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Review

Modulation of snack foods: An approach to overcome hidden hunger in children

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A B S T R A C T

The global snack foods market had grown to 585 billion USD by 2022. Consumption of snacks has gained attention at a commercial level since they are liked by people of all ages, including millennials and elderly people. An increasing trend in snacking provides a potential opportunity for delivering micronutrients to minimize hidden hunger throughout the world. Various strategies are proposed in this review for modifying these snacks to improve snacking. The practical implications, including methodologies and approaches of such strategies, have also been summarized. The raw materials used for snack development can be biofortified for additional mineral content. By-products of fruits and vegetables can be used as ingredients and nutrient sources in the food industry. Organic salts, industrial fortificants, and nutritive substitutes can be used in extrusion processing as an enrichment method. Snacks can also be reformulated to contain more nutrients. Such strategies could greatly improve not only individual health but also the global market.

Introduction

Hidden hunger is a serious public health burden that coexists with the other two forms of malnutrition, i.e., undernutrition and overnutrition. This term is defined as long-term deficiencies of essential nutrients due to poor lifestyle or chronic health disparities. Micronutrient deficiencies often go unnoticed and are exposed when such depletion causes serious health consequences. Hence, these two extremes are termed hidden hunger [1]. Therefore, the need of the hour is to recognize and rectify them with nutritional interventions. There is a need to address the silent epidemic of hidden hunger that has affected at least 2 billion people, primarily in the African, South Asian, and Latin American regions. This hunger is caused by a lack of trace minerals [2]. It stunts growth by compromising immunity and weakens overall potential and general health. Iron, zinc, and vitamin A are widespread deficient micronutrients causing more than 24,000 people's deaths globally. To combat these deficiencies, various strategies have been designed to uplift the nutritional status of food items [3]. The development of snack foods to combat hidden hunger has gained significant attention in recent years. Snack foods are widely consumed across different age groups and socioeconomic classes due to their convenience, affordability, and palatability [4]. According to predictions, the market for snack food products will increase from $584.58 billion in 2022 to $838.60 billion in 2029 [5]. The Pakistani snack market investigated the crisps and chips segment emerging as a leading category, accounting for 37.6% of the total market share in 2017. Moreover, PepsiCo dominates the market with a market share of 81.3% with its popular international brands *i.e.,* Lays, Kurkure, and Cheetos liked by both children and adults [6].

The variation in consumer preference has shown an inclination toward spicy flavors with a wide variety of savors, such as smoke, vinegar, spice, honey, pizza, barbecue, etc. Economic and environmental objects have increased the demand for the conversion of food by-products into useful products by utilizing various technical aspects such as extrusion processing; a highly productive and energy-efficient method with less industrial effluents and economic burden [7]. The market trends and dietary effects of snacks

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are covered in this review. Additionally, we offer some recommendations for how to modify these foods to improve their economic and health benefits. Snack foods are relished by people of almost all ages. However, snack foods are deficient in some vital nutrients which are either not present in their ingredients or are lost during processing. Therefore, snack foods can be utilized to deliver essential minerals and vitamins to make up for the deficits of micronutrients.

Snack foods are being prepared using various methodologies. One common method is extrusion, where ingredients such as flour, starch, and other additives are forced through a machine at high temperatures and pressure to create expanded, crispy snacks. Extrusion is an economical process with low costs, continuous production, and utilizing less energy production by using high-temperature and short-time reliable technologies. Other techniques include baking, which uses dry heat to cook snacks like crackers and cookies, resulting in a crisp texture while preserving nutritional content; frying, a widely used method for creating crunchy textures in snacks like chips; and air drying, which is typically used to preserve and concentrate flavors in products like fruit snacks [8–10]. Each of these methods contributes to the sensory and nutritional properties of the final product, depending on ingredient choice and processing conditions.

Methodology

We employed a comprehensive search methodology using various databases such as PubMed, Google Scholar, and Scopus to identify relevant studies on the modulation of snack foods to enhance nutritional content. The search incorporated the following key terms: hidden hunger, snack foods, micronutrients, biofortification, fruit and vegetable by-products, food fortification, extrusion processing, and reformulation of snacks for improved health benefits. This search yielded about 110 articles, of which 58 focused specifically on snack food development, biofortification, and fortification strategies. Out of these, 31 articles were selected based on their relevance to the current topic, addressing various strategies to improve the nutritional profile of snacks and their impact on health. Only articles published after 2010 were considered for inclusion to ensure the information was up-to-date and relevant to current practices. The literature has been analyzed qualitatively, summarizing the methodologies, strategies, and findings related to improved nutritional outcomes. The final review focuses on the role of biofortified raw materials, the use of by-products, and the impact of fortification and reformulation on the quality of snack foods.

Impact of snacking on overall health and well-being

Snacks have garnered significant commercial attention driven by consumer preferences. However, their nutritional composition is not adequate in macro and micronutrients. Their high fat and sugar content with low protein and fiber are compromising the health of children. The use of fats in processing just adds up calories in snacks and not the essential fatty acids which are basic requirements for proper neural and metabolic support. A higher ratio of saturated fats negatively affects heart health and increases levels of low-density lipoprotein, which changes the lipid profile. Trans-fat is present in higher proportions enhances cholesterol and may damage the arterial walls and coronary health [11]. Refined sweets create an abrupt rise in blood sugar levels that is followed by a sharp decline, creating a spike. Sweets have the highest glycemic index, which stresses the pancreas to secrete insulin, leading to resistance or insufficiency to insulin release in the long run. Teenagers frequently experience hyperglycemia that develops into diabetes. Tooth enamel damage is caused by excessive consumption of sugary treats, caramel and chocolates may cause dental problems [12]. Food products that have undergone excessive processing lose important nutrients. Since B vitamins are water-soluble, and are primarily lost during washing. When the bran portion of various cereals is removed during milling, some phytochemicals and dietary fiber are also lost. Snack consumption reduces fiber intake, which affects digestive health and causes digestive problems in kids. Loss of microbiota alters the normal functioning of the immune system, which is associated with probiotics in the colon [13]. More carbohydrates in snack composition diminish the intake of other macronutrients which are vital for growth and maintenance. Carbohydrates with no or less fiber provide extra energy that gets stored in adipocytes leading to obesity. Obesity is the root of other metabolic diseases such as diabetes, hypertension, liver issues, and abnormal reproductive health in both males and females. Enhancing raw materials through the use of cost-effective, nutrient-dense cereal grains, corn, and pulses serves as a key factor in improving the nutritional value of snacks [14].

An increase in health awareness has grown interest in public health campaigns and nutritional guidelines. UK government, in an initiative named Change4Life Campaign, recommended 100 calories for snacks. Moreover, no more than two snacks should be consumed in a day. This campaign was initiated around snacking of children in 2018 [15]. Fiber intake was also considered by labeling the food items with sources of low fiber (3%) and high fiber (6%). This packaging was done by the European Food Safety Authority (EFSA). In 2015, the Scientific Advisory Committee on Nutrition suggested daily intake of fiber at least up to 30 g for better gut health and combating other serious health-related issues [16]. The development of nutrient-dense snacks involves fortification with essential vitamins and minerals, such as iron, zinc, vitamin A, and folic acid, as well as the incorporation of biofortified ingredients and functional food components [17]. These strategies enhance the nutritional profile of snack products while maintaining their sensory appeal, ensuring consumer acceptance. Since snacking behavior is prevalent globally, leveraging snacks as a vehicle for micronutrient delivery can effectively reduce the burden of hidden hunger in vulnerable populations [18]. Fortified snacks offer a more practical solution for addressing micronutrient deficiencies, in daily dietary habits without requiring major behavioral changes [19].

Strategies for the modulation of snack foods

The aim of reformulation is to enrich snacks with ingredients such as dietary fibers, plant-based proteins, healthy fats, vitamins, minerals, and some bioactive compounds to enhance their nutritional profile and health benefits to improve the micronutrient status of the children. Additionally, micronutrient addition is one of the purposes to address potential deficiencies and promote overall well-being. Various strategies can be employed in the development and modification of snack foods to achieve these goals. The following strategies can be implemented to design better and nutritional snack foods.

Incorporation of biofortified raw materials for enhanced nutritional content

Cereals are one of the ingredients of snack foods; other ingredients include legumes, proteins, fats and oils, dietary fibers, sweeteners, flavor enhancers, emulsifiers, preservatives, and micronutrients such as vitamins and minerals. Cereal-based snacks account for approximately 60–70% segment of the global snack market [20]. According to a report by Coherent Market Insights, Europe is expected to gain a significant market share in the global cereal-based snacks market, driven by the consumption of healthy and protein-enriched foods [21]. Flour, a primary derivative of cereals, plays a crucial role in snack production. It provides structure and texture to baked goods, acting as a binding agent and contributing to the desired consistency. Additionally, flour can enhance the nutritional profile of snacks by adding proteins, fibers, and essential nutrients. The type of flour used can significantly influence the final product's characteristics, affecting factors such as chewiness, crispness, and overall mouthfeel [22]. Incorporating various types of flour allows for versatility in snack formulations, catering to diverse consumer preferences and dietary requirements.

