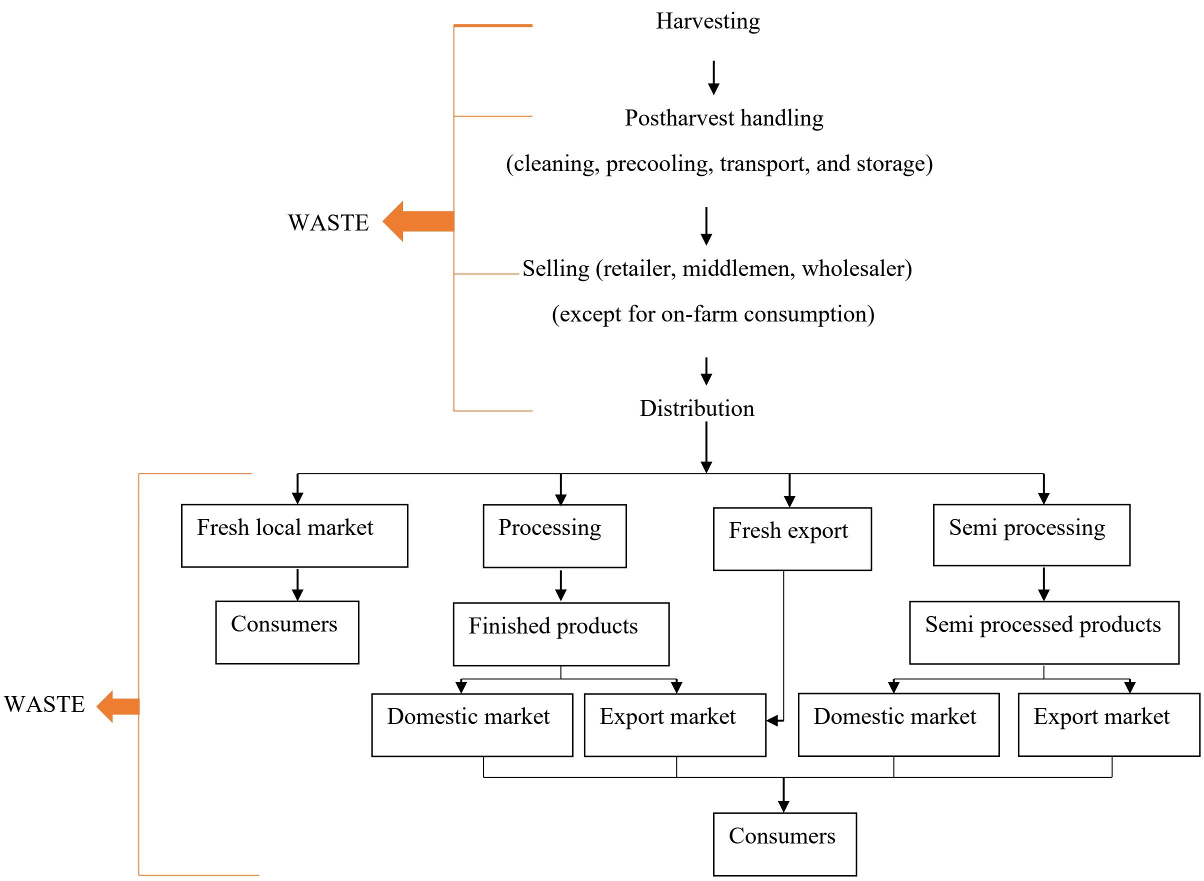

Figure 5. Typical logistics supply chain of fruits and vegetables in Tanzania (modified from Janghu et al. [40]).

These stages also require storage and transportation for market readiness. The storage process, while awaiting market and transportation, necessitates adequate facilities and infrastructure to preserve quality and quantity. Inadequate management of FV at these stages can lead to a decline in quality, quantity, or appearance, resulting in some FV spoiling before reaching the final consumers [36]. This suggests that postharvest waste is mostly associated with systemic supply-chain inefficiencies rather than isolated technical failures, underscoring the need to analyze FVPW within wider socio-economic and infrastructural frameworks [37].

Overall, at every stage of the postharvest process, waste is produced, either from the deterioration of fresh vegetables or from the extraction of undesirable components to acquire the preferred ones. Cleaning at different stages can generate wastewater, but also solid wastes, like fruit peels, result from the removal of inedible parts and are likely to be generated [38]. In Tanzania, like other developing countries with limited mechanization, approximately 30% of FV are lost during the upstream phases of the supply chain, including harvesting, handling, precooling, transportation, and storage prior to reaching processing industries and final consumers [18,39]. The substantial losses in upstream phases indicate that interventions targeting these stages could significantly reduce postharvest waste; however, complete elimination is unlikely, and residual waste streams will still require environmentally sound utilization and management pathways.

3.2. Sources of FVPW

Many factors contribute to FV postharvest losses, spanning preharvest to postharvest stages. Preharvest considerations encompass crop management, maturation, harvesting methods, and timing of harvest. Inadequate crop management throughout growth can lead to substandard output that does not satisfy market and customer demands [41,42]. Insufficient understanding of crop maturity may result in the harvesting of either immature or overripe FV, leading to decreased quality and heightened spoilage. Leafy vegetables left in the field beyond their maturity may become unappealing to most consumers [43]. This indicates that postharvest waste generation is often rooted in decisions made before harvesting, suggesting that preventive interventions should begin at the production stage rather than focusing exclusively on downstream waste management [44].

Factors leading to postharvest losses encompass inadequate pre-cooling technologies, inadequate handling techniques, insufficient transportation facilities, inadequate infrastructure, and inadequate storage facilities. Market accessibility and customer inclinations also exert considerable influence. The variety of FV harvested determines the suitable cooling techniques, storage facilities, and transportation necessities to prolong their shelf life, as FV require careful treatment and attention. Environmental conditions can significantly impact postharvest precooling and storage methods, particularly in rural areas that cultivate a wide variety of FV [43].

Elik et al. [45] reported that harvesting factors, including the technology used, crop maturity, and harvest timing, significantly contribute to fruit and vegetable losses, with more than 20% of produced fruits and vegetables being lost and becoming waste. They additionally observed that postharvest handling and storage result in 8% of losses, packing and processing contribute 10%, marketing and distribution account for another 10%, and consumers represent 5%. Collectively, these factors account for more than 50% of food value losses, with the possibility of greater losses in developing and poor countries [32]. While these percentages may differ by country, in numerous developing countries, such as Tanzania, these factors substantially contribute to food value losses, exacerbating postharvest waste. The distribution of losses across stages suggests that no single intervention can fully address FVPW; instead, integrated strategies spanning production, logistics, and market systems are necessary.

Overall, mitigating these losses requires prioritizing the key factors influencing postharvest management across the supply chain. Besides the waste generated from fruit and vegetable losses during harvesting, handling, and storage, additional waste occurs throughout the processing and consuming stages [46]. Inedible parts, including peels, seeds, cores, rinds, stalks, and fibrous residues discarded during food preparation, juice extraction, canning, or direct domestic usage, constitute these wastes. Examples include banana peels, orange peels, tomato peels, carrot tops, and vegetable trimmings. From a circular economy standpoint, these inevitable processing leftovers signify possible feedstocks for valorization pathways, underscoring the need to connect source identification with the practical utilization possibilities discussed in Section 3.4 of this study.

3.3. Environmental impacts of FVPW

FVPW can have a substantial impact on the environment due to its biodegradable nature. The extent of these impacts varies with the quantity of losses [47]. These impacts can occur either directly or indirectly. Direct impacts result from the greenhouse gas (GHG) emissions generated as FVPW degrades across phases of the postharvest chain. The loss of resources used in production such as water, energy, and fertilizers causes indirect effects, as these resources could have been employed elsewhere or conserved for future use. This difference between direct and indirect impacts highlights that FVPW influences environmental sustainability not just through emissions but also by wasting resources in the food system, which relates to problems noted in circular economy discussions about hidden environmental costs [48].

Munhuweyi et al. [31] studied postharvest losses of cabbages (a common leafy vegetable in developing countries) and found that during the production and postharvest cycle of cabbage, GHGs are emitted as the crop deteriorates. Additionally, energy and water used in production are wasted when food is lost before reaching final consumers. Quantitatively, they reported that cabbage losses (13,000–54,000 tonnes) contributed 1.9–4.2 million tonnes of CO_2 eq. emissions, with 17–38 million MJ of fossil fuel energy and 3–6 million m^3 of water lost. Blanckenberg et al. [49] also quantified three key environmental impacts: GHG emissions, water loss, and energy use loss caused by the postharvest losses of table grapes in South Africa over 2017 and 2018. Their findings showed the loss of 177.43 million MJ of fossil energy, 4.8 million m^3 of freshwater, and approximately 52,263 tonnes of CO_2 eq. emissions. To interpret this data, using the average CO_2 emissions of 2.9 million tonnes, it would require at least 75 million urban trees to sequester this amount of CO_2, based on the United States Department of Energy [50], which estimated 0.039 tonnes of CO_2 sequestration per urban tree. The water lost (3–6 million m^3) could sustain 117,096–234,192 individuals for a year, assuming a minimum demand of 70 liters per person per day. The findings of these studies indicate that while the extent of environmental impacts differs among crops and regions, the consistent pattern of energy, water, and greenhouse gas losses underscores the systemic environmental cost of postharvest inefficiencies. This observation is consistent with broader evidence suggesting that high-moisture horticultural products often produce disproportionately large environmental footprints when losses occur, especially in areas characterized by resource-intensive production methods [51].

Beyond these three major environmental impacts, FVPW also entails the loss of fertilizers and natural nutrients used during farming. Furthermore, the FV losses can harm biodiversity and ecosystems by depriving them of the resources utilized in producing the lost FV [6]. Overall, the cumulative environmental impacts indicate that postharvest waste management must be regarded not merely as a waste handling concern but as a vital area for environmental intervention, emphasizing the need to integrate prevention and utilization pathways to mitigate lifecycle impacts.

