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A systematic review of nutritional enhancement through agricultural by-products utilization

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Abstract
The growing global population and increasing demand for food underscore the need for innovative approaches to enhance nutritional quality while minimizing waste. The study explores the potential of agricultural by-products as a resource for improving nutrition in food systems. By analyzing evidence from various studies, the study examines how by-products from different agricultural sectors, such as weeds, fruits, vegetables, grains, and livestock, can be repurposed to boost food products with vital nutrients, bioactive compounds, and dietary fiber. Furthermore, the review emphasizes the nutritional profiles of key by-products, their processing methods, and how agricultural by-products are integrated into food matrices. The results indicate significant opportunities to improve food security and nutrition through the strategic use of agricultural by-products. This review aims to guide policymakers, researchers, and industry stakeholders on the benefits and challenges of this innovative approach of effective utilization of agricultural by-products to enhance nutrition and also minimize waste

Keywords: Nutrition, agricultural by-products, enhancement, utilization

Introduction
Agricultural activities produce a significant number of by-products that were previously considered waste. Every year, approximately 1.3 billion metric tons of food waste are generated globally, accounting for nearly 28 % of all agricultural land available for cultivation. The production and waste of food by-products pose a serious concern. In addition to being a reflection of inefficiencies in food systems, this astounding amount of waste poses a severe threat to the environment, posing a risk to water pollution, air pollution, and soil degradation (Areti *et al*., 2024) [1]. Thus, food security remains one of the most significant global challenges, particularly as the world's population is expected to reach approximately 10 billion by 2050 (United Nations, 2019) [24]. This demographic shift exacerbates the demand for food, necessitating innovative approaches to enhance the nutritional quality of food systems while simultaneously addressing the issue of agricultural waste. Agricultural by-products, which are often viewed as waste, are produced in substantial quantities across various sectors, including crop cultivation and livestock production. Despite their potential, these by-products are frequently underutilized and overlooked in discussions about nutritional enhancement (Kumar *et al*., 2021) [11]. Research has shown that agricultural by-products, such as fruit peels, vegetable scraps, and crop residues, are rich sources of essential nutrients, bioactive compounds, and dietary fiber (Bhat *et al*., 2020) [3]. For example, citrus peels are recognized for their high content of flavonoids and dietary fiber, which can significantly contribute to improved health outcomes when incorporated into food products (Khan *et al*., 2022) [9]. In addition, spent grains from brewing processes have been demonstrated to enhance the protein and fiber content of baked goods, offering a practical application for these by-products (Zhao *et al*., 2021) [27]. The strategic repurposing of agricultural waste not only mitigates environmental concerns but also provides substantial opportunities to improve the nutritional profiles of various food products.
This systematic review aims to conceptualize nutritional enhancement and agricultural by-products, compile and synthesize existing literature on the repurposing of agricultural by-products for nutritional enhancement. By examining studies across diverse agricultural sectors, including weeds, fruits, vegetables, grains, and livestock, this review highlights successful case studies and processing methods employed to integrate these by-products into

food matrices. Furthermore, it addresses the challenges faced in effectively utilizing these resources.

The insights gained from this review will be valuable for policymakers, researchers, and industry stakeholders, emphasizing the dual benefits of enhancing nutrition and minimizing waste through the innovative use of agricultural by-products. As the global community confronts the challenges of food security and sustainability, harnessing these underutilized resources offers a promising pathway toward developing healthier food systems while promoting environmental responsibility (Thompson *et al*., 2023) [22].