Biofortification is a process of adding nutrients into crops for sustainable and long-term delivery of trace minerals. Breeding of crops is done for higher levels of micronutrients using both conventional and transgenic strategies. Modern technologies of fortification have been utilized in the area of fortification for uplifting the micronutrient status of crops [23]. It comprises of two methods. The first one is agronomic biofortification which is optimized utilization of fertilizers in soil before sowing of a crop to enrich the target nutrient's content in that crop. This approach aligns with sustainable agricultural practices and can be integrated into existing farming systems without necessitating significant changes to traditional cultivation methods. The other one is genetic biofortification which tracks the breeding approach to upsurge the concentration and bioavailability of specific nutrients. It is a sustainable option for limited access to nutritional resources and a cost-effective strategy for addressing micronutrient deficiencies [24]. A variety of rice developed because of genetic engineering showed 4.7 times increase in iron and zinc. Genes responsible for iron concentration, storage, and translocation are engineered from a cassette in a single locus of endosperm. These engineered genes exert synergistic effects to enhance the uptake and utilization of iron. Other metals are also transported along with chelators, so there will be an ample amount of zinc in that variety of crop [25].

Punjab, Pakistan has the largest percentage (24.1%) of people who lack zinc [26]. Enrichment of zinc during processing can restore the mineral status. Another better and sustainable way of maintaining zinc status is biofortification; a sustainable and economic way of improving bioavailable zinc in edible crop [27,28]. Fertilizers are being used in both agronomic and genetic approaches of fortification to deliver vital nutrients through soil into the crops [29]. Biofortified wheat flour (Zincol-2016) has been developed by using zinc-fortified seeds, which not only enhance zinc levels in grain but also improve yield with better economic return. These designed seeds withstand extreme social and climatic conditions compared to traditional varieties. The resultant seeds attained a maximum level of zinc concentration (40 mg/kg) [24]. Before planting, fertilizer application aids in the production of greater minerals content than are conventionally present [30]. Fertilizers are used to strengthen bean and millet types under growth circumstances. Efficacy trials have shown significant health impacts on the body [31,32].

Consultative Group on International Agricultural Research has recommended 59 μg/g iron for dry weight of wheat grain. This content has been constructed on the estimated average requirement of the population for better cognitive and physical health [33]. But traditional crop varieties only provide lower (20–40 μg) iron per g of wheat grain than the recommended level. Most people have to rely on wheat as a staple crop so millions of consumers are becoming nutrient-deficient [34].

Genetic controlling has been adapted to maximize the mineral concentration in crops. Multi-traits and many favorable alleles responding to rich iron in wheat grain have been identified by genome-wide association studies (GWAS) [35]. Quantitative mapping is used to locate genes. Using this technique, nine loci that impact grain's iron content were discovered which can be utilized to enhance minerals from a genetic level [36]. Some microorganisms have the potential to enhance the nutritional value of food crops. These biological preparations are effective in enhancing nutrient uptake and plant growth. The utilization of these microorganisms as biofertilizers improves iron mobility from soil to edible plant parts [37]. Consequently, microbial-assisted iron biofortification offers an alternative for sustainable crop cultivation [38,39].

The utilization of microbiome for genetic qualities along with plant genetics by incorporating engineered plant genes has successful enhanced iron up to 59 μg/g of the final crop [40].More than half of the world's population relies on a diet, which is composed of up to 70% of daily calories from rice. Polished rice loses its nutrients while processing. But biofortified rice contains significant iron, zinc, and other essential minerals and provitamin-A (β-carotene). Many indica and japonica rice varieties have been biofortified worldwide namely high iron rice, low phytate rice, high zinc rice, and high carotenoid rice, etc. [41].

Secondary metabolites in plants play a key role in the biosynthesis, degradation, and storage of products affecting their metabolic equilibrium. In addition, transgenic plants are being designed which have some specific genes derived from bacteria. The role of such genes is to produce β-carotene in the presence of endogenous lycopene. The introduction of another gene for the supply of precursors has increased the product accumulation in the endosperm. Upregulation of endogenous carotenogenic genes causes overexpression of genes involved in carotenoid formation. This modulation of genetic makeup explored another kind of rice with up to 31.78 μg/g total carotenoids in grain as a source of Vit A [42].

Critical considerations, ecological implications, and limitations

Studies have demonstrated that biofortified crops, such as vitamin A-enriched sweet potatoes, can significantly reduce vitamin A deficiency in populations. For instance, a study in Mozambique reported a 24% reduction in vitamin A deficiency among children due to the consumption of biofortified sweet potatoes [43]. The primary investment in biofortification involves research and development costs, including breeding and trials. However, once developed, biofortified crops can be disseminated through existing agricultural systems, potentially reducing the need for expensive supplementation programs. The scalability of biofortification in resource-limited settings depends on farmer adoption, seed distribution in the field, and consumer acceptance level. Integrating biofortified crops into existing agricultural practices can facilitate widespread adoption [44,45]. Biofortified crops are natural sources of essential micronutrients, such as vitamin A, iron, and zinc, which can reduce the need for synthetic supplements and fortificants [46].

Genetically biofortified crops are more resilient to pests, diseases, and climate stress, require fewer chemical inputs (*e.g.,* fertilizers and pesticides), and the ability to thrive under suboptimal soil conditions [47]. More nutrients in a single variety of crops can lead to more efficient use of existing land, reducing the need for the expansion of agricultural land to preserve biodiversity and focus on nutrient recycling [48]. Biofortification can have several negative environmental consequences as well. The increased use of chemical fertilizers can lead to nutrient runoff, water contamination, and soil degradation, contributing to environmental issues like eutrophication. Furthermore, resource-intensive techniques contribute to environmental footprints through the use of energy, water, and chemicals [49]. Table 1 shows biofortified crops with their methodologies and features. The graphical description is given in (Fig. 1A).

Utilization of fruits and vegetable by-products for raw material enrichment

Cereals are used as a staple food due to their significant amount of macro- and micronutrients. Moreover, phytochemicals in them positively impact health [53]. Composite flour is a mixture of different flours milled together, which provide a variety of nutrients. Flour may be obtained from vegetable sources or cereal crops to uplift protein and starch content or other targeted benefits. Mixed flour comprising maize, finger millet, and defatted soy has been used to form extruded products [54]. A blend of flours is done to compensate for the individual nutrient losses. For example, defatted soy is used as a bioactive ingredient and industrial by-product. Various fruits have also been utilized in the food industry for their by-products. Almost 15–25 million by-products of mango fruit are generated per year. Its peel powder and kernel in dried form may be utilized in the food industry to prevent the loss in an economical way [55].

By introducing finger millet into our everyday diet, calcium and iron deficiency can be prevented. Due to a lack of awareness, finger millet is infrequently consumed in the diet. Calcium and iron deficiency can be managed by adding this to food products [56]. The incorporation of peel provided significant advantages over traditional formulations since they exhibited lower glycemic indexes, higher content of dietary fiber, and antioxidant properties were improved. Mango peel powder has been incorporated into macaroni and functional cookies to improve the nutritional profile [57–59].

Pasta consumption has been growing in the domestic as well as international markets. Additionally, useful variants have been created. The incorporation of functional ingredients such as cereals, legume flour, fruit, and vegetable powder contain various antioxidants, vitamins, dietary fiber, minerals, protein, flavonoids, carotenoids, and phenolics increases the nutritive as well as functional properties. Some fortified varieties of pasta have been depicted in the next table showing mango peel powder, mango kernel, carrot powder, and defatted soy flour in pasta formulation [60,61].

Bananas have also been incorporated into extruded snacks to improve the nutritional profile of the product. Flour can also be modulated by making a blend to attain nutrients from different varieties [62]. Composite flours are a better option for this purpose as, these are a blend of starch- and protein-rich flours from tubers (such as cassava, yam, and sweet potato) and cereals (such as maize, rice, millet, and buckwheat), either with or without wheat flour. For example, one of its varieties

Table 1
Recent research on various biofortification techniques used in different food products and their evaluation based on nutrient enhancement