3.4. Practical options for the utilization of FVPW

Improper disposal or poor management of FVPW can generate serious ecological and public health concerns. Therefore, effective FVPW management should aim not only to reduce environmental impacts but also to recover useful materials and products from unavoidable waste streams. This has attracted increasing attention from researchers and practitioners because the adoption of appropriate waste management practices is influenced by differences in technology, awareness, attitudes, knowledge, and institutional capacity across regions [52–54].

Management of FVPW involves the process of ensuring the waste that is produced from postharvest is well kept and utilized in such a way as to protect or reduce its impacts on the environment. The process of managing FVPW should begin with collection, storage, transport, recycling, and recovery, and continue until it reaches the disposal point [47]. The priorities for the management of FVPW should start by ensuring no waste is produced or as little waste as possible is produced. If prevention is impossible, the second option is to reuse waste in other activities. If these two are not possible, then recycling and recovery of some valuable materials are recommended before the least priority of disposal [10].

In this review, the basic methods/techniques/pathways of utilizing the FVPW either for recycling or recovery of some valuable compounds/materials are discussed. Figure 6 illustrates the major pathways that can be used to manage and valorize FVPW. Conventional methods, sometimes called traditional methods, of FVPW involve the combination of physical, chemical, and biological processes to reduce volume, remove some part, or separate and disintegrate the larger part into small particles for other reuse options and for safe disposal options. The common conventional approaches for FVPW are composting, anaerobic digestion, briquetting, and landfilling [55,56].

In contrast, the emerging methods/technologies involve the valorizations where the advanced technology and processes are used to convert waste to valuable or useful products or raw materials. This method may involve processes such as extractions, synthesis, and advanced physical, chemical, or biological conversions [57].

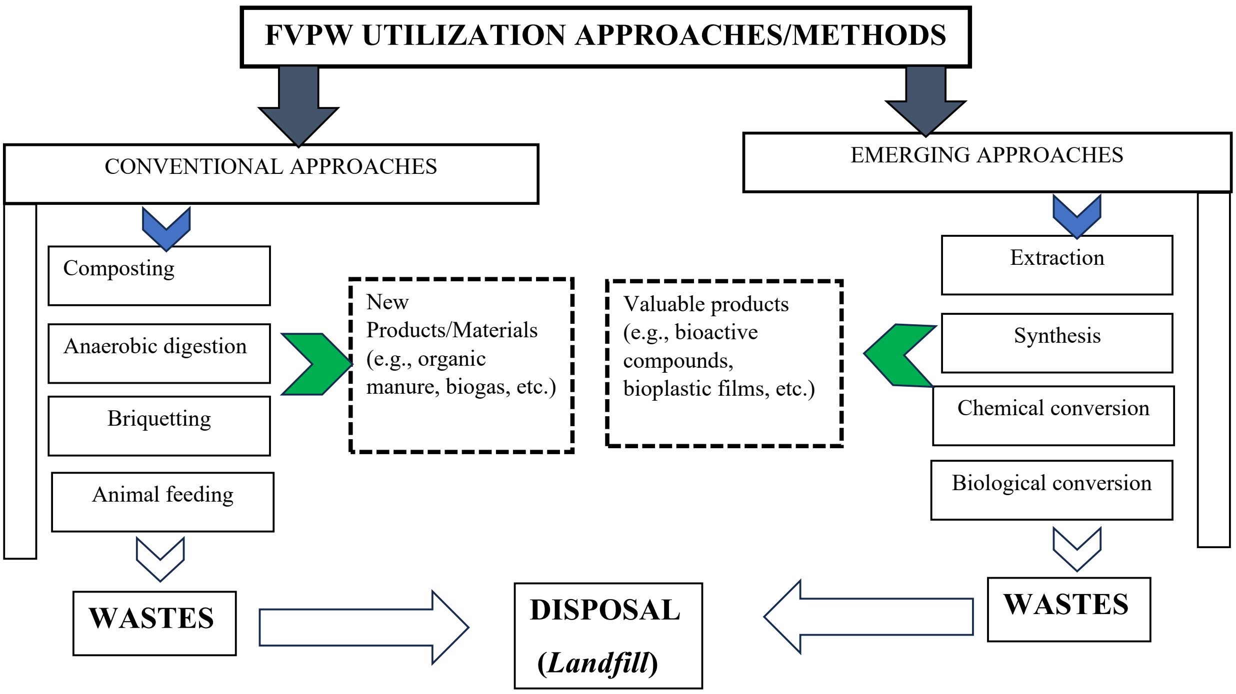

Figure 6. Basic methods/techniques/pathways of utilizing the FVPW.

3.4.1. Composting of FVPW

Composting is the process of transforming organic waste into compost in the presence of oxygen (aerobic conditions). Composting facilitates the decomposition of organic materials, thereby enhancing nutrient availability. When compost, a nutrient-rich fertilizer derived from composting, is applied to soil, it enhances soil fertility, increases water retention capacity, improves soil tilth, suppresses pathogens, and enhances soil structure [58]. The multifunctional advantages explain why composting is often emphasized in sustainability-focused waste management literature as an economical approach that simultaneously mitigates waste issues and enhances soil health.

Composting can treat FVPW, which primarily consists of organic materials, to produce compost [59]. Studies have shown the possibility of using FVPW as a valuable source material for compost production. FVPW used for composting includes apple peels, banana peels, orange peels, kiwi peels, cabbage leaves, potato peels, carrot peels, tomatoes, lemons, pineapple tops, and other organic residues (Table 1). Researchers use FVPW as either co-composting materials or primary composting materials. Hussain et al. [60] reported the use of FVPW in conjunction with other organic wastes, including paddy straw and cow dung. Sawdust and dry grasses were used alongside FVPW to generate compost, as reported by Ghinea and Leahu [61] and Mataba et al. [62]. The objective of incorporating FVPW with other organic waste is to balance moisture content in the feedstock, enhance carbon levels, mitigate odors by restricting anaerobic processes (facilitating aeration), and regulate acidity, as numerous fresh fruits exhibit high acidity. Additional research indicated the use of FVPW in conjunction with other organic wastes, including horticultural waste [63] and organic municipal solid waste [64]. The use of FVPW as a co-composting material has been observed to enhance the composting process [65]. The consistent use of co-composting techniques in several research studies demonstrates that effective FVPW composting frequently relies on an optimal balance of physicochemical characteristics rather than individual waste streams, indicating that feedstock optimization is an essential aspect of process efficiency.

The prevalent methods utilized for composting are vessel-aerobic composting, vermicomposting, and decentralized composting systems (Table 1). Vessel aerobic composting uses containers with varying volumes and ventilation for aeration purposes. Vermicomposting refers to the procedure undertaken in an open area or vessel, utilizing earthworm species to expedite composting by consuming organic waste. In addition to its advantages, vermicomposting is linked to several challenges, including insufficient knowledge and awareness, financial constraints, policy-related issues, pre-processing requirements, transportation difficulties, the need for a continuous supply of substrate (raw organic waste), and potential contaminants in the end product such as trace metals, phytotoxic substances, and salt content [66]. A decentralized system refers to the decomposition of organic waste at the household, community, or small plant level. Composting is a prevalent method that aids in reducing the volume of solid waste that households or communities require municipalities to collect for landfilling. Decentralized and low-technology composting methods seem more suitable for developing countries, where capital-intensive centralized systems may struggle to endure due to infrastructural and governance constraints. This indicates that composting serves as a waste management solution and a locally adaptive approach that conforms to circular economy principles and facilitates community-level resource recovery.

Table 1. Overview of selected studies reporting the use of FVPW for composting.

Raw Materials Used	Methods Used	Purposes	Composting Duration	Reference
Horticultural waste, fruit peels, food waste, and soybean residues	Vessel aerobic composting (270 L domestic compost reactors)	Production of composts (Effects of Horticultural waste to be co-composted with fruit peels, food waste, and soybean residues for composts production).	46 days	[65]
Vegetable kitchen waste, paddy straw, and cow dung	Vermicomposting (Earthworm composter used-Red Californian worm) and Composting.	Production of composts	40-60 days	[60]
Food waste like peel and pomace of fruits (apple, banana, orange, and kiwi) and vegetables (potato, cabbage, and carrots).	Aerobic composting	To develop a composting recipe starting from investigation of food waste like peel and pomace of fruits (apple, banana, orange, and kiwi) and vegetables (potato, cabbage, and carrots).	n.d.	[67]
Fruit and vegetable wastes, biodegradable municipal waste.	Open aerobic composting.	Production of composts.	30 days	[64]
Fruit waste (apple, banana, orange, and kiwi peels) and vegetable waste (cabbage leaves, potato and carrot peels).	Composting	To investigate and evaluate the composting potential of fruit and vegetable waste with sawdust in different combinations and to establish the relationship between microorganisms and physico-chemical parameters.	70 days	[61]
Fruit and vegetable waste from supermarkets (e.g., tomatoes, bananas, lettuce, peppers, clementines, potatoes, and melons)	Composting using an automated thermophilic composting technology.	Design a decentralized composting system that meets supermarket needs	14 days	[68]
Fruit waste (pineapple tops) and garden waste (dry leaves and fresh leaves)	Vessel aerobic composting	To produce and assess the properties of the biofertilizer obtained from this process and evaluate its potential application in agriculture.	48 days	[62]

Note: n.d., not determined.

3.4.2. Animal feeding

Animal feed refers to the sustenance provided to domesticated animals, particularly livestock, during the practice of animal husbandry. Depending on the characteristics of the FVPW, certain types are more likely to be repurposed into animal feed due to their nutrient content.

Essentially, FVPW can be utilized directly as primary feed (in conjunction with other diets) or for the development of secondary feed that can be incorporated into animal diets with other feed sources. The direct use of FVPW as primary feed is a straightforward and well-known practice. In secondary feed production, FVPW can be used as a substrate to rear protein-rich organisms, including earthworms and black soldier fly larvae [30,69,70]. The resulting earthworm biomass and black soldier fly larvae can serve as partial alternatives to traditional protein sources in animal feed.