Conceptual clarifications

Nutritional enhancement

Nutritional enhancement refers to the process of improving the nutritional quality of food products through various means, such as fortification, biofortification, and the incorporation of underutilized ingredients. This concept is increasingly important in addressing global health challenges, including malnutrition, obesity, and diet-related chronic diseases (Areti *et al*., 2024) [1]. The authors further explain that fortification involves adding essential vitamins and minerals to food products to prevent deficiencies in specific populations. For instance, the addition of iodine to salt has significantly reduced the incidence of goitre in many regions. In a similar development, the fortification of flour with folic acid has been widely implemented to reduce neural tube defects (Cawley *et al*., 2018) [4]. Biofortification, on the other hand, focuses on enhancing the nutritional content of crops through agricultural practices or biotechnology. This method aims to increase the levels of micronutrients in staple foods that are commonly consumed by populations at risk of deficiency. For instance, biofortified varieties of sweet potatoes have been developed to contain higher levels of vitamin A, which can help combat vitamin A deficiency in regions where these crops are a dietary staple (Hawkes, 2015) [7]. Another approach to nutritional enhancement involves utilizing underutilized agricultural by-products and ingredients that are rich in nutrients but often discarded. Research by Areti *et al*. (2024) [1] highlights the potential of fruit and vegetable peels, including weeds, which are often high in dietary fiber and antioxidants. Incorporating these by-products into food products can enhance their nutritional profiles while also reducing waste. For example, citrus peels are known for their high flavonoid content, which has been associated with various health benefits, including anti-inflammatory and antioxidant properties (Khan *et al*., 2022) [9]. By integrating such ingredients into food formulations, manufacturers can create products that not only taste good but also contribute positively to health.

Agricultural by-products

Agricultural by-products are materials generated during the production, processing, and consumption of agricultural products that are not the primary product. These by-products often include residues from crops, such as stems, leaves, and peels, as well as waste from livestock farming, such as manure and feathers. While these materials are frequently considered waste, they hold significant potential for various applications, including animal feed, bioenergy production, and food ingredient enhancement (Kumar *et al*., 2017) [9]. Agricultural by-products can be broadly classified into two categories: primary by-products, which are directly related to the main agricultural product, and secondary by-products, which arise from processing activities. For instance, wheat straw is a primary by-product of wheat production, while bran is a secondary by-product resulting from milling (Kumar *et al*., 2021) [10]. Studies have shown that many agricultural by-products are rich in nutrients and can be repurposed for animal feed or human consumption. For example, fruit and vegetable peels are often discarded despite their high fiber and antioxidant content. A study by Bhat *et al*. (2020) [3] highlights the nutritional potential of these peels, suggesting that they can be incorporated into food products to enhance their health benefits. Moreover, agricultural by-products can serve as valuable sources of dietary fiber. According to a review by Kaur (2021) [8], incorporating fibers from by-products such as rice bran and corn husks into food formulations can improve their nutritional profile while also promoting sustainability by reducing waste. Utilizing agricultural by-products can significantly reduce environmental impacts associated with waste disposal and promote sustainable agricultural practices. The conversion of by-products into bioenergy is one promising avenue. For instance, anaerobic digestion of livestock manure can produce biogas, which serves as a renewable energy source (Zhao *et al*., 2019) [28]. This process not only helps manage waste but also reduces greenhouse gas emissions. Additionally, the use of agricultural by-products in composting can enhance soil fertility and structure. Research by Dixion *et al* (2019) [5] demonstrates that composting crop residues, including weeds, improves nutrient availability in soil, thereby supporting sustainable farming practices

Repurposing agricultural by-products to enhance the nutritional quality of food products

Agricultural by-products, often dismissed as waste, can be valuable sources of essential nutrients, bioactive compounds, and dietary fiber. By repurposing materials from various sectors, such as weeds, fruits, vegetables, grains, and livestock, we can enhance the nutritional quality of food products while promoting sustainability. This review compiles evidence from different studies showing how these by-products can be effectively utilized.

Weeds as Nutritional Resources

Weeds are commonly viewed as agricultural nuisances; however, many possess significant nutritional value. For instance, dandelion greens and nettles are rich in vitamins A, C, K, and minerals such as calcium and iron. A study by Dixon *et al*. (2019) [5] found that incorporating edible weeds into salads and smoothies can significantly increase the intake of essential nutrients. Additionally, Mabhaudhi *et al*. (2019) [12] highlighted that certain weeds contain high levels of antioxidants and polyphenols, which contribute to health benefits such as anti-inflammatory effects.