Product	Approach	Methodology	Product evaluation	Reference
Biofortified beans	Agronomic biofortification	• Group 1: Foliar zinc • (0, 120, 240, 480, 720, or 1,200 g ha^{-1}) • Group 2: Soil zinc • (0, 5, or 10 kg ha^{-1}) combined with foliar zinc (0, 1, 1.5, 3, 6, or 10 kg ha^{-1})	5 kg ha^{-1} ZnS and 7.8 kg ha^{-1} ZnF produced the highest concentration of Zn in grain *i.e.*, 67.5 mg kg^{-1}	[50]
Biofortified rice	Genetic combination of three genes (AtIRT1, AtNAS1, and PvFERRITIN) in a single locus for synergistic effect of iron production in transgenic breeding	Four promoter-gene constructs were used • MIF (pMsENOD12B with AtIRT1 and pOsGLB-1 with PvFER) • IIF (pAtIRT1 with AtIRT1 and pOsGLB-1 with PvFER) • MINF (pMsENOD12B with AtIRT1, pCaMV35S with tNAS1, and pOsGLB-1 with PvFER) • IINF (pAtIRT1 with AtIRT1, pCaMV35S with AtNAS1, and pOsGLB-1 with PvFER)	Significant increase in iron up-to 10.46 µg/g and zinc up-to 33.17 µg/g in IINF	[25]
Carotenoid rich rice	Over expression of AtDXS and AtOR gene to boost carotenoid accumulation in rice grain	Four transgenes were produced (combined expression of ZmPSY1, PaCRTI and AtOR gene) • ZmPSY1 • PaCRTI • Selectable marker hpt • AtOR gene with glutenin promoter	Final product had 31.78 µg/g total carotenoids in grain as a source of vit A	[42]
Iron-biofortified finger millet	Agronomic biofortification 25 kg $ZnSO_4$ fertilizer per ha	Group 1: 20 kg ha−1 $FeSO_4$ + 25 kg ha−1 $ZnSO_4$ + NPKS Group 2: 5 kg ha−1 $ZnSO_4$ + NPKS Group 3: NPKS Group 4: 30% NPKS Group 5: 20 kg ha−1 $FeSO_4$ + NPKS	60.2 mg iron per kg grain	[51]
Zinc biofortified wheat	Agronomic biofortification	(8 mg zinc in the form of $ZnSO_4{\cdot}7H_2O$ per kg fertilizer added in soil before sowing)In industrial zone soil • Faisalabad-2008 • Zincol-2016 In peri-urban zone soil • Faisalabad-2008 • Zincol-2016	32% increase in grain zinc concentration in Zincol-2016 grown in peri-urban soil	[24]
Zinc biofortified wheat	Agronomic biofortification	Group 1: Whole wheat flour Group 2: 1.25 kg zinc EDTA (13%) per ha was applied to soil before sowing the crop	3-6 mg additional zinc were provided than whole wheat flour	[30]
Zinc biofortified wheat (Zincol-2016)	Agronomic biofortification	Group 1: 0 mg Zn per kg soil Group 2: 3 mg Zn per kg soil Group 3: 6 mg Zn per kg soil Group 4: 12 mg Zn per kg soil Group 5: 24 mg Zn per kg soil	53 mg zinc per kg grain	[52]

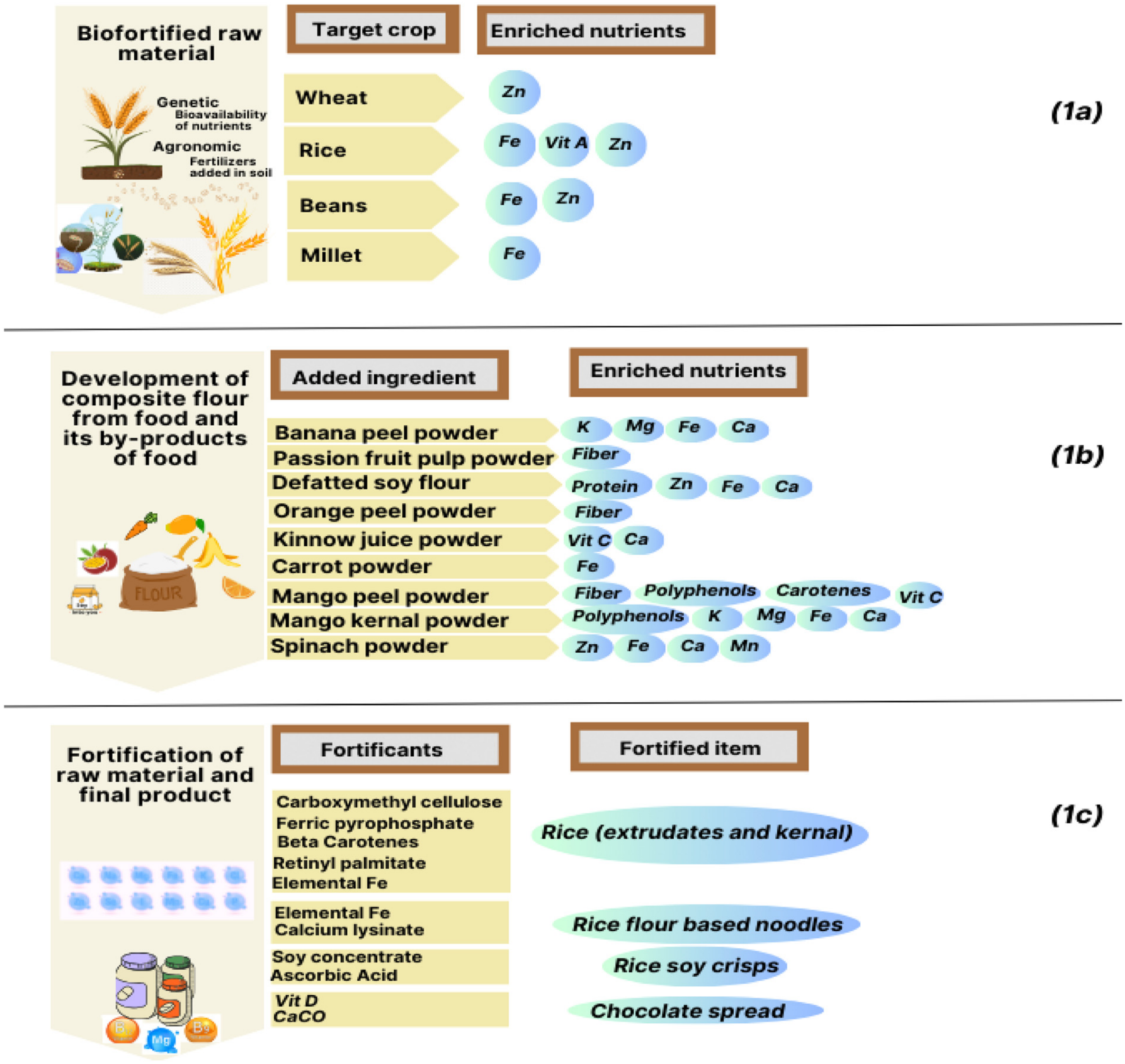

Figure 1. Illustration of biofortification techniques: (1A) Biofortification of raw materials to enhance nutrient content, (1B) Fortification through the use of by-products from fruits and vegetables incorporated into mixed flour, and (1C) Application of fortificants in the food industry to enrich food products with essential nutrients.

was developed by using ragi flour (40%), rice flour (30%), and corn flour (30%). Cheese (3%) was also added as a flavor enhancer. Banana peel is an excellent source of vitamins (vitamin B_6, vitamin C), fiber, and minerals (magnesium and potassium). Banana chips are also economical in a way to minimize the wastage of by-products. They can be eaten as a snack, which gives more calories and nutrients. Chips of banana and fried potato chips are better in quality and acceptability than baked bananas. Banana chips have high market potential with high energy density and packed with minerals like potassium and phosphorous, etc [63]. Cookies prepared from banana peel flour and wheat flour showed higher content of calcium, potassium, magnesium, iron, sodium, and potassium than cookies made only with wheat flour [64]. Apricot bars have been made by using blanched spinach, corn flour, nuts (almonds and pistachios), chickpeas, and coconut powder. Spinach powder improves the status of micronutrients in bars. Mineral contents with a delicious sweet taste would be attractive to consumers as an alternative to conventional snacks available in the market [65].

Another confectionary product *i.e.*, dark chocolate was prepared by passion fruit and orange. Dark chocolate usually contains high amounts of flavonoids including catechin, epicatechin, and procyanidin. It contains antioxidants and exerts a positive effect on cognitive function and mood [66]. Pulp of passion fruit and orange fruit can be added to chocolate to improve its bioactive and mineral profile. In this way, a healthier snack variety can be designed from fruits [67]. Burfi is a popular traditional dairy dessert; however, its low nutritional value and short shelf life limit its commercial viability. The addition of citrus items in making this sweet improved the phytochemical profile and shelf stability in which pectin from citrus fruit was added at different concentrations [68].

Critical considerations, ecological implications, and limitations

By-products of fruits and vegetables, such as peels, seeds, and pulp, are rich in nutrients like fiber, vitamins, and antioxidants, making them suitable for use in a variety of food products, including snacks, beverages, and fortified flours [69]. Technologically, processes like drying, grinding, and fortification can be applied to these by-products to turn them into valuable ingredients, but the feasibility depends on factors like the availability of by-products, governmental approval for new ingredients in food formulations, and consumer acceptance [70]. It is economical to enhance raw materials with fruit and vegetable by-products to generate extra income and offset waste disposal expenses. Investment in processing technology and adherence to food safety laws may be among the initial expenses, but over time, the total savings and possible income from product innovation may make this worthwhile.

