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Review Article

From Food Insecurity to Nutrition Security: Tackling Malnutrition

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ABSTRACT

The global focus in public health is gradually shifting from ensuring food availability to ensuring nutritional adequacy. While traditional approaches emphasized calorie intake, emerging evidence highlights the importance of consistent access to nutrient-rich foods that support growth, immunity, and long-term health. This review explores the major contributors to malnutrition, including wasting, stunting, and micronutrient deficiencies, particularly among children under five years of age. It evaluates current interventions such as Ready-to-Use Therapeutic Foods (RUTF), biofortified crops, and fruit-based nutritional supplementation. The findings suggest that addressing calorie deficiency alone is insufficient to combat "hidden hunger," which results from inadequate micronutrient intake. A more integrated strategy combining clinical nutrition, food-based approaches, and community-level interventions is essential. This paper proposes a framework that prioritizes nutrient density and bioavailability to achieve sustainable nutrition security.

INTRODUCTION

Malnutrition continues to be one of the leading causes of illness and mortality among children worldwide [1,8]. Earlier public health strategies primarily focused on food security, which was defined in terms of sufficient caloric intake [2]. However, recent understanding emphasizes that adequate calories alone do not guarantee proper nutrition.

The concept of nutrition security has therefore emerged, highlighting the need for diets that provide essential vitamins, minerals, and other nutrients required for optimal health [2,13]. Many populations may meet their energy requirements but still suffer from deficiencies due to poor dietary quality.

Malnutrition today reflects a complex "triple burden," including undernutrition, micronutrient deficiencies, and increasing rates of overweight

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and obesity [15,36]. Among these, children under five remain particularly vulnerable, often requiring both clinical care and community-based interventions [1,3].

This review aims to examine modern strategies for addressing malnutrition, with a special focus on nutrient-dense food approaches such as fruit-based supplementation and their role in improving long-term nutritional outcomes.

Types of Malnutrition

1. **Undernutrition:** Includes wasting (low weight for height), stunting (low height for age), and underweight (low weight for age).
2. **Micronutrient Deficiencies:** A lack of essential vitamins and minerals such as iron, vitamin A, iodine, and zinc.
3. **Overnutrition:** Manifests as overweight, obesity, and diet-related non-communicable diseases like diabetes and hypertension.
4. **Imbalanced Nutrition:** Involves the consumption of nutrients in the wrong proportions.

Natural fruit-based supplements offer a viable alternative due to their richness in vitamins, minerals, and antioxidants. This study focuses on a fruit powder formulation—comprising Watermelon, Orange, Strawberry, Lemon, and Mango—designed to provide a convenient source of nutrition. These fruits contribute essential components like Vitamin A for vision, Vitamin C for immunity, and electrolytes for hydration. The objective is to develop a cost-effective product that improves nutrition security and strengthens the immune systems of children in malnourished communities.

1. HISTORICAL BACKGROUND

The history of malnutrition is closely linked with poverty, famine, disease, and the unequal distribution of resources [2,3]. In earlier civilizations, it was primarily a consequence of natural disasters like droughts and crop failures [45]. Ancient records from Egypt, Mesopotamia, China, and India describe periods of severe hunger leading to widespread death [25,45].

Scientific understanding began in the 18th and 19th centuries when industrialization caused rapid urbanization, leading to protein deficiency and diseases like scurvy and rickets [32,34]. After World War II, global hunger became an international concern, leading to the formation of the FAO in 1945, followed by the WHO and UNICEF [13,15]. In India, the Bengal Famine of 1943 highlighted the severity of the issue, prompting post-independence initiatives such as the Mid-Day Meal Scheme (MDM) and the Integrated Child Development Services (ICDS) [7,24]. In recent decades, the focus has shifted from mere food security to "nutrition security," emphasizing access to safe, nutrient-rich, balanced diets [1,13].

2. PATHOLOGY OF MALNUTRITION

Malnutrition can be described as a condition in which the body does not receive adequate energy, protein, or essential micronutrients, resulting in significant physiological dysfunction [1,32]. It commonly manifests as protein-energy malnutrition, including conditions such as marasmus and kwashiorkor, often accompanied by micronutrient deficiencies [9,15].