Fruit by-products

Fruit processing generates substantial by-products, including peels, seeds, and pulp. These by-products are often rich in dietary fiber and bioactive compounds. For example, apple peels have been shown to contain high levels of dietary fiber and antioxidants. According to Bhat *et al*. (2020) [3], incorporating apple peels into baked goods can enhance their fiber content and antioxidant properties, leading to improved health benefits for consumers. Similarly, the seeds

of fruits such as grapes and pomegranates are rich in polyphenols and flavonoids. Ranjan *et al*. (2020) [17] demonstrated that grape seed extract could be used as a natural preservative in food products while also boosting their antioxidant capacity.

Vegetable by-products

Utilization of vegetable residues is a key area of interest in the food industry, aiming to reduce waste and create value-added products as well as utilize vegetable by-products as functional ingredients in the food sector (Ravindran & Jaiswal, 2016) [18]. Vegetable by-products, including stems, leaves, and peels, are often discarded but can be repurposed for their nutritional benefits. Carrot tops, for example, are rich in vitamins A and K and can be used in pesto or salads. A study by Kumar *et al*. (2021) [11] indicated that incorporating vegetable tops into soups and sauces not only reduces waste but also enhances the nutritional profile of these dishes. Another notable example is the utilization of potato peels, which are high in dietary fiber and phenolic compounds. Research by Babu *et al*. (2020) [2] showed that adding potato peel powder to bread increases its fiber content and antioxidant activity, making it a healthier option for consumers.

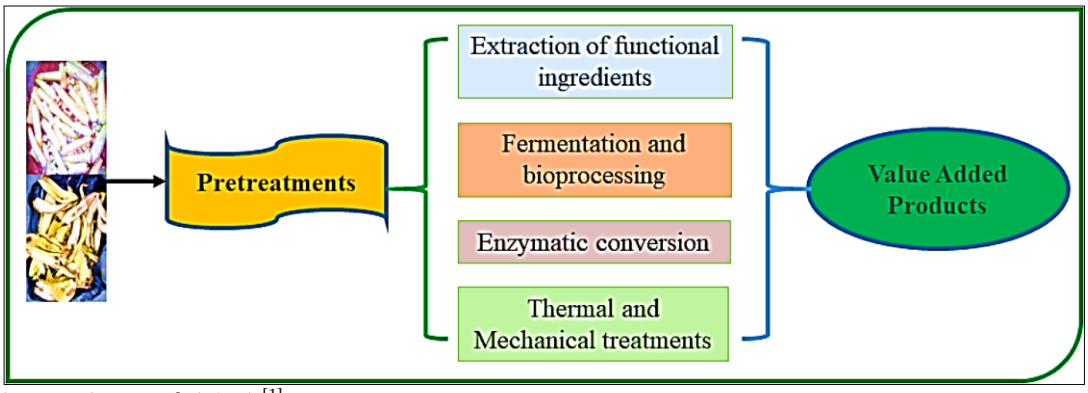
Grain by-products

By-products from grain processing, such as bran and germ, are excellent sources of dietary fiber and essential nutrients. For instance, wheat bran is rich in insoluble fiber, which aids digestion and helps prevent chronic diseases. A review by Slavin (2013) [20] emphasized the health benefits of whole grains and their by-products, noting that incorporating wheat bran into baked goods can improve their overall nutritional value. Similarly, rice bran, a by-product of rice milling, is high in unsaturated fats, vitamins B and E, and antioxidants. According to Martínez *et al*. (2020) [13], rice bran can be incorporated into snacks and cereals to enhance their nutrient density while providing health benefits such as cholesterol reduction.