For local or specialty markets, this strategy can work quite well on a small scale, particularly in areas with sizable food processing businesses. However, acquiring by-products consistently and reliably, investing in processing equipment, and aligning with supply chain logistics are all necessary for scaling up to a bigger, industrial level [71]. The use of fruit and vegetable by-products has a generally positive environmental impact; it helps reduce food waste, which minimizes the environmental burden associated with disposing of these by-products, such as methane emissions from landfills; it reduces the need for new raw materials, which conserves natural resources and lowers carbon footprints; however, the energy and water consumption in the processing steps can influence the environmental impact, so sustainable practices must be used to ensure minimal environmental harm. Besides, it also has some negative impacts on ecosystem as well [72]. By-product processing may use a lot of water and energy, which, if not controlled well, can harm the environment. Furthermore, increasing the use of by-products might result in an excessive dependence on waste resources, which, if not carefully balanced with other sustainability initiatives, could jeopardize attempts to reduce overall food waste. Additionally, the use of by-products in food items may provide issues with customer acceptance since some people would be leery of goods created from food waste, which might impede market expansion. If appropriate handling and processing procedures are not followed, there is also a chance of contamination, which might raise issues with food safety [73]. Table 2 shows the studies showing composite flours and by-products of fruits and vegetables. The pictorial representation is given in (Fig. 1B).

Fortification of raw materials and final products for optimal micronutrient levels

Classical fortification has gained popularity over time, but its purpose has evolved from preventing deficiencies to enhancing people's health. As a result, locally available foods should be used as natural fortifiers in staple diets and processed foods to compensate for micronutrient deficiencies and even better public health. These meals should be abundant in one or more types of micronutrients and may also have the benefit of supplying some extra, unintended qualities [74].

Table 2
Fortification of snack products with fruit and vegetable by-products

Product	Added ingredient	Methodology	Product evaluation	Reference
Apricot bars	Spinach powder	T_0: 0 g SP T_1: 1 g SP T_2: 2 g SP T_3: 4 g SP	Fe: 93.61 ppm Zn: 18.17 ppm Mn: 10.15 ppm Ca: 28.45 ppm	[65]
Burfi	Kinnow juice	(~43% kinnow juice) T_0: 1% pectin T_1: 2% pectin T_2: 3% pectin T3: 4% pectin	Ascorbic acid: 4.52 mg/100g Ca: 29 mg/100 g	[68]
Cookies	Mango peel powder	T_0: 0% MPP T_1: 1% MPP T_2: 3% MPP T_3: 6% MPP	Carotenes: 400.07 mg/100g	[58]
Cookies	Banana peel flour	T_0: WF and BPF (100:0) T_1: WF and BPF (89:11) T_2: WF and BPF (87:13) T_3: WF and BPF (85:15)	Ca: 150 mg/100g K: 40 mg/100g Mg: 55 mg/100g Fe: 4.76 mg/100g	[64]
Dark chocolate	Passion fruit pulp powder and orange peel powder	T_1: 3 g PFP and 3 g OPP	3.06% ↑ in dietary fiber	[67]
Macaroni	Mango peel powder	T_0: 0% MPP T_1: 2.5% MPP T_2: 5% MPP T_3: 7.5% MPP	Dietary fiber: 7.8% Polyphenols: 1.80 mg/g Carotenoids: 84 µg/g	[57]
Pasta	Mango peel powder	T_0: 0 g MPP T_1: 1 g MPP T_2: 2 g MPP T_3: 4 g MPP	Ascorbic acid: 67.34 mg/100g	[60]
Pasta	Mango fruit kernel powder	T1: 5% MFKP T_2: 10% MFKP	Protein: 7.29% Phenolics: 535.16 mg GAE/100 g Antioxidant activity: 27.28 µmol TE/g Potassium: 912.4 mg/100 g Magnesium: 198.0 mg/100 g Iron: 12.8 mg/100 g Calcium: 263.6 mg/100 g	[61]
Pasta	Carrot powder	T_0: WF and CP (100:0) T_1: WF and CP (95:5) T_2: WF and CP (90:10) T_3: WF and CP (85:15)	Fe: 9.21 mg/100 g in T_2	[60]
Wheat semolina	Defatted soy flour	T_0: WF and DSF (100:0) T_1: WF and DSF (95:5) T_2: WF and DSF (90:10) T_3: WF and DSF (85:15)	Protein: 39.73% Zn: 4.48 mg/100 g Ca, Fe: 2X	

Another method of delivering nutrients through an extruded source was executed by Ayoub *et al.* [75]. In this process, nutrients added prior to extrusion were sufficiently reserved through extrusion and cooking. Thus, extruded rice was acceptable to consumers. A customized premix of vitamins and minerals was added as fortificants purchased from the market. Rice kernels were extruded with a premix of nutrients in a study. Fortification was done in four ways including coating of rice kernels with a mixture of premix, spraying of premix on normal rice kernels that are later mixed with normal rice in a 1:99 ratio, cold extrusion of rice flour with premix at room temperature which are thereafter mixed with normal rice and hot extrusion of rice and premix in a heating chamber. Losses of nutrients were observed in the cooking of rice after the extrusion process and retention of vitamins and minerals was recorded [76].

Rice analogues fortified with iron and zinc could be utilized in food fortification to serve as a source of micronutrients to target malnourished populations where staple food is rice [77]. Soy protein concentrate and toasted defatted soy flour are incorporated in rice flour for the preparation of rice-soy crisps through supercritical fluid extrusion. Soy adds protein content and improves the amino acids, providing a more nutritious food product. Moreover, fortification of other nutrients such as vitamins A, and C and minerals Fe and Zn also add up to worth of snacks [78]. Hackl *et al.* [79] directed a study of the co-fortification of extruded rice products and iron and different zinc salts. Two fortificants for zinc fortification *i.e.,* zinc oxide and zinc sulphate were used in this experiment. The latter one was preferable due to more bioavailability and having less acid affinity than zinc oxide which enhances the solubilization of salt. Moreover, another technique named as redox modulation has the advantage of forming complexes that help disguise the metallic taste and prevent colour changes driven on by the addition of Fe salts. If the degree of such complex development is not properly controlled, it might cause food matrices to become soured and darker [80].

Puffed rice and rice noodles were considered as a carrier for delivering calcium. They were prepared through extrusion processing and then fried and cooked respectively. The addition of nutrients before and after frying/cooking were recorded to evaluate losses and retention values. Three types of salt were used *i.e.,* calcium lysinate, calcium carbonate and tricalcium phosphate. Their bioavailability was evaluated through dialysis for these salts indicating that the formation of calcium-phosphate complexes in the intestine hinders its bioavailability [81].

Extruded rice has also been prepared by fortifying them with 8% soybean protein powder. The addition of soybean dietary fiber was done in two treatments 6% and 9%. The product achieved a taste value of up to 70 and was thus suitable for industrial application. Fiber intake is closely related to digestive and cardiovascular health. Intake of fiber has been recommended for various chronic diseases like obesity and diabetes [82].

An alarming rate of deficiency has been seen for vitamin B_{12}. Its prevalence has generated a focus on developing fortified foods through better and more stable fortificants. Cyanocobalamin was added as a fortificant in snacks to enrich the level of vitamin B_{12}. To achieve the desirable retention of vitamin B_{12}, hydrocolloids such as carboxymethyl cellulose were added at 5 g/kg of rice flour. Excellent retention was observed after extrusion and cooking [83].

Chocolate spreads are flavored with sugar, hazelnuts, and vegetable fats. They are used in delicious confectionary products and baked items. However, their composition imparts a negative impact on health, as they are loaded with fats and sugars. Chocolate hazelnut spread has also been formulated which composition is free of palm oil. Inulin and maltitol were used as a substitute for sugar and fortified with vitamin D and Mg-$CaCO_3$ nanoparticles. This spread attained a significant level of micronutrients after fortification [84].

Critical considerations, ecological implications, and limitations

Fortification of snack foods with essential nutrients involves several critical considerations, ecological implications, and limitations. The bioavailability of nutrients in fortified snacks is essential for ensuring proper absorption and maximizing health benefits. [85]. Additionally, compatibility between fortificants and the food matrix must be considered to avoid nutrient degradation during processing and storage [86]. Regulatory compliance is necessary to ensure that fortification practices meet safety standards set by authorities like the FDA or WHO [85]. Consumer acceptance also plays a vital role, as fortificants may alter the taste, texture, or appearance of snacks [87]. From an ecological perspective, the production of fortificants can contribute to resource depletion and environmental degradation, especially when sourcing raw materials requires intensive agricultural practices or when waste is generated during manufacturing [88]. Furthermore, energy consumption in fortificant production and snack processing can increase the carbon footprint [74]. The cost of fortificants, particularly those derived from specialized or organic sources, may also limit the affordability of fortified snacks, particularly in resource-limited settings. Nutrient stability is another concern, as certain vitamins and minerals may degrade over time or during processing [89]. Lastly, there is the potential risk of over-fortification, which could lead to toxicity or imbalances in nutrient intake if not carefully controlled [90]. Therefore, fortification strategies must balance the benefits of enhanced nutrition with these environmental, economic, and health.

Additionally, the carbon footprint may rise due to energy use in snack processing and fortification manufacturing [91]. The price of fortifiers, especially those made from organic or specialized sources, may also make fortified snacks unaffordable, especially in environments with limited resources [92]. Fortification plans must thus strike a compromise between these economic, health, and environmental factors and the advantages of improved nutrition. The following Table 3 depicts the experimental studies showing fortificants used in the snack industry. The pictorial depiction is stated in (Fig. 1C).