The disorder affects multiple organ systems. One of the most evident effects is the breakdown of muscle tissue due to increased protein degradation and reduced synthesis, leading to weakness and impaired physical development [40,43]. At the same



time, fat reserves are mobilized to meet energy requirements, resulting in severe weight loss [1,12].

In protein-deficient states, reduced plasma protein levels may lead to fluid accumulation in tissues, causing edema [1,23]. The liver may also accumulate fat due to impaired lipid transport mechanisms, contributing to hepatic dysfunction [32,45].

The immune system is significantly compromised, with reduced lymphocyte activity and increased susceptibility to infections such as pneumonia and diarrheal diseases [8,25]. Additionally, structural changes in the gastrointestinal tract impair nutrient absorption, further worsening the condition [12,40].

Hormonal and metabolic alterations, including reduced levels of growth-related hormones, contribute to delayed growth and impaired recovery [32,36].

2.1 General Pathological and Metabolic Changes

Malnutrition affects multiple organ systems through adaptive and maladaptive responses:

- **Muscle Wasting:** Progressive breakdown of skeletal muscle proteins due to increased proteolysis and reduced protein synthesis, leading to weakness, delayed motor development, and reduced functional capacity [40,43].
- **Emaciation:** Severe loss of subcutaneous fat and body mass as adipose tissue is mobilized to meet energy demands [1,12].
- **Edema:** Commonly observed in Kwashiorkor, resulting from **hypoalbuminemia**, increased capillary permeability, sodium retention, and impaired lymphatic drainage [1,23].

- **Fatty Liver (Hepatic Steatosis):** Caused by impaired synthesis of apolipoproteins and reduced export of triglycerides from hepatocytes [32,45].
- **Immune Suppression:** Characterized by thymic atrophy, lymphoid tissue depletion, reduced T-cell function [8,25], and impaired antibody production, leading to increased susceptibility to infections such as pneumonia, diarrhea, and measles.
- **Gastrointestinal Changes:** Villous atrophy, reduced digestive enzyme activity, and impaired nutrient absorption, further exacerbating nutritional deficits [12,40].
- **Endocrine and Metabolic Alterations:** Reduced insulin, insulin-like growth factor-1 (IGF-1), thyroid hormones, and altered cortisol levels, resulting in growth retardation and impaired tissue repair [32,36].

2.2. Pathology of Marasmus

Marasmus results from severe and prolonged calorie deficiency, affecting both protein and energy intake [1,42].

- **Severe Muscle Atrophy:** Extensive loss of skeletal muscle and fat stores, giving the characteristic “skin and bones” appearance [3,12].
- **Growth Failure:** Marked stunting and wasting with delayed physical and cognitive development [15,37].
- **Absence of Edema:** Serum albumin levels are relatively preserved compared to Kwashiorkor [1,23].



- **Liver Changes:** The liver is small and shrunken, typically without fatty infiltration [32,40].
- **Adaptive Metabolism:** The body adapts by reducing basal metabolic rate and conserving protein, allowing survival despite extreme energy deprivation [43,45].

2.3. Pathology of Kwashiorkor

Kwashiorkor arises from severe protein deficiency in the presence of relatively adequate caloric intake, often carbohydrate-based diets [1,32].

- **Edema:** Generalized or localized edema, particularly in the face, limbs, and abdomen [1,34].
- **Fatty Liver:** Marked hepatic steatosis [34,45] due to defective lipoprotein synthesis [32,40].
- **Skin Changes:** Hyperpigmentation, hypopigmentation, desquamation (“flaky paint” dermatosis), and poor wound healing.
- **Hair Changes:** Sparse, brittle hair with depigmentation and the “flag sign.”
- **Severe Immune Dysfunction:** Higher risk of infections and mortality compared to marasmus.
- **Psychological and Behavioral Changes:** Apathy, irritability, and anorexia [12,40].