Preprocessing FVPW is crucial to ensuring its suitability as animal feed, facilitating its integration with other diets, and minimizing potential health risks. In this context, approaches have been documented by scholars for the pre-processing of FVPW to diminish moisture content, including sun drying, heat treatment, pressing, microwave drying, and pulse combustion drying, as shown in Table 2. Many methods rely on lowering the moisture content of FVPW to reduce odor, decrease weight, and prolong its shelf life. Additionally, certain treatments assist in eliminating microorganisms that may induce health complications after animal consumption. It is crucial to consider the appropriate conditions for the technologies employed in drying FVPW, as Esteban et al. [71] found that such waste contains vital nutrients for swine diets; drying at temperatures over 65°C may reduce digestibility.

Esteban et al. [71] reported that FVPW can serve as an energy source for growing swine, as it has a significant percentage (65%) of nitrogen-free extract (mostly sugars and carbohydrates) and fiber, which aids digestion. Other studies have indicated that the incorporation of FVPW into feed enhances the milk quality of lactating Holstein cows [72]; improved daily weight gain and digestion in bulls, while preventing 0.43 gigagrams (Gg) of methane emissions annually [73]; reduced blood urea levels in bulls [73]; and sustained normal growth in Hanwoo steers, alongside benefits such as decreased feed costs and minimized food waste [74]. Furthermore, as detailed in Table 2, many researchers have reported the presence of animal feeding ingredients in FVPW in differing quantities, including neutral detergent fiber (NDF), soluble carbohydrates, crude protein, carbon, and nitrogen. The existence of these nutrients indicates the significance of incorporating certain FVPW into animal diets, as researchers have examined the substitution of FVPW in animal diets at different percentages and discovered that the benefits outweigh the drawbacks [71,73,75].

Table 2. Overview of selected studies reporting the use of FVPW for animal feeding.

Raw Materials Used	Drying Technologies Used	Nutritional Composition for Studied Fruit-Vegetable Wastes	Objectives/Purposes	Reference
Fruit–vegetable and fish wastes from shops in the city of Salamanca (Spain)	Heat treatment to reduce moisture content	65% Nitrogen-Free Extract, 12% Crude Protein, 13% Crude Fiber, 8% Ash (minerals), 2% Ether Extract (fat).	To find out whether fruit–vegetable waste and fish waste could be safely and effectively used as feed for pigs (especially during the growing and finishing stages of pig farming).	[71]
Fruits and Vegetable wastes Collected from Minorista Market, Antioquia, Colombia	Sorted and dried	10% protein (PC), 36.6% NDF (Neutral detergent fibre), 29.6% Acid Detergent Fiber, 0.59% Ca, and 0.21% P	The use of FV as feedstuff for diets of lactating Holstein cows with an emphasis on milk yield and quality so as to reduce environmental pollution of FV waste.	[75]

Raw Materials Used	Drying Technologies Used	Nutritional Composition for Studied Fruit-Vegetable Wastes	Objectives/Purposes	Reference
Vegetable waste generated in the Basque region	Pulse combustion drying, oven and microwave	n.d.	Production of new ingredients from vegetable waste for animal feed.	[72]
Household and market vegetable waste	Blended using high-speed blender (1400 rpm) and Sun-dried and milled into fine particles.	For household /market waste; 140/169 g/kg DM crude protein, 370/410 g/kg DM Neutral Detergent Fiber, 300/350 g/kg DM Acid Detergent Fiber, 66.8/63.3 % Total Digestible Nutrients, 15.3/15.2 MJ/kg DM Gross Energy	To determine the chemical composition and nutritional value of vegetable waste (VW) of households and the marketplace for their suitability as ruminant feed.	[76]
Vegetable waste (cucumber, bitter gourd, spotted gourd, brinjal, pumpkin, potato, tomato, finger, and snake gourd)-Bangladesh.	Sundried for about 32 to 40 h	When level of vegetable waste is 30%, then; 161.4 g/kg DM Crude Protein, 567.3 g/kg DM Neutral Detergent Fiber, 254.7 g/kg DM Acid Detergent Fiber, 22.20 g/kg DM Ether Extract	To test whether processed vegetable waste (VWP) can be safely and effectively used as part of the feed for bulls.	[73]
Cabbage, Chinese cabbage peels, and, Fruit-vegetable byproducts (orange, apple, tomatoes, onion, bell pepper, etc.) obtained from a wholesale fruit and vegetable distribution center - Korea.	Dried at forced-air ovens connected to the sucking fan 60 °C for over 24 hours	For Cabbage/Chinese Cabbage/mixed fruit-vegetable; 18.69/20.20/10.07 % Crude Protein, 22.31/28.83/13.94 % Neutral Detergent Fiber, 44.93/24.69/66.72% Non-Fiber Carbohydrates.	To evaluate nutritional value and in situ degradability of fruit-vegetable byproducts and their feeding effects on performance of growing Hanwoo steers.	[74]
Fruits and Vegetable wastes Collected from General Wholesale Market in Milan, Italy.	Pressing to remove water	Before/After pressing; 12.37/11.9 % Crude Protein, 22.43/25.6% Neutral Detergent Fiber, 8.12//8.04% Ash, 30.51/25.9% Soluble Sugars, 43.73/42.8% Carbon, 1.97/1.84% Nitrogen.	To assess the possibility of reallocating fruit and vegetable waste into livestock nutrition based on the nutritional analysis.	[77]

Note: n.d., not determined.

Collectively, these studies indicate that animal feeding paths provide environmental and economic advantages by decreasing dependence on traditional feed suppliers and concurrently redirecting organic waste from landfills. The heterogeneity in nutritional concentration among FVPW indicates that standardized quality evaluation and handling protocols are crucial for safe and consistent implementation. The use of FVPW for animal feeding exemplifies a pragmatic application that adheres to circular economy principles by converting inevitable food waste into usable resources within agricultural production systems.

3.4.3. Anaerobic digestion of FVPW

Table 3. Overview of selected studies reporting the use of FVPW for AD.

Raw Materials Used	Facilities Used	Digestion Duration	Biogas Production Rate	Purposes	Reference
Fruit and vegetable wastes (FVW) (avocado, papaya, mango, tomato, banana peel), food waste (FW) and cow manure (CM) as an inoculum.	Plastic biogas digesters (Semi continuous system, and batch system (20 L and 1.4 L))	55 days	FVW = 37ml/g FW = 47ml/g	The production of biogas from fruit and vegetable wastes mixed with cow manure in an anaerobic digester.	[79]
Fruit and vegetable wastes (pineapples, mangoes, watermelons, avocados, oranges; paw paws and ripe bananas) from Urafiki market (FVW), Cattle manure (CM), and wood ash (WA).	Biogas digesters (batch system)	> 20 days	FVW = 0.1 L FVW + WA = Decent biogas output FVW + WA + CM = 34.2 L	To quantify and characterize the fruit wastes generated from the Ubungo Urafiki Market in Ubungo Municipality and to establish the potential treatment of these wastes by anaerobic digestion.	[82]
Food waste (FW), Fruit waste (FrW), Tuber waste (TW), Vegetable waste (VW), and sewage sludge from Moi University's sewer system as an inoculum.	Plastic bottle reactors (Batch system 1.5 L)	> 10 days	FW = 732 ml/g VW = 214 ml/g FrW = 357 ml/g FW:TW = 306 ml/g FrW:VW = 927 ml/g TW:FrW = 2907 ml/g	Co-digestion of food waste to produce biogas	[80]
Fruit waste (FrW) Vegetable waste (VW) from fruit shops and markets in Hyderabad and buffalo dung as an inoculum.	Biochemical Methane Potential Test System (BMPTS)	40 days	FrW = 407 mL/g VS VW = 367 mL/g VS	To evaluate the fruit and vegetable wastes for methane generation through biomethanation process.	[81]

Anaerobic Digestion (AD) is a controlled process where microorganisms break down the organic materials in the absence of oxygen to produce biogas and other byproducts in semiliquid form (digestate). In this process, various factors are considered and controlled for the purpose of ensuring maximum production of the targeted end product, which, in most cases, is biogas (methane gas). Temperature, pH, and moisture content are commonly controlled conditions [78]. AD is a popular technology for the treatment of organic waste due to the economic benefit of its products, as it can be used as an energy source, and the remaining semisolid materials can be used as organic fertilizer. As they are organic in nature, many researchers reported the successful results in converting the FVPW alone or in combination with other organic materials into biogas and digestate by using AD, as summarized in Table 3.

Conversion of FVPW into biogas sometimes needs to be combined with other organic waste and inoculum as a source of microbes for maximum yield. The common inocula used by researchers include cow dung/manure [79], sewage sludge [80], and buffalo dung [81]. The main purpose of the inoculum is to add required microbes for AD and balance the nutrients. The prevalent dependence on co-digestion and inoculum supplementation in several experiments indicates that FVPW alone may not consistently yield an appropriate nutritional equilibrium for stable digestion, underscoring the need for substrate optimization as a critical operational factor.

Many researchers have identified some factors that can limit the production of biogas in the FVPW, such as mixing ratio, pH levels, and temperature. For example, Aloyce et al. [82] studied the production of biogas from market fruits (pineapples, mangoes, watermelons, avocados, oranges, pawpaws, and ripe bananas) and found that the addition of wood ash could increase the production of biogas, as it helped raise the pH of feedstock and favors microbiological activity. Furthermore, Mrosso et al. [80] found that an equal ratio in mixing fruits and a temperature above 40 °C has better results for biogas production, indicating that these factors are critical in studying the possibility of FVPW to produce biogas in AD processes. Conversely, reports indicate that the feedstock-to-inoculum ratio plays a crucial role. Korai et al. [81] reported the potential of FVPW in methane production, but a better yield was obtained at a mixing ratio of 30:70 (30% waste + 70% inoculum), and vegetable waste gave better results than fruit waste, indicating the high potential of vegetable waste in methane production. These studies demonstrate that AD performance is significantly influenced by feedstock composition and operating conditions, indicating that establishing standardized process parameters across contexts may be challenging. This variation signifies that site-specific optimization is crucial, especially in developing countries where feedstock composition and operational control may vary.