Development of nutritious snack alternatives for improved health outcomes

Some food products can be designed as substitutes for snacks, offering better nutritional adequacy and an improved nutrient profile compared to conventionally produced snacks, which are typically made using traditional methods. These methods often involve simpler, more manual techniques such as frying, baking, or drying, where the emphasis is placed on taste, convenience, and preservation rather than maximizing nutritional content. While traditional methods have cultural significance, they often lack the latest nutritional advances, making them less balanced than modern snacks designed for better health benefits. Making strategic snack substitutions can improve health outcomes and give a boost of energy for the entire day. The following are some strategies to adopt for better nutrition.

Fruit leather

Fruits constitute the major portion of the human diet. They are often consumed as snacks and are equally popular among youngsters and older adults. They are indispensable sources of micronutrients tasty and convenient energy sources with low calories

Table 3
Fortificants used in the snack industry to enrich snack foods and their evaluation based on nutrient enhancement

Product	Fortificants	Approach	Methodology	Product evaluation	Reference
Broken rice flour	Ferric pyrophosphate and zinc oxide	Addition of micronized salt of iron (6.34 mg) and zinc (2.10 mg)	T_0: Control T_1: 6.34 mg MFPP T_2: 2.10 mg ZnO T_3: 6.34 mg MFPP and 2.10 mg ZnO	Retention of: • Fe: 99.85% • Zn: 99.7% in T_2	[77]
Chocolate spread	Vit D and Mg-$CaCO_3$	Nanoparticle fortification	T_0: Control T_1: No palm T_2: NP-No sugar T_3: NP-NS and VD (166 μg/kg) T_4: NP-NS, VD (166 μg/kg) and Ca (11.6 g/kg) T_5: NP-NS and Ca (11.6 g/kg)	Retention of: • Vit D: 15X • Ca: 9X in T_5	[84]
Ground roasted coffee	Ferrous bisglycinate chelate, ferrous sulfate, zinc lactate, zinc bisglycinate chelate, calcium lactate	Redox modulation and Geometric dilutions of fortificants	T_0: Control Electric dripping by T_1: Filter paper and T_2: Nylon cloth T_3: Espresso	Retention of: • Fe: 80.8% • Zn: 75.4% • Ca: 72.1% in expresso	[93]
Puffed rice	Cyanocobalamin	Fortification	T_0: Control T_1: Guar gum (5 g/kg) T_2: Guar gum (10 g/kg) T_3: Xanthan gum (5 g/kg) T_4: Xanthan gum (10 g/kg) T_5: Carboxymethyl cellulose (5 g/kg) T_6: Carboxymethyl cellulose (10 g/kg)	77% retention of vit B_{12} in T_6	[83]
Rice noodles	Calcium lysinate, calcium carbonate, and tricalcium phosphate	Extrudate formation and fortification	(7.11 g of fortificant blended with 1.05 kg of rice flour) T_0: Control T_1: Ca lys T_2: $CaCO_3$ T_3: TCP	Ca: 6-7.2 g/kg	[81]
Rice extrudates	Elemental iron, zinc oxide, vitamins A and vitamin C	Premix formation and extrusion	T_0: Control T_1: Micronutrien Fortified (5% w/w vitamin and mineral premix constituting Fe, ZnO, vit A and vit C) T_2: Fiber Fortified (5% w/w fibersol-2) T_3: Bran Fortified (5% w/w bran) T_3: Emulsifie Enhanced (2% w/w extract emulsifier)	(Retention of micronutrients after processing) • Vit A: 40% • Fe: 96% • Vit C: 60% • Zn: 95% in T_1	[75]
Rice	Ferric pyrophosphate, vitamin B_{12}, folic acid, zinc oxide and retinyl palmitate	Incorporation of premix (458 mg FPP, 7 mg vit B_9, 100 mg retinyl palmitate, 50 mg vit B_{12} and 183 ZnO /g) in normal grains	• CO1 and CO2 (Coating of premix on grains) • CE1 and CE2 (Cold extrusion) • HE1 and HE2 (Hot extrusion)	Retention of: • Zn: 88.8% • Fe: 99.8% • Vit A: 43.4% • Vit B_{12}: 89.4% • Vit B_9: 74.4% in CO1 and CO_2	[76]
Rice kernels	Isotopic ferric pyrophosphate and zinc sulphate	Co-fortification	T_0: Control T_1: 4.4 mg FPP and 4.4 mg Zn T_2: 4.4 mg FPP and 4.4 mg ZnO T_3: 64.4 mg FPP and 4.4 mg $ZnSO_4$	Bioavailability of Fe: 1.6 X in T_3	[79]
Rice soy crisps	Soy protein concentrate, retinyl palmitate, NaFeEDTA, and vitamin C	Extrusion	(24 mg Fe, 10,090.09 IU vit A and 147 mg vit C per 100 g of concentrate)• RSC-SPC 25 (25 g/100 g) • RSC-SPC 40 (40 g/100 g) • RSC-SF 25 (25 g/100 g) • RSC-SF 40 (40 g/100 g)	Fe: 26.19 to 32.09% Vit A: 4,769-5,005 IU/100 g Vit C: 71.42-78.88 mg/100 g in T_4	[78]
Rice grain	Soybean protein, soybean fiber and dietary fiber	Extrusion	T_0: Control T_1: SP, SF and DF (92:8:0) T_2: SP, SF and DF (89:8:3) T_3: SP, SF and DF (92 SP and DF (86:8:6) T_4: SP, SF and DF (83:8:9) T_5: SP, SF and DF (80:8:12) T_0: SP, SF and DF (77:8:15)	Highest soluble fiber (14 mg/g) in T_4	[82]

loaded with rich minerals and vitamins. Their pulp is being used in industry to make various healthier products that can be utilized instead of snacks, which lack nutritious components. Fruit leather is a dehydrated form of pulp at 50°C. In the conventional method of leather making, the pulp of fruits is boiled or mashed to make the puree. Preservatives and flavoring agents are added and blended. The concentrate of fruit mix is then layered on a tray, which is then kept in a dehydrator. Added preservatives enhance their shelf life making them acceptable in market [94].

Malnutrition has been a serious issue arising due to deficiency of protein in diet or inaccessibility of protein in available food. Fruit leathers fortified with protein-rich items can provide both plenty of trace minerals as well as high-quality protein with the correct balance of amino acids. There are various food ingredients that can be utilized in the development of fruit leathers. Peach is a widely consumed stone fruit whose leather has been made with fortification of soy slurry for greater protein content [95].

Strawberries and kiwi are mixed with apple pomace in pureed form to make leather. These combinations were utilized to develop preservative-free fruit bars for new markets. Final product was also microbiologically safe because pH and water activity obtained were low, even there was no added preservative [96].

Plums are most important stone fruits in Pakistan after peaches. They are prone to postharvest losses and are discarded with various vital nutrients along-with them. Total losses after harvesting in marketing channels were recorded up-to 21.51%, out of which 8.64% are at consumer level [97]. Therefore, the best way to preserve and innovate eatables is to make leather of fruit. It has been prepared as a snack item with greater amount of vitamin C making it an antioxidant food item [98]

For example, apple and figs are used as main ingredients to make leather. These leathers fortified with moringa oleifera, a native plant of India, a super food rich with antioxidants. Fruits will offer adequate amounts of micronutrients and strengthening agents *i.e.,* moringa will improve bone health. It was proven to be effective for bone health due to being rich in calcium [99]. Fruit leather prepared from 50% puree of apple and 50% of peach was acceptable to sensory panelist with better antioxidant capacity [100].

Iron-fortification of underutilized food is an emerging objective in Pakistan. Jamun was selected for iron supplementation in the form of jamun leather in a study. It is rich in carbohydrates along-with fiber, ascorbic acid and other bioactive ingredients which accounts for its health promoting properties. It is fortified by using ferrous sulphate as a source of iron providing 60% RDA of iron. Desi and raw jamun were used in making leather but desi varieties are better one according to sensory and organoleptic properties of sample [101].

In addition, guava and banana are two typical fruits with distinct flavors that are also digestive and nutritious. Guava are rich source of vitamin C, while bananas are loaded with potassium [102]. Fruit leathers are made from these two fruit mixes with addition of hydrocolloids to improve digestibility and physicochemical indices. Among hydrocolloid agents, kappa carrageenan is an independent variable to enhance the organoleptic as well as antioxidant properties of fruit leather. About 50–70% banana puree was acceptable in terms of sensory properties [103].