Livestock by-products

Livestock farming generates various by-products that can be repurposed for human consumption or animal feed. For instance, animal bones can be used to produce bone broth, which is rich in collagen and minerals. A study by Zhao *et al*. (2019) [28] discussed how bone broth has gained popularity for its health benefits, including joint support and gut health improvement

Processing strategies for integrating agricultural by-products into food matrices



Source: Areti *et al*. (2024) [1]

Fig 1: The cutting-edge strategies for utilizing by-products to extract bioactive compounds from agricultural and food industry waste materials.

Fermentation

Fermentation is a biological process that utilizes microorganisms to convert organic compounds, such as sugars, into alcohol or acids. Agricultural by-products like fruit peels, spent grains, and whey can be fermented to produce value-added products like vinegar, bioethanol, or probiotic-rich foods. (Pandey *et al*, 2015) [16] .

Extrusion

Extrusion is a high-temperature and high-shear processing technique that transforms raw materials into a continuous product. Agricultural by-products such as corn bran or rice husks can be extruded to create snacks or fortified food products, enhancing their nutritional profile while minimizing waste (Oduro *et al*., 2016) [14].

Enzymatic Treatment

Enzymatic treatment involves using specific enzymes to modify the properties of agricultural by-products. For instance, pectinase can be used to extract juice from fruit pomace, and proteases can help in tenderizing meat by utilizing by-products such as soybean meal or fish waste (Tiwari and Mullen, 2017) [23].

Drying and Powdering

Drying is a common method for preserving agricultural by-products and making them easier to incorporate into food products. By-products like vegetable leaves or fruit skins can be dried and powdered to create flour or seasoning blends that enhance the nutritional value of processed foods (Teboho and Oluwabiyi, 2022) [21].

Source: Teboho and Oluwabiyi, (2022) [21]

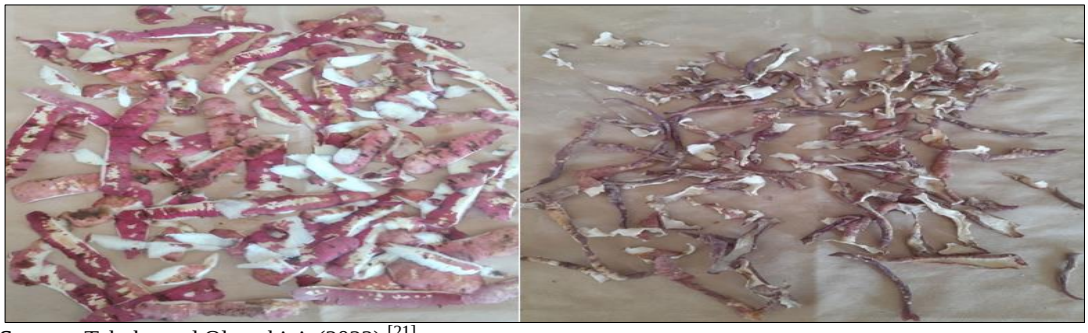
Fig 2: Sweet orange peels before and after drying

Source: Teboho and Oluwabiyi, (2022) [21]

Fig 3: rish potato peels before and after drying

Source: Teboho and Oluwabiyi, (2022) [21]

Fig 4: Banana peels before and after drying



Source: Teboho and Oluwabiyi, (2022) [21]

Fig 5: Sweet potato peels before and after drying

Additionally, agricultural residues play a vital role in the food industry by serving as valuable sources of nutrients and beneficial ingredients that promote health. Table 1 offers a comprehensive look at the nutritional and functional characteristics of agricultural by-products, underscoring their nutrients in enhancing product development and supporting human well-being.

Table 1: Nutritional profile of banana, orange, Irish potato, cassava, and plantain peels.