3.4.4. Briquetting

Briquetting is the process of compressing loose, tiny, or less dense materials into dense solid blocks to generate briquettes. This process is prevalent for agricultural residues, which are mixed with other materials to enhance their binding potential and subsequently crushed to create pellets that serve as alternatives to charcoal. The briquettes show superior physical and combustion properties compared to the original residue due to their high density. The predominant raw materials used for briquetting include cotton stalks, coconut husks, bagasse, and wheat straws. The use of FVPW for briquettes can reduce open dumping and reliance on wood-based fuels; however, energy and processing requirements may influence overall sustainability outcomes depending on local technological capacity.

Table 4 indicates studies that entailed the utilization of FVPW for briquette production. Diverse raw materials, processing techniques (such as drying, fermentation, and carbonization), and binders (paper or clay) were employed. The briquetting techniques encompassed manual and hydraulic presses. The objective in all instances was to convert waste into fuel and mitigate environmental damage. The diversity of raw materials and processing methods reported across studies suggests that briquetting is a flexible technology that can be adapted to locally available feedstocks, which is particularly relevant for decentralized applications in developing-country contexts.

Table 4. Overview of selected studies reporting the use of FVPW for briquette production.

Raw Materials Used	Steps for Treating Raw Waste	Binder	Briquette Making Methods	Purposes	Reference
Fruit and Vegetable (Carrot and cabbage leaves)	Sun-drying, Pulverizing, Torrefying, and Fermentation	Paper waste	Manual briquette press (piston-type press)	To reduce organic waste at the market, and to create alternative fuel to firewood or charcoal.	[83]
Orange and banana peels	Drying, Pressing, Carbonization	None	Uniaxial hydraulic press and a cylindrical mold	To turn orange peels and banana peels into solid fuel briquettes that could be used for cooking, heating, or even as raw materials for activated carbon (AC).	[84]
Vegetable market waste collected from near Karicode Market, Kollam, Kerala and sawdust.	Sun-drying, Crushing, and Mixing	Bentonite clay	Manual compression method	To reduce amount of vegetable market waste (VMW) being improperly managed and to reduce reliance on firewood consumption.	[85]

The performance and quality of briquettes derived from FVPW are markedly affected by the nature of the feedstock used, the pre-treatment techniques employed, and the ratio of binder to waste. Akande and Olorunnisola [83] established that increasing the binder ratio improved the combustion rate and thermal efficiency of briquettes, although it adversely impacted briquette integrity by complicating the briquetting process and inducing surface cracks. Notably, it was noted that igniting time increased with increased binder ratios for cabbage briquettes, while the contrary was observed for carrot briquettes.

Moreover, treatment techniques, including torrefaction and fermentation, significantly enhance density while decreasing moisture content and smoke emissions. Karimibavani et al. [84] found that briquetting pressure influences ignition quality, with banana peel briquettes performing optimally at 5 tonnes/cm^2 and orange peels at 3 tonnes/cm^2. However, carbonization, although advantageous for generating longer-burning fuel, results in a delayed ignition period. The variability in optimal conditions across feedstocks suggests that briquetting performance is strongly material-dependent, requiring context-specific process adjustments rather than universal production parameters. These findings offer valuable insights for enhancing briquette manufacturing from organic waste and can direct future research toward more efficient and sustainable biofuel technologies.

3.5. Emerging technologies (ET)

Emerging technologies are innovative ones established for waste management. The primary goal of most of these technologies is to outperform conventional methods by enhancing the value of the waste. These technologies involve the process of extracting valuable materials, synthesis to form valuable materials, and physical, chemical, or biological conversion to form more valuable materials. While most of these technologies are new, some are older; however, advanced techniques are used to enhance and optimize the processes without compromising the targeted end products.

As with other wastes, emerging technologies are applied to manage the FVPW by either extracting, synthesizing, or converting it into new value products. Many researchers have reported the use of FVPW to produce other valuable products such as biochar, natural bioactive compounds, bioethanol, and bioplastic films. These products are produced from a certain process or after a series of processes.

3.5.1. Biochar production

Biochar is a charcoal-like material derived from biomass via a process known as pyrolysis, which involves heating biomass in a low-oxygen or oxygen-free environment. Although charcoal and biochar undergo nearly identical production processes, their characteristics change due to variations in the uses. Biochar serves as a soil amendment in agriculture (to boost water retention, improve nutrient availability, etc.), for carbon sequestration, and as an adsorbent. Charcoal is primarily used as a smokeless fuel for cooking, heating, and steel production [86,87].

3.5.1.1. Biochar as soil amendment

Biochar is used in the soil to modify its physical, chemical, and biological characteristics to improve soil health and promote plant growth. Table S2 highlights the research conducted by several scholars who have attempted to utilize FVPW in the synthesis of biochar for agricultural soil applications. Researchers have reported the application of FVPW in biochar production to enhance agricultural soil quality, thereby promoting plant growth [88], facilitating carbon sequestration and nutrient cycling [89], improving soil fertility and water retention [90], enhancing microbial activity [91], and increasing crop yield [92]. The FVPW utilized in biochar production for soil amendment includes banana peels, spinach, peas, tomatoes, orange peels, cauliflower, cabbage remains, mangoes, and apple waste. Each of these basic ingredients, whether used together or independently, has shown outstanding performance. Table 5 presents the performance of different biochar derived from FVPW in distinct manners. The variety of feedstocks reported in the research indicates that biochar synthesis can be adapted to locally accessible waste streams, rendering it a compelling choice for transforming organic matter wastes into valuable agricultural inputs.

Table 5. Overview of selected studies reporting the use of FVPW for biochar production.

Fruits/vegetables raw material used	Other raw materials used	Method Used	General characteristics of produced biochar	Purposes of Applications	Efficiency	Sources
Durian peel, Mangosteen rind, Corncob, Banana peel	Shrimp shell	Pyrolysis (temperature not specified)	Heat of combustion: Corncob biochar highest (75.151 Kcal/g)	Plant growth enhancement	Significant improvement in Swamp morning glory growth (t-test confirmed)	[88]
None	Empty Fruit Bunch	Pyrolysis at 400–600°C	pH 10.88, CEC 35 meq/100g, BET surface area varies, highest at 400°C	Carbon sequestration, soil fertility improvement	High yield (50.60%) at 400°C	[93]
Spinach, Pea, Tomato, Banana, Orange	None	Integrated fermentation + Pyrolysis at 500°C	Surface area 28.43 m^2/g (spinach), density 1.93 g/cm^3, pore volume 0.59 cm^3/g, yield 59.04%	Carbon sequestration, nutrient cycling, bioenergy	Profit from pyrolysis: $3.66/kg; highest total: $5.21/kg (fermentation + pyrolysis)	[89]
Cauliflower, Cabbage, Banana peels, Corn cobs	None	Pyrolysis at 300–600°C	pH 7.2–11.6, CEC 17–cmolc/kg, ECE 0.15–1.00 mS/cm	Improve soil fertility, water retention	Best characteristics at 400°C with small particle size	[90]
Mango, Apple, Pomegranate, Orange peels	Nut shells (peanut, almond, walnut)	Muffle furnace at 550°C for 2 hours	Presence of carbon nanotubes, circular pores, crystalline nature	Improve soil fertility, microbial activity, plant growth	Highest biomass at 1% mixed biochar; improved microbial counts and soil EC	[91]
Cauliflower, Cabbage, Banana peels, Corn leaves and cobs	None	Pyrolysis at 400°C	pH 8.0, CEC 53.2 cmolc/kg, reduced EC, porous, high-water retention	Improve water retention, nutrient content, crop yield	Doubled water retention and biomass yield at 2–6% application	[92]

To enhance plant development, Takolpuckdee [88] reported a notable improvement in the growth of swamp morning glory, whereas Soltan et al. [89] claimed a profit of $3.66 per kilogram. Additional experiments indicated better effectiveness of biochar derived from cauliflower, cabbage, banana peels, and maize cobs in enhancing microbial activity, water retention, nutritional content, and crop yield [92]. Moreover, binti-Ab-Aziz et al. [93] and Pradhan et al. [90] researched and identified enhancements in soil fertility, evidenced by improved cation exchange capacity (CEC), rising pH levels, and augmented nutrient availability. These findings suggest that utilizing certain FV waste in biochar production as a soil amendment is feasible, potentially improving agricultural soil fertility to boost crop yield and occasionally serving as a means of carbon sequestration [93]. The utilization of FVPW-derived biochar connects waste valuation with climate-smart agriculture by simultaneously tackling waste reduction, soil restoration, and carbon management. The effectiveness of this method may be contingent upon pyrolysis conditions [94] and local agronomic circumstances [95], necessitating site-specific assessment before large-scale implementation.

3.5.1.2. Biochar as adsorbents

An adsorbent is a solid material that can attract and hold liquids or gases on its surface, playing a vital role in environmental applications, including water and gas treatment. Efficient adsorbents often possess a substantial surface area, a porous structure, and chemical properties that enhance contact with the target pollutants (adsorbates). FVPW has become a viable feedstock for the development of economical and sustainable adsorbents, owing to its substantial carbon content, prevalence, and capacity to form porous structures by thermal or chemical processing.

Annadurai et al. [96] conducted a study, illustrating the effectiveness of banana and orange peels sourced from local fruit booths for the removal of dyes from aqueous solutions. The adsorbents were synthesized through oven drying (100–120°C) without chemical activation. Despite a relatively low surface area (20.6–23.5 m^2/g), the materials efficiently eliminated dyes, including methyl orange, methylene blue, Rhodamine B, and Congo red, demonstrating the utility of minimally processed FVPW. These findings indicate that even low-technology processing methods can yield functional adsorbents, suggesting potential suitability for low-resource settings where advanced activation technologies may be inaccessible.