Feasibility, ecological implications, and limitations. The key ingredient in fruit leather is fruit puree, which can be obtained from fresh, frozen, or dried fruit. Hence, using surplus or imperfect fruit can reduce costs and minimize food waste. This process requires equipment like dehydrators or ovens, which may have initial setup costs but can be relatively low-maintenance once in place. The growing interest in healthy, portable, and sustainable snacks makes them appealing to health-conscious, eco-friendly consumers thus enhancing their marketability [104,105]. It doesn't require refrigeration and can be kept at room temperature for months, making it a practical and cost-effective choice for both manufacturers and consumers. Fruit leather production uses surplus or imperfect fruits, reducing food waste and lowering production costs. Fruit leather can be produced using local, organic fruits, which helps support sustainable agriculture and reduce environmental impact. Packaging significantly affects ecological impact, with eco-friendly materials like biodegradable or recyclable options being more sustainable. Energy consumption during production, especially from nonrenewable sources, can increase carbon footprints. Fruit leather helps reduce food waste by utilizing surplus fruits, contributing to a circular economy. However, nonorganic farming practices can be resource-intensive, requiring significant water and pesticides. Sustainable practices, like organic cultivation and water efficiency, help address these concerns. Low-energy drying technologies can further reduce carbon emissions. The ecological impact of fruit leather is also influenced by transportation, energy use, and packaging. Sourcing fruit locally and using renewable energy can reduce emissions. While fruit leather can support biodiversity by using various fruits, monoculture practices may harm ecosystems. Additionally, it may lack the diversity of fresh fruits, which could limit its appeal to some consumers [106–108]. While some consumers may find the chewy, leathery texture unappealing, especially if it's too tough or dry [109]. Some fruit leather products come in non-recyclable or excessive packaging, contributing to environmental waste. While fruit leather is popular in some markets, it may not have the same broad appeal or availability as other snack options, limiting its potential consumer base [110]. The following Table 4 describes the fruit leather development in some studies. The (Fig. 2A) contains its graphical depiction.

Herbal food products

Food item made with herbal varieties are becoming the basis of innovative products for incoming food industry. Some studies illustrate that *M. oleifera* with its bioactive constituents could play a vital role in the prevention of several chronic and degenerative diseases arising from oxidative stress. As it is packed with all necessary nutrients and bioactive compounds (terpenoids, polyphenols, flavonoids, glycosylates, alkaloids and carotenoids) [111].

Dachana *et al.* [112] demonstrated significant increase in protein, iron and calcium level, respectively, in cookies was observed with addition of moringa leaves powder in ration of 0–15%. The highest increase in mineral contents *i.e.,* iron and calcium were found in moringa added pasta. Pasta was prepared by using wheat and millet in a ratio of 50:50. Moringa was best accepted for sensory properties when 3% powder of leaves were added [60].

Amaranth is a pseudo-cereal and is used to fortify various cereal products like bread, muffins, pancakes, cookies, and crackers. As, cheese bread has been made by Lemos *et al.* [113] through incorporation of 10% amaranth. It resulted in an increase in some nutrients such as 17% of protein, 18 times the amount of fiber, and 3 times iron compared to conventional maize porridge. Celiac patients could have this breakfast as it was a gluten free product. significant addition in iron level was observed in porridge made from amaranth and maize flour [114].

Vasileva *et al.* [115] designed bread by using herbs to enhance its nutritional and storage values. The industry has been improvising to enhance the quality of bread by adding valuable ingredients or other technological processes. Formulation of bread flour by supplementing it with 1–5% waste from agro, food, and essential oil industry is being explored. Lavender and melissa in bread exerted a significant effect on its quality as well as its nutritional properties. The

Table 4
Nutrient evaluation of various herbal food products developed using different herbal ingredients

Fruits	Approach	Methodology	Product evaluation	Reference
Apple, figs and moringa	Oven drying at 50^{o}C for 2 hours	T_0: Control T_1: AP and FP (25:75) with 2.5 g MLP T_2: AP and FP (50:50) with 2.5 g MLP T_3: AP and FP (75:25) with 2.5 g MLP	Ca: 314 mg/100 g Fe: 1.36 mg/100 g Antioxidant activity: ↑33.3−41.6% Total phenolic content: ↑25−27% in T_3	[99]
Apple and peach	Oven drying at 60^{o}C for 8 hours	T_0: Control T_1: AP and PP (100:0) T_2: AP and PP (75:25) T_3: AP and PP (50:50) T_4: AP and PP (25:75) T_5: AP and PP (0:100)	20.6 mg ascorbic acid per 100 ml 0.15 mg iron per 100 g, 6.1 mg magnesium per 100 g in T_3	[100]
Apple strawberry and kiwi	Oven drying at 60^{o}C for 20 hours.	T_0: Control With Arabic gum T_1: SP and AP (50:50) T_2: SP and AP (50:50) With kappa-carrageenan T_3: SP and AP (60:40) T_4: SP and AP (60:40)	Higher protein in strawberry leather *i.e.,* 3.1% Higher crude fiber in kiwi fruit leather *i.e.,* 4.7% in T_3	[96]
Guava and banana	Oven drying at 60^{o}C for 8 hours.	T_0: Control With Arabic gum T_1: GP and BP (50:50) T_2: GP and BP (50:50) With kappa-carrageenan T_3: GP and BP (60:40) T_4: GP and BP (60:40)	Protein: 3.61% Antioxidant activity: 57% in T_2	[103]
Peach and soy	Oven drying at 60^{o}C for 2 hours	T_0: Control T_1: PP and SP (100:0) T_2: PP and SP (95:5) T_3: PP and SP (90:10) T_4: PP and SP (85:15) T_5: PP and SP (80:20) T_6: PP and SP (75:15) T_7: PP and SP (70:30)	Vit C: 23.54 mg/100g Protein: 3.40% in T_7	[95]
Plum	Oven drying at 70^{o}C for 24 hours.	T_0: Control T_1: Plum and Sugar (50:50) T_2: Plum and Sugar (60:40) T_3: Plum and Sugar (70:30) T_4: Plum and Sugar (80:20) T_5: Plum and Sugar (90:10) T_6: Plum and Sugar (100:0)	Vit C: 4.83 mg/100g in T_3	[98]

acceptable quantity of lavender that has been added to bread was monitored up-to 2.5%. The addition of this quantity in bread raised the shelf life of bread to 4 days at 22^{o}C, 30^{o}C, and 37^{o}C. 5% addition showed an increase in dietary fiber (3X) and polyphenol (4X) content. Moreover, bagels have also been prepared by using aqueous extract of lavender by Manzoor, Rakha [116]

Marjoram is also a beneficial herbaceous plant which contains remarkably high levels of zeaxanthin, β-carotene, lutein, and cryptoxanthin. Its addition in snacks have been used to enhance the bioactive potential of snack item. Chilli, tomato, and marjoram (1:1:0.8) were added. They have ability to improve the hemoglobin of the body, as they contain iron and folate [117,118]. Mint and spearmint are antioxidant, anti-neoplastic, fungicidal, insecticidal, and antiallergenic [119]. Being fortificants, they increase iron, zinc, calcium, β-carotene, and fiber content in final product. Fruit bars are non-baked, vegan, easy to develop, and stable in terms of shelf life. They are supplemented with apricot kernel for better organoleptic characteristics [120]. Wheat rusks were prepared by adding fenugreek seed powder after debittering with curd. It enhanced dietary fiber along-with other trace elements [121].

Extruded corn snacks are popular among people of all ages, but they have little nutritional value. Therefore, they have been prepared by using ginger, bay leaves, and turmeric powder. Iron, potassium, calcium, and zinc levels were observed in a final product which was significantly higher than conventional corn snacks [122].

Feasibility, ecological implications, and limitations. The demand for herbal medicines is projected to grow due to an aging population and a consumer preference for natural therapies. However, the consistency and safety of herbal products may be impacted by the absence of standardized quality control and regulation [123,124]. Degradation of ecosystems and a loss of biodiversity can result from overharvesting medicinal plants. Water shortages and soil erosion can be caused by unsustainable farming methods. On the other hand, biodiversity may be enhanced and conservation efforts supported by sustainable harvesting and agriculture [125]. Prescription drugs and herbal products may interact negatively, causing side effects. There is insufficient scientific proof to support the effectiveness of many herbal treatments. Product safety may be jeopardized by quality control problems like pesticide or heavy metal contamination. The safety and quality of herbal products vary because regulatory frameworks such as DRAP and GMP are frequently insufficient [126]. The studies showing herbal products made through fortification are depicted in the following Table 5. The (Fig. 2B) contains its pictorial depiction.