Peel type	Calories per 100g	Carbohydrate (g)	Protein (g)	Fat (g)	Fibre (g)	Key nutrients Mg	Source of information
Banana	89	23	1.1	0.3	2.6	Potassium 358 & magnesium 37	Shuka and Gupta, (2015) [19]
Orange	97	24	0.9	0.2	10.6	Vitamin C 136	Wang, *et al* (2017) [25]
Irish Potato	77	12	2	0.1	2.2	Potassium 425	Ghosh and Ghosh (2018) [6]
Plantain	82	21	1.5	0,6	3.7	Potassium 450	Osei *et al* (2020) [15]

Challenges of these innovative approaches to the effective utilization of agricultural by-products

1. **Technological barriers:** Technological challenges include the development of efficient extraction methods to recover bioactive compounds from by-products and the optimization of processing techniques to maintain product quality (Areti *et al*., 2024) [1]. Thus, one of the primary challenges in the innovative utilization of agricultural by-products is the lack of appropriate technologies for processing and converting these materials into usable forms. As highlighted by Areti *et al*. (2024) [1], many smallholder farmers lack access to advanced processing technologies that could enhance the nutritional value of agricultural by-products. This technological gap limits the ability to transform waste into valuable products.
2. **Economic viability:** The economic aspect of utilizing agricultural by-products poses another challenge. The initial investment required for processing facilities can be very expensive for many farmers and small enterprises. According to a study by Weber *et al*. (2020) [26] while there is potential for profitability in the long term, the upfront costs and risks associated with developing new products from by-products can deter investment. The authors in their study examines the practical and financial feasibility of repurposing sweet potato waste to create bioethanol and distilled beverages. This research not only aims to minimize food waste but also aims to advance the principles of a circular economy. This study underscores the importance of exploring innovative ways to utilize agricultural by-products efficiently.
3. **Market Acceptance:** Consumer acceptance of products derived from agricultural by-products is crucial for their success in the market. Research by Areti *et al*. (2024) [1] indicates that consumers often perceive these products as inferior or less desirable compared to conventional food items. Overcoming this stigma requires effective marketing strategies and education about the nutritional benefits of these by-products.
4. **Regulatory frameworks:** The regulatory environment surrounding food safety and product labelling can also hinder innovation in this area. As noted by Tiwari *et al*. (2020) [23], stringent regulations may restrict the use of certain agricultural by-products in food products, even if they are safe and nutritious. Navigating these regulations can be complex, particularly for small-scale producers.

Conclusion and recommendations

In conclusion, the pressing challenges posed by the expanding global population and the rising demand for food necessitate creative solutions to enhance nutritional quality while reducing waste. This study has investigated the potential of utilizing agricultural by-products as valuable resources for improving nutrition within food systems. Through a comprehensive analysis of existing research, it has been demonstrated that by-products from various agricultural sector including weeds, fruits, vegetables, grains, and livestock can be effectively repurposed to enrich food products with essential nutrients, bioactive compounds, and dietary fiber. The findings highlight the promising opportunities for enhancing food security and nutritional outcomes through the strategic incorporation of agricultural byproducts. By examining the nutritional characteristics of key by-products and their processing techniques, this review provides insights into how these resources can be integrated into food matrices. Finally, this study serves as a guide for policymakers, researchers, and industry stakeholders, outlining both the advantages and challenges associated with the innovative utilization of agricultural by-products. By embracing this approach, we can not only improve nutritional quality but also contribute to waste reduction in our food systems, paving the way for a more sustainable future. Based on these findings, the study recommended the following;

- Engaging local communities in the development and utilization of agricultural by-products can foster acceptance, thereby reducing waste
- Government at all levels should support the circular economy and encourage investment in research and development initiatives focused on identifying and optimizing the nutritional benefits of various agricultural by-products.
- There should be a collaboration between farmers, food manufacturers, nutritionists, and policymakers to create a streamlined approach for integrating agricultural by-products into food systems. These partnerships can facilitate knowledge sharing, improve supply chain logistics, and promote best practices for sustainable utilization, ultimately leading to increased acceptance and implementation of by-product use in food production and environmental waste management.

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