Conversely, Negroiu et al. [97] employed an advanced technique, utilizing two-stage pyrolysis (700°C and 800°C) with NaOH activation to transform banana peels into a high-performance adsorbent. The altered material (particularly the ALG–BPA version) attains complete removal efficiency for Cr, Cu, Pb, and Zn in synthetic water. Nevertheless, owing to the small particle size and recovery difficulties of the ash-based material, researchers have integrated biopolymeric matrices (alginate and chitosan) to augment reusability, illustrating the progression toward more practical and regenerative adsorbents. The contrast between simple and highly engineered approaches illustrates a trade-off between processing complexity and adsorption performance, highlighting that higher efficiency often comes at the expense of increased technical and economic requirements.

Other FVPW have been productively employed. Mallampati and Valiyaveettil [98] investigated the effectiveness of tomato peels in eliminating several contaminants, including heavy metals (e.g., Pb^{2+}, Cr^{6+}), dyes, and pesticides. Through basic boiling and drying methods, they observed elevated adsorption effectiveness attributed to functional groups, including –OH, –COOH, and $–NH_2$, on the peels, which offer numerous binding sites. Changmai et al. [99] further illustrated the adaptability of FVPW-derived adsorbents by creating a composite adsorbent from carrot and tomato waste coupled with PET plastic, which was chemically activated with $ZnCl_2$ and pyrolyzed at 500°C. This composite has demonstrated excellent performance in eliminating Co (II) from aqueous solutions, with an outstanding adsorption capacity of 312.5 mg/g, one of the highest reported for bio-waste-derived adsorbents. Comparing these studies suggests that functional group composition and activation methods strongly influence adsorption capacity, indicating that material design plays a critical role in determining the applicability of FVPW-derived adsorbents for specific contaminants.

Furthermore, Lam et al. [100] employed banana and orange peels to generate biochar through pyrolysis at temperatures from 400 to 500°C, yielding a material with a surface area of 105 m^2/g. This adsorbent effectively treats palm oil mill effluent (POME), decreasing pollutants, including BOD, COD, TSS, and oil and grease, up to 57%, indicating promise for wider industrial wastewater applications. QinYing et al. [101] conducted pyrolysis of pomegranate peels at two temperatures (300°C and 600°C), resulting in biochar with distinct surface characteristics. All biochar demonstrated effective Cu(II) adsorption capabilities (~52 mg/g), and the biochar-amended soil markedly enhanced Cu retention relative to unamended soil, hence endorsing its use for in-situ soil remediation.

The findings collectively confirm the considerable potential of FVPW, specifically banana, tomato, carrot, and citrus peels, as effective and economical precursors for adsorbent production. The method offers viable solutions for pollutant removal from water and soil while enhancing waste valorization and minimizing organic waste sent to landfills, in accordance with circular economy principles. Table S3 presents a summary of studies on the use of fruit and vegetable waste for adsorbent production. While advanced activation techniques typically improve adsorption performance, the studies reviewed indicate that simpler and less energy-intensive processing methods may offer more viable options for large-scale implementation in resource-constrained environments, underscoring the need to balance technological efficiency with practical feasibility in the selection of adsorbent production strategies.

3.5.2. Natural bioactive compounds

Natural bioactive compounds are molecules that are found in nature, particularly in animals, plants, and other living organisms such as fungi. These molecules are considered to provide health benefits [102]. Some FVPW are among the feedstocks that are reported to produce the natural bioactive compound by extraction processes. This technique of utilizing FVPW in the production of bioactive compounds is considered to add more advantage to waste management, as it reduces the consumption of fresh raw materials for the production of these compounds, but it also reduces the quantity of waste going to landfills [103]. The natural bioactive compounds extracted from the FVPW have many applications, as some of them are used for green synthesis to produce nanoparticles [104–107], antioxidation [108], food flavoring [109, 110], natural food coloring [111], and phyto-compounds [112]. This wide range of applications suggests that FVPW-derived bioactive compounds occupy a higher position in the waste valorization hierarchy compared with energy or compost-based pathways, as they can generate products with greater economic value and industrial relevance. The summary of the studies that used FVPW to produce bioactive compounds for different applications is presented in Table S4. However, while the reported applications exhibit considerable potential, the scalability of extraction methods may be contingent upon aspects such as extraction efficiency, processing expenses, and uniformity of feedstock composition. The use of FVPW for extracting bioactive compounds presents a novel possibility to merge waste management with green chemistry and bioproduct development, thus enhancing resource efficiency and sustainability in industrial systems.

3.5.2.1. Nanoparticles

In green synthesis, the extracts from plants act as the reducing agents that convert metal ions into nanoparticles. This means that the extract contains a functional group that donates electrons to the metal ions, causing them to be reduced and form zero-valent metal atoms [113]. Nava et al. [104] studied a green synthesis of zinc oxide nanoparticles using fruit peels (tomato, orange, grapefruit, and lemon) and found better performance (97%) for photodegradation of methylene blue compared to chemically synthesized commercially available zinc oxide nanoparticles. The researchers used a water bath at 60°C for the extraction of extract, which was later used for the green synthesis of zinc oxide nanoparticles (ZnONPs). The enhanced performance indicated in this work implies that the phytochemical components in FVPW extracts may improve catalytic activity, showing that materials obtained from waste can rival or exceed traditional products in some applications.

By using hot water, Boomi et al. [105] produced extracts from the *Coleus aromaticus* leaf and used it for green synthesis of gold nanoparticles (AuNPs). The synthesized AuNPs showed favorable properties and their potential to be used in the protection of UV light as antibacterial agents and as anticancer agents. Omran et al. [107] and Kadam et al. [106] used mandarin waste peels and cauliflower leaf waste (*Brassica oleracea* var. botrytis), respectively, for the production of silver nanoparticles (AgNPs), which were used in photocatalytic degradation of dyes. All these produced AgNPs showed the low cost compared with the chemically synthesized ones. Analysis of these reported findings reveals that FVPW-derived extracts function as adaptable reducing and stabilizing agents in metal systems, underscoring the flexibility of this approach for a range of environmental and biological applications.

This process of green synthesis using FVPW to obtain nanoparticles leaves the green materials after the extraction of extract (liquid part); these remaining materials can be recycled again and used as compost or sometimes to produce AC [107]. The sequential utilization of residues exemplifies a multi-phase valuation strategy, wherein waste streams are progressively converted into products, enhancing circular economy principles and optimizing overall resource efficiency. However, despite encouraging laboratory-scale outcomes, broader application may hinge on scaling difficulties, the standardization of extraction procedures, and evaluations of economic viability. Nanoparticle synthesis from FVPW is a novel, high-value approach that integrates waste management with advanced material manufacturing, all while upholding environmental sustainability principles.

3.5.2.2. Antioxidation compounds

Some FVPW contains bioactive compounds that can exhibit antioxidant properties, such as phenolics, flavonoids, and carotenoids. Different FVPW are reported to produce these compounds in varying amounts depending on the types of FVPW used. Wolfe and Liu [108] extracted the phenolics, flavonoids, and anthocyanin from apple peels using chilled 80% acetone or 80% ethanol. They found that 1 g of powder (powder extracted from apple peels) has an antioxidant activity equivalent to 220 mg of vitamin C, indicating it can be used in food productions to add phytochemicals and promote good health.

Sir Elkhatim et al. [114] used citrus fruit (lemon, orange, and grapefruit) waste for the production of phenolics, flavonoids, and vitamin C from different parts of those citrus fruits. They found that the peels contain higher antioxidant activity than the inner parts (pulp and seeds). In terms of the studied citrus fruits, they found that grapefruit peels have the highest amount of total phenolic content (77.3 mg of gallic acid equivalent/g of peels), while orange peels have a high quantity of flavonoids (83.3 mg of catechin equivalent/g) and vitamin C (110.4 mg/100 g) compared to the peels of the other citrus fruits. Those findings indicate the potential use of citrus fruit peel in the production of phenolics, flavonoids, and vitamin C, which can be used in the food industry as a natural antioxidant, other than sending them directly to landfills.

3.5.2.3. Food ingredients

On the other hand, some scholars reported the possibility of recovering substances that can be added to food to achieve a desired effect, such as enhancing flavor, texture, or nutritional value (food ingredients) from FVPW. Researchers have reported the use of FVPW in the production of flavor/aroma and color ingredients and other food ingredients [109,110,115]. Generally, many methods are used to extract those ingredients from the FVPW, with each method having its own advantages and disadvantages.

Lalou et al. [109] reported the utilization of orange peel hydrolysate as a sugar-dense substrate for the synthesis of flavor-active chemicals by *Saccharomyces cerevisiae* yeast, evaluated in free-cell and immobilized-cell systems. Their research demonstrated that immobilized yeast generates a higher amount of fruity aroma esters, including phenylethyl acetate, ethyl hexanoate, ethyl octanoate, ethyl decanoate, and ethyl dodecanoate. Moreover, chemicals inherently found in orange peel essential oil, such as limonene and α-terpineol, were identified due to their accumulation within the immobilisation beads. The hydrolysis of orange peels into a sugar-rich liquid provides a cost-effective feedstock, contributing to the reduction of initial material expenses for microbial flavor synthesis. These findings indicate that FVPW can serve not only as a substrate for extraction but also as a functional bioprocessing medium, expanding its potential role within food innovation systems.

Bas-Bellver et al. [115] reported the valorization of vegetable byproducts, specifically carrot, leek, celery, and cabbage waste, derived from fresh and ready-to-eat processing lines, via the creation of functional powders. The researchers employed two drying processes, hot-air drying and freeze-drying, alongside varying grinding intensities and storage conditions to treat vegetable waste. The findings indicated that hot-air drying yields stable powders with less water activity and improved functionality, notably increasing antioxidant potential. These functional powders possess potential applications in the food industry as natural colorants, flavoring agents, preservatives, and nutritional enhancers for the reformulation of processed foods to augment their health values.