Reformulation for better snack composition

Some ingredients found in snacks, when consumed in excess, can sometimes be health-compromising, but they are not inherently harmful when consumed in moderation. Some of the vital nutrients are lost during processing which declines the nutritional

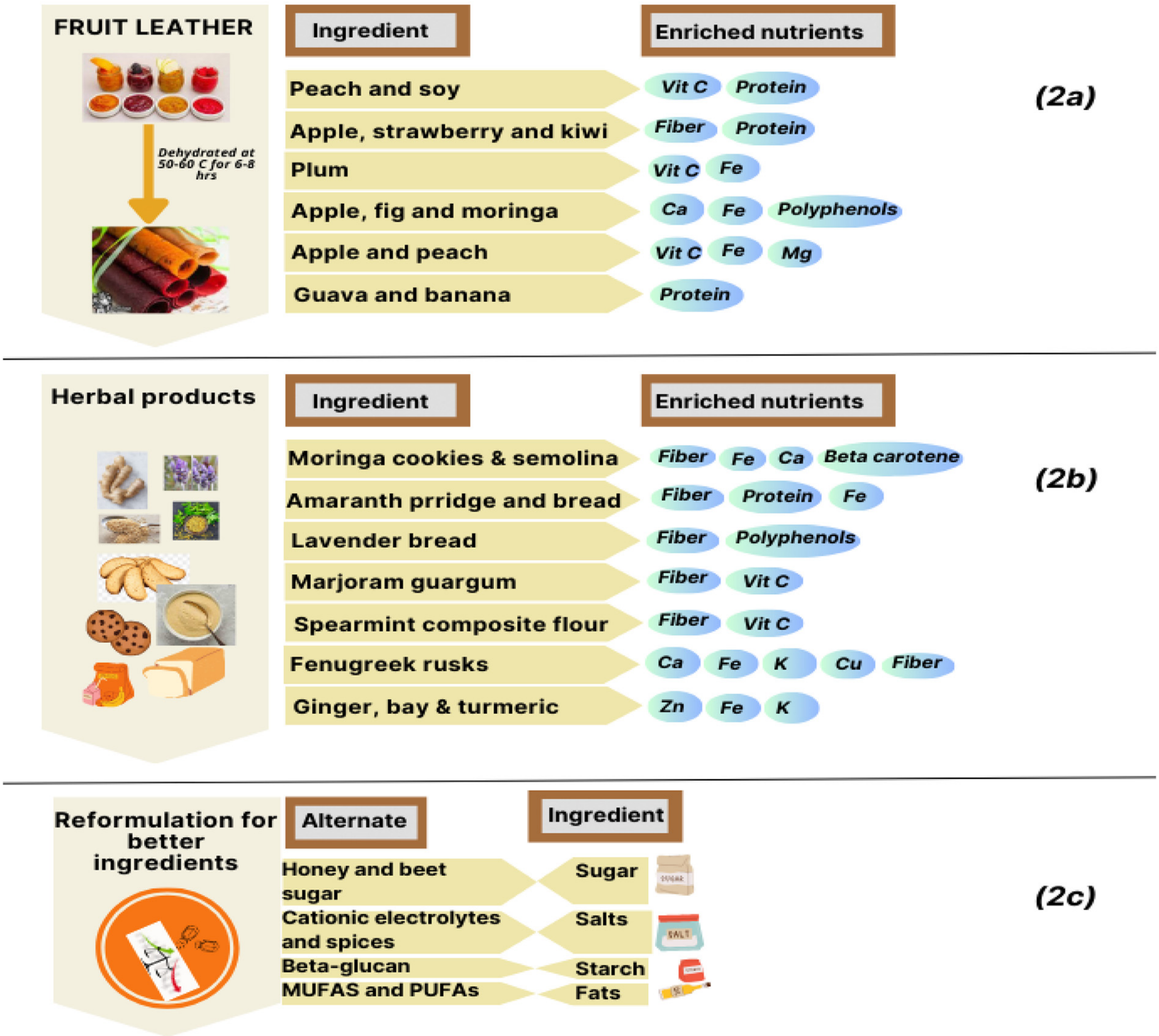

Figure 2. Illustration of strategies for developing healthier snacks: (2A) Identification of nutrient-rich ingredients, (2B) Incorporation of functional ingredients for improved health benefits, and (2C) Reformulation techniques to enhance nutritional profiles of snacks.

value of the final product. Some of the nutrient losses such as mineral deficiencies including iron, calcium, and zinc are either made up by biofortification through agronomic or genetic approaches or compensated by fortifying them with different flour varieties, by-products of fruits, vegetables, and herbal ingredients. as discussed earlier but the reduction of these factors is done by adapting some strategies discussed below.

Salt can be partially replaced by adding cationic electrolytes such as potassium, magnesium, and calcium to maintain the optimization of blood volume. They can help to manage blood pressure by slightly reducing the negative effects of a high sodium intake. Meanwhile, replacing NaCl with other electrolytes allows for the maintenance of electrolyte levels required to optimize process efficiency while also having potential health benefits [127]. At low concentrations, acidic flavors such as citric, lactic, and tartaric acids can enhance the salty perception without affecting taste. Anions may also be a good replacer of salt such as glutamate [128]. Perception of saltiness can be masked off by adding an aromatic flavor booster. Addition of herbs and spices *i.e.,* garlic, ginger, herbal blends, saffron and deadnettle family plants impart flavor to snacks that masks sensation of low salt in food item. Therefore, usage of plant-derived seasonings have shown good acceptance at consumer level [129]. For example, lovage is a popular flavoring ingredient that has been used as a salt substitute. Salty sensation can be increased by adding up more fat content with sodium in aqueous form within emulsion-based products. Unsaturated fatty acids appear to be beneficial in this regard. As by increasing the concentration of canola oil up-to 40%, the intensity of NaCl and KCl will increase in terms of salinity [130]. Technological aspects have been utilized to minimize the sodium concentration in snack items. Internalized salt can be stabilized with gelatinized waxy rice starch to release less concentration of salts [131]. The encapsulated aqueous salt phase has revealed a 23.7% reduction of salt without affecting the perception of saltiness [132]. Spray drying can reduce the size and bulk density of salt. This technique has delivered 30% KCl with NaCl. This substitution reflects small salt particles with a higher salinity level [133]. Furthermore, using electromagnetic atomization drying (EAD) to create nanoscale salt crystals increases salinity and reduces sodium content in potato chips by up to 65% [134]. Atomization drying can also be accomplished using ultrasound techniques. Ultrasound treatment has reduced salt size by up to 0.75%, resulting in a 30% reduction in sodium content [135].

Table 5
Development of herbal food products

Herbs	Product	Methodology	Product evaluation	Reference
Amaranth	Cheese bread	T_0: Control T_1: 10% AF T_2: 15% AF T_3: 20% AF	Protein: 17% Fiber: 18X Iron: 3X in T_1	[113]
Amaranth	Porridge	T_0: Control T_1: Unrefined maize (4.1 mg) T_2: Unrefined maize and AF (30:70) with iron (23 mg)	35% ↑ in T_2	[114]
Tamarind	Tamarind candies	T_0: Control T_1: Ferrous sulphate T_2: Ferrous fumarate T_3: Charoli seeds and ferrous sulphate T_4: Charoli seeds and ferrous fumarate	Fe: 32.54 mg/100g in T_2	
Debittered fenugreek flour	Wheat rusk	T_0: Control T_1: 5%DFF T_2: 10%DFF T_3: 15% DFF T_4: 20% DFF	20% ↑ in: Fe, Ca, K, and Cu Fiber: ↑ 41.7% in T_3	[121]
Lavender	Bread	T_0: Control T_1: 2.5% lavender leaves powder T_2: 5% lavender leaves powder	Fiber: 3X ↑ TPC: 4X ↑ Shelf life: 4 days ↑ in T_2	[115]
Marjoram	Extruded snack (blended with guar gum and then dehydrated)	T_0: Control T_1: Chilli, tomato and marjoram (1:0:0) T_2: Chilli, tomato and marjoram (1:1:0) T_3: Chilli, tomato and marjoram (1:1:0.08)	Vit C: 15.56 mg Fiber: 11.16% in T_2	[117]
Moringa leaves powder	Cookies	T_0: Control T_1: WF and MLP (95:5) T_2: WF and MLP (90:10) T_3: WF and MLP (85:15)	Fiber: 4.3% Fe: 5 mg/100 g Ca: 272 mg/100 g β-carotene: 1600 μg/100 g in T_2	[112]
Moringa leaves powder	Pasta	T_0: Control T_1: WF and MLP (97:3) T_2: WF and MLP (95:5) T_3: WF and MLP (92:8)	Fat: 5.23% Ash: 10.16% Fe: 141.98 mg/100 g Ca: 1,623.18 mg/100g Total carotenoids content: 55.17 mg/100g in T_1	[60]
Powdered form of ginger, bay leaves and turmeric	Extruded rice product	Premix made with ginger, bay leaves and turmeric (1:1:1) T_0: Control T_1: 1% premix T_2: 3% premix T_3: 5% premix	Zn: 1.29 mg/100 g K: 320 mg/100 g Fe: 29 mg/100 g in T_2	[122]
Spear mint powder	Fruit bars	Spearmint powder added with apricot kernel in ratio of 75:25. Then, it is mixed with T_0: Control T_1: Synthetic Fe fortified (18 mg) T_2-T_{10}: Dried apricot and spearmint powder (75:25) with iron fortification (10.75- 18.29 mg)	11.23% fiber 60.1 mg iron/100 g in T_3	[120]

Concentrated sugarcane or sugar beet juices derived from the sucrose crystallization process are another option. Crystallization inhibitors accumulate in residual syrups, which are referred to as molasses [136]. Maple syrup is a natural sweetener derived from the maple tree species native to Canada. It contains phenolic compounds, which are responsible for its antioxidant, anti-mutagenic, and anti-proliferative properties in human cancer [137]. Coconut sugar has a faster digestion rate and a lower glycemic index. It contains few calories but a lot of vitamins. The syrup has been derived from dates, which possess potential health benefits due to its high nutritional profiles being rich in unsaturated fatty acids. It reflects good tooth decay protection and stimulates immune function [138]. Stevia is a zero- or low-calorie sweetener with a sweetness intensity 40−450 times higher than sucrose [139].