2.4. Micronutrient Deficiencies and Their Pathology

Micronutrient deficiencies frequently coexist with protein–energy malnutrition and contribute substantially to morbidity and mortality [2,13].

Vitamin A deficiency can impair vision and increase vulnerability to infections, particularly in

children [17,35]. Iron deficiency affects hemoglobin synthesis, leading to anemia and reduced cognitive and physical performance [6,27].

Vitamin D deficiency interferes with bone mineralization, resulting in rickets in children and osteomalacia in adults [5,17]. Zinc deficiency compromises immune response, delays wound healing, and affects growth [17,27].

Iodine deficiency disrupts thyroid hormone production, potentially causing goiter and developmental impairments [17,32]. These deficiencies often coexist and interact, making comprehensive nutritional strategies essential for effective management.

2.5. Long-Term Consequences of Malnutrition

- **Growth Retardation and Stunting** [15,36].
- **Impaired Cognitive and Behavioral Development** [8,9].
- **Increased Risk of Chronic Diseases** in adulthood (metabolic syndrome, cardiovascular disease) [9,31].
- **Intergenerational Effects**, including low birth

3. Mechanism of Malnutrition

Malnutrition is not merely a state of being underweight; it is a complex physiological breakdown where the body systematically reallocates its dwindling resources to maintain core survival [1,12,32]. When the body faces a deficit in energy or specific nutrients, it enters a catabolic state, breaking down its own tissues. Initially, this manifests as the depletion of subcutaneous fat and significant muscle wasting [1,12,43]. However, the internal damage is often more profound. For



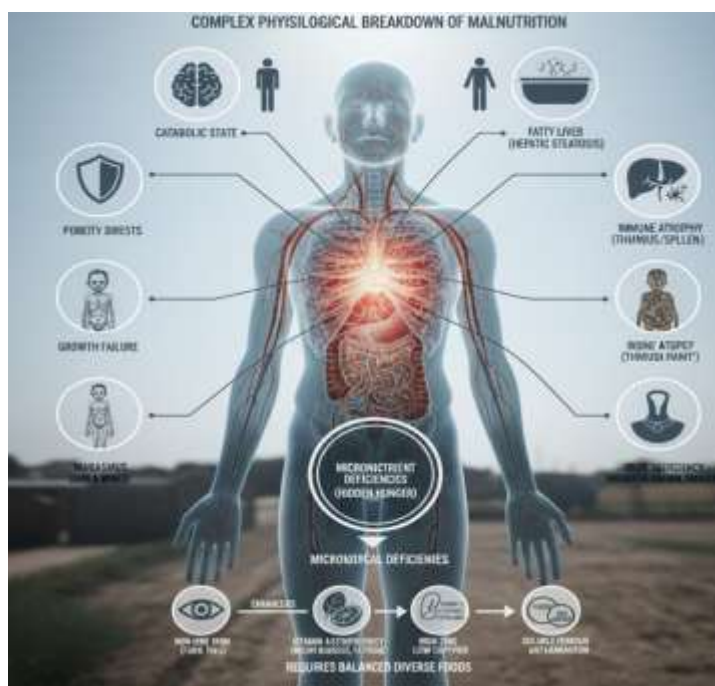
instance, the liver—the body's metabolic hub—frequently becomes "fatty" (hepatic steatosis) because it lacks the proteins necessary to synthesize lipoproteins, which are required to transport fats out of the liver cells [32,40,45]. Simultaneously, the immune system undergoes "nutritional thymectomy," where lymphoid tissues like the thymus and spleen atrophy, leaving the individual caught in a lethal cycle where malnutrition invites infection, and infection further drains nutrient reserves [8,9,25].