Jayesree et al. [116] examined the valorization of carrot peel waste, an agro-industrial byproduct abundant in carotenoids and pectin, utilizing a sustainable extraction technique termed carotene-pectin hydrocolloidal complexation. By employing water as the medium and optimising conditions through the response surface approach, they successfully co-extracted β-carotene (1.17 mg/100 g with 96% purity) and pectin from carrot peels, utilizing fewer processing steps than traditional solvent extraction methods. The extracted β-carotenes had significant antioxidant activity, and the process offered an eco-friendly and cost-effective means of recovering bioactive chemicals, with potential uses as natural antioxidants, colorants, and functional food components.

Other researchers reported extracting vanillic acid and vanillin from pineapple cannery waste by using fermentation [110], extracting oligosaccharides, phenolics, and proteins from melon peel waste by using sodium acetate/urea [117], and extracting anthocyanins, hydroxycinnamic acids, and flavanones from red oranges and olive leaves by the pressing method. Similarly, some vegetables such as spinach were reported to produce phyto-compounds such as lutein and chlorophyll [112].

Vanillin, vanillic acid, anthocyanins, hydroxycinnamic acids, and flavanones are extensively utilized in the food industry as flavoring agents, natural colorants, and antioxidants. Oligosaccharides and proteins can serve as prebiotics and nutritional supplements in functional foods. Although many of these have direct applications, phenolic extracts can also be employed in nutraceuticals or as natural preservatives beyond food use. Lutein is widely used as a natural colorant and antioxidant in functional foods and dietary supplements, while chlorophyll is applied as a natural green pigment, detoxifying agent, and potential health-promoting additive in food products.

3.5.3. Bioplastic films

Bioplastic films are plastic films made from renewable biological sources such as plants, bacteria, and algae. Bioplastic films are considered sustainable alternative materials to petroleum-based films because they have a lower carbon footprint, as they are made from renewable sources and they can naturally degrade under specific conditions. Bioplastic materials can be utilized in many applications, including packaging [118,119], in agriculture [120], in textiles [121], and in the construction industry [46,122].

Table S5 outlines research that entailed FVPW, including banana peels, mixed vegetable wastes (carrot, parsley, radicchio, and cauliflower), carrot peels, orange peels, and tomato peels, for the production of bioplastic films. Each study utilized a distinct processing method, frequently integrating waste with plasticisers (e.g., glycerol) or other biopolymers (e.g., starch or gelatine), and applied chemical treatments such as acids or alkalis to facilitate film production. The primary objectives of these researchers were to analyze the viability of FV wastes as feedstock for bioplastics, enhance film characteristics via alternate solvents or coatings, and evaluate their prospective applications in packaging or other sustainable domains. The diversity of formulations and treatments suggests that the performance of FVPW-derived bioplastics is highly formulation-dependent, indicating that optimization of feedstock composition and additives is central to achieving commercially viable films.

A radar chart (Figure 7) was utilized to comparatively evaluate the performance of bioplastic films based on their characteristics provided in the examined studies. Five principal parameters frequently evaluated in bioplastic research were chosen for comparison: mechanical strength, water resistance, biodegradability, thermal stability, and functional capabilities, including antioxidant or barrier effects. Due to the discrepancies in units and testing methodologies (such as MPa for tensile strength or % swelling for water absorption), a standardized scoring system was established on a scale of 1 to 5, where higher scores indicated superior performance. The scores allocated to each property for the various films are shown in Table S6.

The comparison study indicated that carrot peel films [123] exhibited superior overall performance, integrating exceptional mechanical strength with adequate water resistance and thermal stability, rendering them among the most balanced and promising bioplastics developed from FVPW.

Films made from vegetable waste of carrot, parsley, radicchio, and cauliflower [124] exhibited exceptional functional qualities, including antioxidant capacity and gas barrier performance, underscoring their suitability for food packaging applications. Tomato peel films [125] had exceptional water resistance because of the inclusion of cutin; however, their mechanical and thermal durability was low. Conversely, orange peel bioplastic films [126] and banana peel bioplastic films [127] exhibited great biodegradability but worse performance in other aspects, with banana peel bioplastic films demonstrating the lowest total mechanical strength.

Collectively, these findings suggest that although FVPW wastes can be effectively processed into bioplastic films, their quality is significantly affected by the composition of the raw materials and the processing techniques employed. When formulating bioplastics for specific purposes, a thorough analysis of the intrinsic properties of each feedstock is crucial.

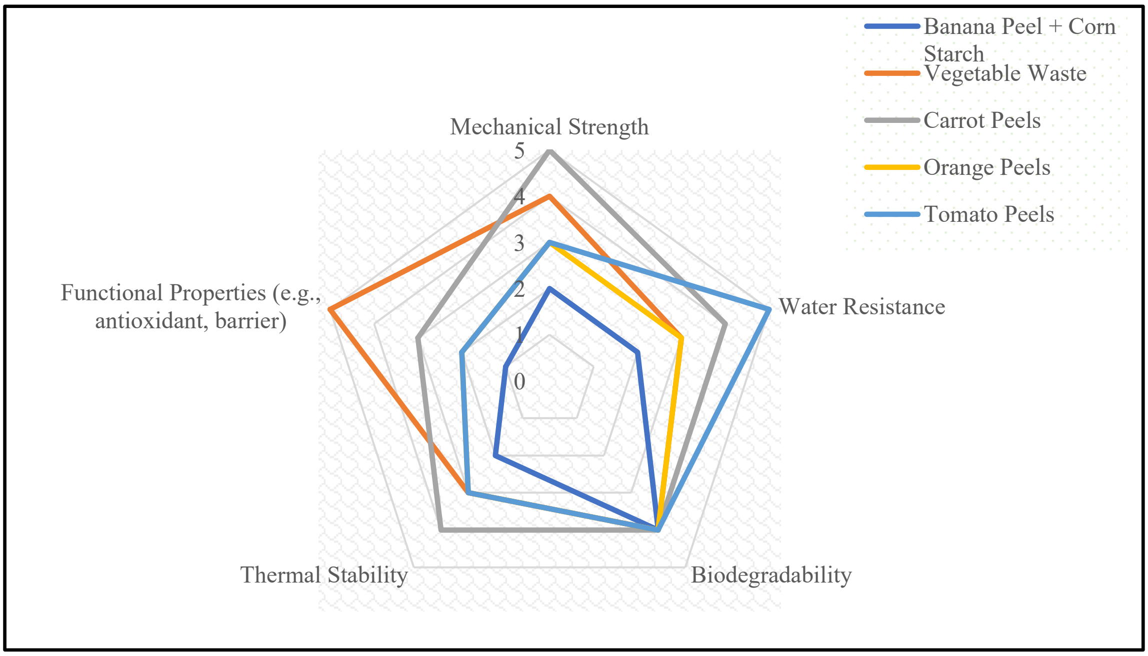

Figure 7. Comparison of the bioplastic film properties from different FVPW.

3.5.4. Bioethanol

Bioethanol is an alcoholic substance derived from many cellulose-rich plants, including sugarcane, sugar beet, and certain grains like corn. While it is feasible to grow these vegetable raw materials for direct bioethanol synthesis, this fuel can also be derived from forestry residues and agricultural waste. Ethanol is employed in gasoline blending [128,129], cooking fuel [130], green solvent [131], disinfectants and sanitizers [132], and many more applications.

Bioethanol can be produced from FVPW, as certain varieties are abundant in sugar. The prevalent techniques employed in the synthesis of bioethanol from biomass involve a combination of hydrolysis as a pretreatment and fermentation. Table S7 summarizes extensive research that utilizes various FVPW for bioethanol production. It outlines the microorganisms implicated, pretreatment, and fermentation methodologies, as well as chemicals employed to improve process efficiency. The diversity of pretreatment and fermentation methods reported in the literature demonstrates that process optimization is crucial for maximizing ethanol yield, implying that technological design may be as significant as feedstock selection.

Table 6. Ethanol production performance from fruit and vegetable wastes, showing concentration, process duration, and calculated productivity (g/L/h).

Fruit/Vegetable Waste Used	Ethanol Concentration (g/L)	Note	Time Used (h)	Ethanol Productivity (g/L/h)	Source
Banana peels	157.0747	Highest yield at pH 6 (157.0747 mg/ml)	96	1.636	[133]
Citrus waste	52.3	Fed-batch fermentation	52	1.006	[134]
Pineapple residues	54	g/L (converted from 5.4% v/v)	72	0.750	[135]
Mixed fruit peels (citrus, banana, apple, pear)	29.5	Max yield 93.1%	48	0.615	[63]
Mango seed kernel	39.85	g/L (converted from 3.985%)-modified SS&F	96	0.415	[137]
Apple pomace	8.748	Yield 0.945 g/g	48	0.182	[138]
Pineapple peel	5.98	Direct from the study	48	0.125	[139]
Banana peels	0.08	Converted from 80 ppm (alkaline pretreatment)	72	0.001	[140]
Pineapple waste	0.9	Ethanol concentration reported as a spot value on day 5 for pineapple and sweet potatoes waste and day 3 for others	264-Total process duration	n.d. — peak ethanol observed on day 5 and 3 depending on raw materials; spot measurement only, not cumulative yield.	[136]
Indian water chestnut	0.45				
Jackfruit waste	0.45				
Sweet potato waste	0.79				

Note: n.d., not determined.

Table 6 illustrates a comparison of bioethanol yields derived from FVPW employing fermentation methodologies. Hamzah et al. [133] attained the maximum ethanol concentration of 157.07 g/L utilizing banana peels at pH 6 after 96 hours, yielding a productivity of 1.636 g/L/h, which was the most effective outcome among the studies examined. Additional potential substrates comprise citrus waste (52.3 g/L; 1.006 g/L/h) and pineapple residues (54 g/L; 0.750 g/L/h), as reported by Vadalà et al. [134] and Gil & Maupoey [135], respectively. This research utilized either fed-batch fermentation or simultaneous saccharification and fermentation (SSF) to enhance conversion efficiency. Analysis of these studies indicates that enhanced yields frequently correlate with improved fermentation conditions and integrated processing methods, underscoring the need of combining biochemical and operational characteristics to improve productivity.