Simple sugars and starchy foods, contribute most of the energy, should be reduced by substituting dietary fiber derived from natural or synthetic sources [140]. Fiber is important for better gut health, that is lost mostly in processing techniques. An ample amount of fiber is necessary to modulate colonic bacteria for improved digestion and prevention of various chronic diseases like cardiovascular disorders and digestive health issues. Due to their satiating and viscosity, some ingredients have been added to snacks to increase the dietary fiber content, such as β-glucan, lupin kernel fiber, rye bran, whole grain rye, or mixed high fiber sources. It increases stomach retention time and colon fermentation, both of which cause satiety responses [141]. Polydextrose, resistant starch, inulin, oligofructose, β-glucan, and glucomannan are the most common fiber sources used to reduce energy density [142,143]. Polydextrose is a soluble fiber that is widely used in the food industry. It is partially fermented in the colon, with nearly 60% excreted. It also provides calories at 1 kcal/g [144]. Another source of fiber is glucomannan, which is commonly found in reformulated products and low-caloric food items [145,146].

The fat content of snacks also needs to be improved by lowering the level of saturated and trans-fat. Unsaturated fatty acids are proven to be healthier substitutes in reformulation strategies *i.e.,* monounsaturated fatty acids and polyunsaturated fatty acids may be used as substitutes for saturates. Hydrocolloids are long-chain polymers that form viscous dispersions. when in contact with water, are another possible candidate. Among these are carboxymethyl cellulose, xanthan gum, high methyl-esterified pectin, low methyl-esterified pectin, sodium alginate, and iota-carrageenan. It has been proposed that these hydrocolloids replace saturated fat in chocolate, such as cocoa butter, to produce low-calorie products. Furthermore, the product of enzymatic hydrolysis of soluble fiber-rich oat flour (β-glucan) can be used as a fat substitute, retaining physical and rheological properties in formulations with 40% to 60% substitutions. Furthermore, monoglyceride organogels such as monoglyceride emulsion, sunflower, and palm oil are being considered as saturates and trans-fat alternatives. It has also been reported that replacing palm oil with hydrogel may result in significant reductions in saturated fat in bread varieties [147]. Figure 2A contains its visual depiction.

Concluding insights: reducing hidden hunger through the strategic modulation of snack foods

Fortifications can be crucial in eliminating hidden hunger if snack foods are released into the market in a way that suits customer preferences. Adding fortification to commonly consumed snack foods can increase the benefits of food fortification, which has already been shown to significantly reduce micronutrient deficiencies, including a 72% reduction in iron deficiency anemia and a 58% reduction in vitamin A deficiency [90]. Snacks are becoming more and more popular among all age groups, and if they are enhanced with vital micronutrients, they may be a quick and easy way to provide the public with important nutrients.

Additionally, a consumer-driven formulation that guarantees flavor, texture, and price might increase the acceptability of fortified snacks, establishing them as a long-term remedy for hidden hunger [148].

Fortified chips, biscuits, energy bars, and extruded snacks enhanced with iron, zinc, vitamin A, and other vital micronutrients can be used to address deficits in communities with limited access to a variety of foods. Numerous factors including implementation size, target groups, and consumption patterns make it difficult to estimate the exact reduction in hidden hunger that can be achieved with snack food fortification over the next ten years Large-scale food fortification programs, for example, have helped to lower shortages in vital minerals like vitamin A, iron, and iodine. Modulated snack foods have the potential to significantly reduce the prevalence of hidden hunger in the years to come if they are broadly recognized and consumed, particularly in areas with limited access to diversified meals. However, it has been estimated that every 1$ spent for fortification can return it 27$ and has been proven to be effective both economically and nutritionally [149,150].

A strategic plan entitled Harvest Plus plans to reach 20 million farming households with biofortified planting material by 2020, and by 2030, one billion people are expected to consume biofortified foods worldwide. Over the next five years, it aimed to accelerate this scale-up by investing in 30 priority countries chosen based on their potential to turn biofortification into the next major food movement [151]. By the end of 2017, 6.7 million farming households in 14 countries across Africa, Asia, Latin America, and the Caribbean had received biofortified planting material, benefiting approximately 33 million people [152]. Therefore, the utilization of such techniques to enrich snack foods, replace them with healthier substitutes based on consumer acceptability, or reformulate them for better snack composition can be effective in uplifting the status of micronutrients globally.

Such strategies can be executed at large scales and also set up on a smaller scale as an initiative or start-up to support the nutrition of low and middle-income groups. Some household practices can complement efforts to reduce hidden hunger. The incorporation of diverse vegetables and fruits into daily meals to enhance the intake of vitamins and minerals is one of them [153]. Moreover, using leftover vegetable peels and fruit seeds to make smoothies, soups, or snacks ensures minimal waste and maximizes nutrient intake. Fortification of staple foods at home, such as adding powdered micronutrient supplements (e.g., iron, vitamin A) to daily dishes like rice, lentils, or porridge, has proven an effective method of home-based enrichment [154]. Incorporating biofortified crops, such as fortified rice or maize, ensures a steady intake of essential vitamins and minerals. Home fortification methods, including the use of fortified cooking oils or premixed nutrient powders, can further boost the nutrient profile of meals [153]. Adding nutrient-rich herbs and spices like turmeric or moringa to everyday cooking provides additional health benefits. Preparing nutrient-dense snacks like energy bars, granola, or baked goods using locally available ingredients such as seeds, nuts, and dried fruits can enhance daily nutrient consumption [155].

Fermenting foods like yogurt and pickles increases probiotic content, aiding gut health and nutrient absorption. Proper food storage, such as keeping fruits and vegetables in cool, dark places, helps preserve their nutritional value. Furthermore, participating in already executing community-based nutrition programs such as the World Food Programme fosters awareness about food handling, preservation, and fortification, enabling households to make informed dietary choices and combat hidden hunger effectively [156].

The following Table 6 shows some low-income methodologies of fortification interventions, which can significantly improve nutritional status to control hidden hunger.

Fortification and supplementation strategies are effective approaches to combat micronutrient deficiencies, particularly in vulnerable populations like infants and young children. The studies reviewed indicate that home fortification with micronutrient powders significantly reduces anemia and iron deficiency, while interventions such as vitamin A and zinc supplementation contribute to better health outcomes, including improved immune function and growth. Additionally, iodine fortification plays a crucial role in cognitive development. These findings emphasize the importance of targeted fortification programs in regions with high prevalence of micronutrient deficiencies

Conclusion

Snacks are gaining importance in the global market since children and adults like snacking and it has thus become part of the dietary pattern. However, the inadequate nutrient composition of those snacks has negative consequences on the health of individuals. Micronutrient deficiencies are prevalent worldwide, leading to hidden hunger. These realities can be advantaged by using snacks as vehicles for delivering trace minerals. Over the past 10 years, research has suggested various approaches to modulate the nutritional value of snacks efficiently. An efficacious perspective on the future would be the preservation of food resources and development of innovative techniques in regions suffering from undernourishment and food shortages, since these disadvantages exacerbate food insecurity, resource depletion, and environmental damage along with financial losses. Additionally, the nutritional interventions outlined in this study should include thorough physicochemical and bioactive analyses. Ensuring continuous monitoring of their therapeutic effects at the community level is essential. Additionally, modern processing techniques should be employed to minimize the loss of essential nutrients. The bioavailability of nutrients and their interaction with fortificants should also be

Table 6
Low-income setting fortification programs to combat hidden hunger

Intervention	Target issue	Target population	Results	References
Home fortification with multiple micronutrient powders (MNP)	Iron deficiency, anemia	Infants (6-23 months)	Reduced anemia by 31%, improved iron levels	[157]
Iron and folic acid supplementation	Iron deficiency, anemia	Children under 5 years	Similar effect to MNP but lower compliance	[157]
Vitamin A fortification	Vitamin A deficiency	Infants and young children	Increased vitamin A levels, reduced morbidity	[157]
Zinc supplementation	Growth stunting, diarrhea	Children under 5 years	Improved growth, reduced diarrheal episodes	[157]
Iodine fortification in salt	Iodine deficiency disorders	General population	Improved iodine status and cognitive benefits	[157]
Micronutrient supplementation and fortification in children under five	Malnutrition, vitamin and mineral deficiencies	Children under 5 years	Effective in reducing micronutrient deficiencies and improving health outcomes	[158]
Multiple micronutrient fortification of food	Iron deficiency, anemia, malnutrition	General population		[159]
Vitamin A, Calcium, and Vitamin D fortification	Vitamin A, D, and calcium deficiency	Women of reproductive age	Enhanced overall health of women.	[160]

considered. Further research is needed to implement these strategies in human-based clinical trials to confirm their efficacy in terms of therapeutic potential.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

CRediT authorship contribution statement

Sana Manzoor: Writing – review & editing, Formal analysis, Data curation, Conceptualization. **Ammar B. Altemim:** Writing – review & editing. **Allah Rakha:** Supervision. **Hina Rasheed:** Writing – review & editing. **Muhammad Shaffay Ali Khan:** Writing – review & editing, Visualization. **Seemal Munir:** Writing – review & editing. **Zuhaib F. Bhat:** Writing – review & editing. **Rana Muhammad Aadil:** Investigation.

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