The specific clinical presentation of malnutrition depends heavily on whether the deficiency is caloric or protein-based [32,34]. Marasmus represents the body's ultimate adaptation to starvation, characterized by a "skin and bones" appearance as the body consumes nearly all its adipose tissue and skeletal muscle for fuel [1,12,45]. In contrast, Kwashiorkor is a more complex metabolic crisis typically driven by severe protein deficiency despite some carbohydrate intake [32,45]. This leads to a decrease in plasma albumin, which disrupts the body's osmotic pressure, causing fluid to leak into the tissues (oedema) and creating the characteristic "potbelly" appearance [1,23,34]. This state is often accompanied by dermatosis, where the skin becomes flaky and hyperpigmented, resembling "flaky paint"[34,45]

Beyond calories and proteins, "Hidden Hunger" or micronutrient deficiency acts as a silent disruptor

of biochemical pathways [2,13,17]. Vitamin A deficiency is the leading cause of preventable blindness in children, progressing from night blindness to xerophthalmia, where the cornea literally begins to melt (keratomalacia) [17,32,35]. Iron deficiency impairs the synthesis of hemoglobin, leading to microcytic anemia where red blood cells are too small and pale to effectively transport oxygen, causing chronic fatigue and cognitive delays [6,9,27]. Meanwhile, Iodine deficiency stunts the production of thyroid hormones, leading to goiter (enlargement of the thyroid) or irreversible developmental delays known as cretinism [17,32].

Ultimately, the impact of these nutrients is governed by bioavailability—the proportion of a nutrient that is actually absorbed and used [26,32]. Many nutrients do not work in isolation. For example, non-heme iron (found in plants) has a low absorption rate because it is often bound to phytates or tannins. To overcome this, the body requires "enhancers" like Vitamin C or citric acid, which reduce the iron to a more soluble ferrous state [5,6,19]. Conversely, high doses of one mineral can inhibit another; for instance, excessive zinc can interfere with copper absorption [17,26]. This synergy highlights that solving malnutrition requires a sophisticated balance of diverse food groups rather than just increasing food volume [5,8,31].



4. MATERIALS AND METHODS

The formulation developed in this study incorporates five nutrient-rich fruits: Watermelon (*Citrullus lanatus*), Orange (*Citrus sinensis*), Strawberry (*Fragaria × ananassa*), Lemon (*Citrus limon*), and Mango (*Mangifera indica*) [4,6,21]. These fruits were selected due to their high nutritional value, presence of bioactive compounds, and their ability to complement each other in providing essential vitamins, minerals, and antioxidants.

Phytochemical and Nutrient Profiles

- **Watermelon:**

Watermelon consists of approximately 91% water and is recognized as a rich source of lycopene, which accounts for nearly 90–95% of its carotenoid content. It also contains the amino acid L-citrulline, which contributes to cardiovascular health and metabolic processes [19,21].

- **Orange:**

Oranges are well known for their high vitamin C content, typically providing 50–60 mg per 100 g of fruit. They also contain important flavonoids such as naringenin, which exhibit antioxidant and anti-inflammatory properties [6,21].

- **Strawberry:**

Strawberries contain significant amounts of anthocyanins, ellagic acid, and organic acids, including citric and malic acid. These compounds contribute to antioxidant activity and support immune health [19,20].

- **Lemon:**

Lemons are characterized by a high concentration of citric acid, usually ranging between 5–8%, and also contain essential oils such as limonene, which contribute to both nutritional and antimicrobial properties.

- **Mango:**

Mangoes provide natural sugars that serve as an energy source and are particularly rich in β-

carotene (provitamin A). They also contain polyphenolic compounds such as mangiferin, which possess antioxidant and immunomodulatory effects [6,21,35].

Processing Method

To enhance stability and improve shelf life, the selected fruits are processed into powdered form while preserving their nutritional and phytochemical components [11,18,28]. Converting fruits into powders allows for higher nutrient concentration and easier storage and transportation.

Among the available processing techniques, freeze-drying is considered highly effective for preserving thermolabile nutrients such as vitamin C because it operates at low temperatures and minimizes nutrient degradation. However, spray-drying is often preferred in large-scale production due to its lower cost, faster processing time, and suitability for industrial applications [18,28,29].

These processing methods enable the development of a stable fruit-based nutritional formulation that retains essential micronutrients and bioactive compounds while maintaining a longer shelf life.