In contrast, Gosavi et al. [136] reported ethanol concentrations as discrete values recorded on certain days over prolonged fermentation (e.g., 0.9 g/L on day 5 for pineapple waste for a total duration of 264 hours). The variation in reporting metrics among studies hinders direct performance comparison and highlights the need for standardized reporting frameworks to enable a more rigorous evaluation of FVPW-based bioethanol technology.

All these investigations demonstrate the possibility for bioethanol production from FVPW, with varying performance contingent upon the raw materials, pretreatment procedures, production techniques, and microorganisms employed. From a sustainability perspective, bioethanol production from FVPW provides a means to transform sugar-laden waste into renewable energy, thereby alleviating landfill pressures; however, the need for regulated fermentation conditions and pretreatment processes indicates a moderate to high level of technical complexity relative to more straightforward alternatives like composting or animal feed. The research reviewed suggests that bioethanol production is a viable energy recovery method that can advance circular bioeconomy objectives if it is backed by suitable technical infrastructure and process optimization.

3.6. Landfilling

Landfilling is the most common method used for the final disposal of waste. Under this option, the waste is disposed of under proper care to ensure that it will not cause environmental pollution. As FVPW is organic in nature, after disposal, the natural digestion process begins to take place and produces large amounts of greenhouse gases such as methane [141]. Modern landfills are equipped with gas collection systems that capture and separate methane, a potent greenhouse gas, for use in energy production. However, these systems are complex to operate, posing challenges for implementation in many developing countries. Consequently, large amounts of methane are released into the atmosphere, contributing to air pollution and climate change. Methane gas from the landfill waste decomposition has been reported as the third largest anthropogenic source of methane gas in the atmosphere [142].

Another critical environmental concern associated with landfills is leachate formation. Rainwater percolating through waste accumulates at the base of landfills, forming leachate. Without adequate collection and treatment systems, this contaminated water can seep into groundwater, risking aquifer pollution. Depending on its composition, leachate must be treated as wastewater before being safely discharged into the environment [57]. From a comparative angle, landfilling markedly differs from conventional utilization methods (composting, animal feeding, anaerobic digestion, and briquetting) and emerging high-value methods (biochar, adsorbents, bioactive compounds, bioplastics, and bioethanol production), which prioritize resource recovery and the circular use of materials over permanent disposal. Conventional pathways often necessitate smaller technology inputs and are often more readily applicable in developing countries, whereas emergent pathways offer greater economic benefit but require enhanced technical capacity, process control, and investment. Conversely, landfilling constitutes a linear conclusion that extracts minimal value while posing considerable environmental hazards due to methane emissions and leachate production. This review indicates that prioritizing prevention, reuse, and valorization strategies prior to disposal is more consistent with circular economy principles and sustainability objectives, relegating landfilling to a last-resort management option for unavoidable FVPW.

3.7. Contextual feasibility analysis of FVPW conventional and emerging methods for Tanzania

Effective management of FVPW in Tanzania necessitates balancing technological readiness, financial feasibility, environmental impacts, and infrastructure requirements. As shown in Table 7, this study identifies composting and animal feed production as high-readiness and cost-effective strategies. Composting is a common practice among smallholder farmers in East Africa [14,69]. It requires relatively low initial investment and it makes the soil more fertile while reducing the amount of waste that goes to landfills. Similarly, the conversion of clean, sorted FVPW into animal feed has proven effective in reducing feed costs and waste volumes in low-income contexts [143], making it particularly suitable for peri-urban markets and livestock systems. These options' strong feasibility largely stems from their alignment with agricultural practices, low technological complexity, and limited infrastructure requirements. Importantly, this practical suitability is reinforced by Tanzania's regulatory framework. The Environmental Management Act [144] mandates local authorities to minimize and manage solid waste, while the Environmental (Solid Waste Management) Regulations [145] emphasize waste segregation, recovery, and integrated waste management systems. These provisions directly support decentralized, low-cost recovery pathways such as composting and feed utilization. In addition to their contextual practicality, these high-readiness pathways directly support Sustainable Development Goal (SDG) 2 (Zero Hunger) through improved resource efficiency in food and livestock systems and SDG 12 (Responsible Consumption and Production) by reducing postharvest losses and promoting circular use of organic residues.

Medium-readiness technologies identified in Table 7 are AD, biochar production, and bioethanol production, all of which offer greater environmental benefits but face more substantial implementation constraints. AD can generate renewable biogas and nutrient-rich digestate, as demonstrated in sub-Saharan Africa [56, 146], yet its adoption in Tanzania is constrained by high capital costs, feedstock aggregation challenges, and operational requirements. Similarly, biochar production from lignocellulosic residues such as pineapple peels, banana stems, and mango seeds [56,147] demonstrated potential for carbon sequestration and soil enhancement, but scaling requires investment in pyrolysis systems and the development of stable markets. Although sugarcane industries have established bioethanol production technology, feedstock variability and integration challenges continue to constrain it. These limitations are not only technical but also institutional and financial.

The National Environmental Policy (2021) [148] explicitly identifies inadequate financial resources and weak implementation capacity as persistent barriers to environmental management, emphasizing the need of improved resource mobilization and coordinated policy execution. In parallel, the National Solid Waste Management Strategy [149] promotes waste recovery, including composting and energy generation, but also emphasizes that effective implementation depends on financial mechanisms, stakeholder coordination, and investment support. Thus, the medium-readiness classification reflects a mismatch between technological potential and enabling conditions within the Tanzanian system. Nevertheless, these pathways are relevant to SDG 7 (Affordable and Clean Energy) and SDG 13 (Climate Action) because they can contribute to renewable energy production, greenhouse gas mitigation, and carbon sequestration if the necessary technical and financial conditions are strengthened.

At the low-readiness level, bioactive compound extraction and bioplastics production remain largely confined to research and pilot stages, as indicated in Table 7. Laboratory studies have demonstrated the feasibility of extracting valuable compounds such as polyphenols and pectin from tropical residues [150,151] and the use of starch- and pectin-rich materials for biodegradable packaging [147]. However, Tanzania lacks the advanced processing infrastructure, stringent quality control, and reliable supply chains necessary for these pathways. Broader systemic factors, such as market readiness, regulatory clarity, and technical expertise, constrain their feasibility. This observation aligns with the Investment Guide on Waste Management in Tanzania [152], which identifies waste management as a sector with high economic potential but limited infrastructure, insufficient budget allocation, and weak enforcement capacity. Consequently, the implementation of these emerging technologies primarily hinges on investment conditions rather than technical viability, despite their higher economic returns per unit of waste. Even so, they remain strategically important because they can contribute to SDG 8 (Decent Work and Economic Growth) by creating opportunities for value-added industries, green employment, and higher-value circular bioeconomy activities.

Given these dynamics, strategic scaling of FVPW valorization pathways must prioritize high-readiness solutions while progressively enabling more advanced technologies, as synthesized in Figure 8. Figure 8 translates the readiness-based assessment into a phased implementation framework for Tanzania, linking immediate, medium-term, and long-term valorization options with enabling policy, infrastructure, and financing mechanisms. This approach is consistent with Tanzania's regulatory and policy direction, where waste minimization and resource recovery are embedded in legal and strategic frameworks. The Environmental Management Act [144] and supporting regulations provide a legal basis for waste reduction and recovery, while the National Solid Waste Management Strategy [149] promotes circular approaches, including reuse, recycling, and energy recovery. This strategic direction is further reinforced by Tanzania's National Postharvest Management Strategy (2019–2029) [18], which prioritizes reduction of postharvest losses, value addition, and improved handling systems, thereby creating a policy basis for integrating FVPW valorization into broader agri-food system efficiency. In this context, composting and animal feed production represent immediate, policy-aligned interventions that can address urgent waste management challenges, particularly in rural and peri-urban areas. Furthermore, medium- and low-readiness pathways require targeted support through infrastructure development, technical capacity building, and market creation. Such investments are also consistent with SDG 9 (Industry, Innovation, and Infrastructure), since they foster technological upgrading and strengthen innovation ecosystems necessary for the gradual development of emerging bio-based industries.

Table 7. Contextual Feasibility Analysis of different FVPW utilization methods for Tanzania

Conventional/Emerging Approaches	Technology Readiness in Tanzania (TRL*)	Estimated Cost Level	Environmental Benefit	Required Infrastructure	Key Barriers	Potential for Scaling
Composting	High (TRL 8–9) – widely practiced in small-scale farming	Low	Moderate – reduces landfill waste, improves soil health	Land area, basic tools	Limited training, inconsistent quality control	High – can scale via community composting hubs
Anaerobic Digestion (AD)	Medium (TRL 6–7) – few pilot plants	Medium–High	High – renewable energy, GHG reduction	Digesters, gas storage, feedstock logistics	High upfront investment, skilled operators	Medium – rural cooperatives & urban markets feasible
Biochar Production	Medium (TRL 5–6) – experimental in few regions	Medium	High – carbon sequestration, soil amendment	Pyrolysis units, feedstock supply chain	Capital cost, market development for biochar	Medium – potential in cash crop areas
Animal Feed Production	High (TRL 8–9) – common with some FVPW streams	Low–Medium	Moderate – offsets feed imports, reduces waste	Milling & drying equipment	Regulatory barriers (safety standards), sorting	High – especially near processing hubs
Extraction of Bioactive (Pigments, Polyphenols, Pectin)	Low–Medium (TRL 4–6) – mainly research stage	High	High – high-value products, minimal waste	Extraction facility, lab equipment	Technical expertise, high CAPEX, market access	Low–Medium – niche markets initially
Bioplastics / Packaging	Low (TRL 3–5) – R&D phase in Tanzania	High	High – replaces petroleum plastics	Specialized processing units	Expensive technology, weak local demand	Low – requires policy incentives
Bioethanol Production	Medium (TRL 6–7) – sugarcane-based plants exist, but not from FV waste	Medium–High	Moderate – renewable fuel	Fermentation tanks, distillation units	Feedstock logistics, competition with another biomass uses	Medium – integration with agro-industries possible

Note: TRL, Technology Readiness Level.

A critical dimension influencing this transition is the availability and structure of financing mechanisms. The shift toward advanced FVPW valorization pathways typically involves high upfront capital investment and delayed economic returns, creating a structural financing gap [153]. Green finance has been identified as a key mechanism to address this challenge by mobilizing capital toward environmentally sustainable investments and supporting circular economy transitions [154]. Instruments such as green bonds, sustainability-linked loans, and blended finance models can reduce investment risk and improve the attractiveness of emerging waste valorization technologies [153]. Within the Tanzanian context, this need is reflected in national frameworks. The National Financial Inclusion Framework (2023–2028) [155] emphasizes expanding access to financial services, particularly for Micro, Small, and Medium Enterprises (MSMEs) and smallholder producers, through innovative financial products, credit mechanisms, and public–private collaboration. This is particularly relevant for FVPW valorization, where high-readiness pathways can be supported through community-based financing and small-scale enterprises, while medium- and low-readiness technologies require more sophisticated financial arrangements, including public–private partnerships and blended finance structures. In this sense, financing is not simply a supporting condition but a core determinant of whether Tanzania can progress from basic waste recovery toward higher-value circular systems.

Furthermore, the policy environment plays a complementary role in shaping investment flows. The Environmental Management Act [144] provides for economic instruments to support environmental protection, including incentives and financial mechanisms, while national strategies highlight the importance of investment promotion and private sector participation in waste management. These provisions indicate that financial readiness is not separate from policy but embedded in it. However, implementation gaps suggest that these instruments are not fully operationalized, limiting their effectiveness in supporting emerging technologies, such as waste-to-energy systems and recycling innovations. As noted in the green finance literature, regulatory clarity and policy incentives are essential to align financial systems with sustainability objectives and stimulate green investment [154]. Consequently, the transition from traditional to advanced utilization pathways involves not only technological advancement but also institutional, financial, and market evolution.

The contextual feasibility analysis shows that Tanzania needs a phased and integrated strategy to make FVPW valorization sustainable and scalable. Immediate emphasis should be placed on proven, low-cost solutions such as composting and animal feed production, while medium- and low-readiness pathways are progressively supported through investment in infrastructure, innovation, and market development. Such a strategy is consistent with Tanzania's broader sustainability direction and reflects the integrated nature of the SDGs. By combining technological innovation, policy coherence, capacity development, and green financing strategies, Tanzania can gradually transition toward a more circular and resource-efficient waste management system that strengthens food-system resilience, promotes cleaner production, advances climate action, and creates new economic opportunities.

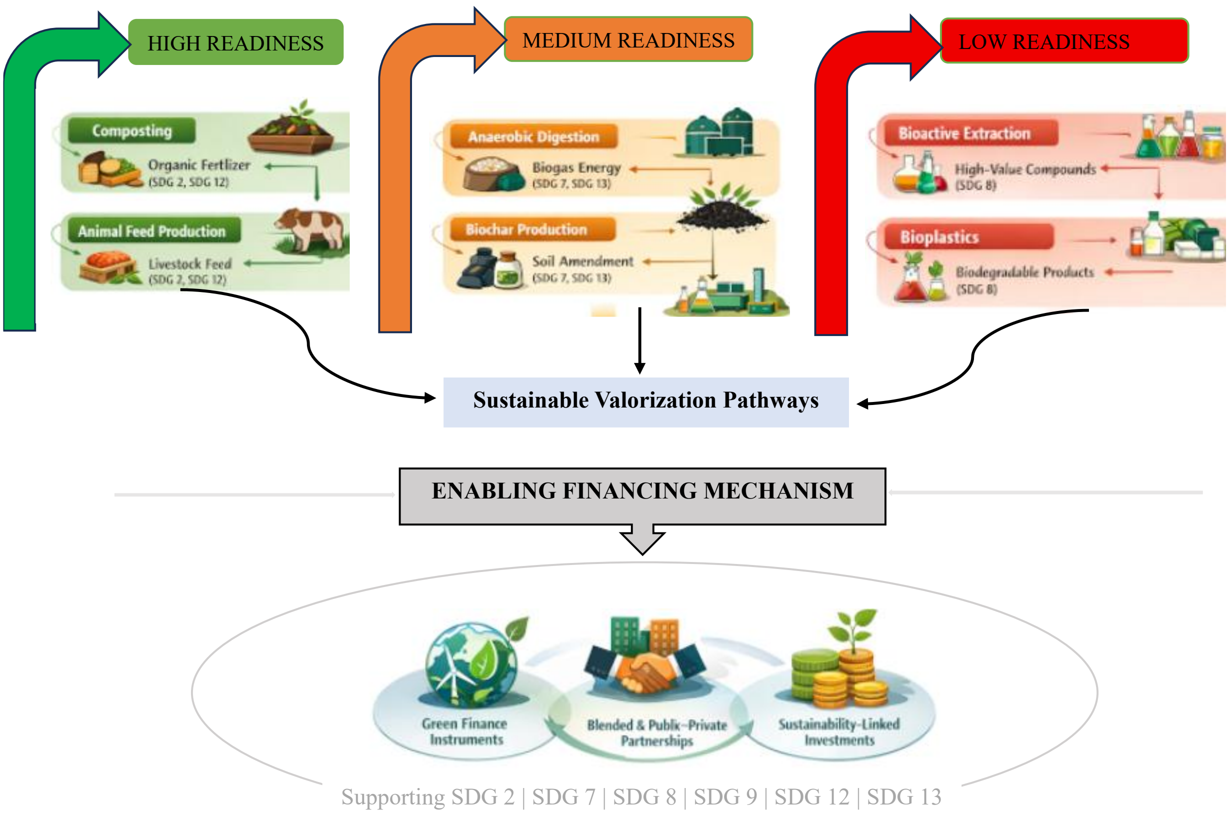

Figure 8. Integrated framework for fruit and vegetable postharvest waste (FVPW) valorization pathways in Tanzania.

4. Conclusion and future directions

In this review, we found that conventional and new techniques for the valorization of fruit and vegetable postharvest waste (FVPW) are available, although their practicality significantly differs based on technological readiness, infrastructure requirements, and contextual factors in Tanzania. Within the Tanzanian context, the most feasible methods for implementation are composting and animal feeding, as they correspond with established practices, necessitate relatively minimal investment, and yield immediate environmental and socio-economic advantages. Emerging and technologically advanced methods, such as biochar production for adsorbents or soil enhancement, extraction of bioactive compounds, bioethanol production, and bioplastic film synthesis, present greater potential environmental and economic benefits but are hindered by infrastructure constraints, technical capacity demands, and market preparedness. The findings suggest that high-readiness technologies provide immediate solutions for FVPW management, whereas lower-readiness but high-value paths signify strategic long-term potential as enabling conditions advance. Importantly, this differentiation in technological readiness is closely associated with varying financing requirements, where low-cost, high-readiness options can be supported through localized and MSME-driven financing, while advanced valorization pathways depend on structured financial mechanisms capable of mobilizing larger and longer-term investments.

From a practical and policy standpoint, enhancing FVPW utilization/valorization necessitates the development of supportive legislative frameworks, explicit quality requirements, and coordinated management methods that promote waste segregation, resource recovery, and innovation. Enhancing institutional coordination, offering incentives for adopters, and facilitating applied research and pilot demonstrations might expedite the shift from conventional methods to advanced valorization methods. These policies would promote congruence between national waste management objectives and broader sustainability initiatives, encompassing responsible consumption, climate mitigation, and the advancement of a circular economy. In this context, the integration of green finance instruments, such as green bonds, sustainability-linked loans, and climate-oriented investment facilities, alongside blended finance models that combine public and private capital, becomes essential for de-risking investments and enabling the scale-up of medium- and low-readiness technologies. Furthermore, sustainability-linked investment frameworks can incentivize performance-based outcomes by aligning financial returns with environmental targets, thereby strengthening accountability and long-term viability of FVPW valorization systems.

In future studies, researchers should focus on context-specific pilot testing of new technologies in Tanzania, particularly the development of tangible products derived from FVPW that can replace environmentally harmful alternatives, such as traditional plastic packaging. Other priorities encompass techno-economic assessments, life-cycle analysis, and supply-chain studies to examine practical feasibility, environmental performance, and scalability of various use alternatives. These investigations are crucial for connecting laboratory data with practical application and for facilitating evidence-based decision-making. Additionally, researchers should examine the design and applicability of innovative financing models within the Tanzanian context, including mechanisms for improving access to credit for MSMEs, structuring public–private partnerships, and evaluating the effectiveness of blended finance in supporting circular bioeconomy initiatives.

The advancement of higher-value valorization pathways will rely on sustainable funding structures and public-private investments that may facilitate innovation, infrastructure development, and market establishment. A phased transition model, starting with immediately implementable solutions and gradually including higher-value technologies, can facilitate a robust and circular postharvest waste management system. This transition will be significantly strengthened by aligning financing flows with sustainability objectives through integrated financial frameworks that support risk-sharing, investment mobilization, and long-term system resilience. By overcoming these obstacles, Tanzania can reduce environmental effects, enhance food-system resilience, and fulfill global obligations on climate action and sustainable consumption.

Use of AI tools declaration

The authors declare that ChatGPT Plus was used to assist in identifying typographical, grammatical, and language-related errors that were not easily detected during manual proofreading. It was also used for language polishing and grammar checking. QuillBot Premium, an AI-powered writing assistant, was used to support grammar correction and improve text clarity. After using these tools, all authors carefully reviewed, verified, and approved the manuscript content, including the references, interpretations, arguments, and conclusions. The authors take full responsibility for the accuracy, integrity, and final content of the manuscript.

Data availability statement

Data are available upon request.

Conflicts of interest

The authors declare no conflict of interest.

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