5. Nutritional Interventions: From Clinical Protocol to Fruit-Based Solutions

The management of malnutrition is typically organized according to the severity of the patient's clinical condition [1,3,12]. Children suffering from Severe Acute Malnutrition (SAM) often require intensive medical treatment in healthcare facilities. In such cases, stabilization is achieved through specialized therapeutic diets, particularly F-75 and F-100 formulations, which are designed to provide controlled energy and nutrient intake during different stages of recovery [3,12,23].

Once the patient's condition improves, or in cases of Moderate Acute Malnutrition (MAM), treatment can often be continued in outpatient settings. This phase commonly utilizes Ready-to-Use Therapeutic Foods (RUTF), such as peanut-based formulations like Plumpy'Nut, which supply high amounts of energy and essential nutrients in a convenient form. These products are advantageous because they do not require preparation with water and can be stored without refrigeration, making them suitable for use in low-resource environments [10,14,30].

An important strategy supporting these interventions is the Community-Based Management of Acute Malnutrition (CMAM) approach. This system focuses on improving access to treatment at the community level through home visits, nutritional monitoring, and simplified diagnostic methods. One of the most widely used screening tools is the Mid-Upper Arm Circumference (MUAC) tape, which allows healthcare workers to assess the level of muscle wasting and quickly identify children who require treatment [1,14,39]. By using this community-centered model, many children with malnutrition can receive care without needing hospitalization.

In addition to clinical therapeutic foods, there is increasing interest in incorporating nutrient-rich fruits into nutritional recovery programs. Fruits provide a wide range of vitamins, minerals, antioxidants, and bioactive compounds that support metabolic recovery and immune function [19,21]. For example, watermelon (*Citrullus lanatus*) contributes to hydration and provides citrulline, which can be converted to arginine and may help support vascular health and circulation. Its high lycopene content also provides antioxidant protection.

Similarly, citrus fruits such as oranges and lemons are valuable sources of vitamin C and citric acid,



which significantly improve the absorption of non-heme iron from plant-based foods. This property is particularly beneficial for addressing iron-deficiency anemia, which frequently accompanies malnutrition [5,17,19].

Other fruits also contribute important nutritional benefits. Strawberries contain bioactive compounds such as anthocyanins and manganese, which help reduce inflammation and support bone health [19,20]. Mangoes (*Mangifera indica*) are rich in β -carotene, a precursor of vitamin A that is essential for vision, immune function, and cellular growth. Mangoes also contain mangiferin, a phytochemical currently being investigated for its potential role in modulating immune responses during nutritional recovery [6,32,35].

The integration of these fruit-based nutrients into nutritional intervention strategies provides a promising complementary approach alongside established therapeutic foods. By combining clinical nutrition protocols with natural, nutrient-dense food sources, it may be possible to improve both the effectiveness and sustainability of malnutrition treatment programs.

6. The Biochemical Potential of Fruit Matrices

The incorporation of specific fruits into nutritional formulations provides a scientifically supported approach for improving recovery from malnutrition due to their rich composition of vitamins, minerals, antioxidants, and bioactive compounds [19,21]. These nutrients play important roles in supporting metabolic functions, strengthening immunity, and improving nutrient absorption during the recovery process.

Watermelon (*Citrullus lanatus*) contributes significantly to hydration because it contains approximately 92% water, making it beneficial for maintaining fluid balance in malnourished

individuals. In addition, watermelon is a natural source of citrulline, an amino acid that is converted into arginine in the body and contributes to nitric oxide production, which helps maintain vascular function and circulation. The fruit is also rich in lycopene, a carotenoid with strong antioxidant properties that may help reduce oxidative stress in the body.

Citrus fruits, particularly oranges and lemons, are valuable for their high concentrations of vitamin C and citric acid, which function as natural enhancers of mineral absorption. These organic acids improve the bioavailability of non-heme iron, a form of iron commonly found in plant-based foods that is typically less efficiently absorbed by the human body [5,17,19]. By converting iron into a more soluble form, vitamin C significantly enhances its absorption and helps address iron deficiency, a common condition among malnourished populations.

Other fruits included in the formulation provide additional nutritional benefits. **Strawberries** contain a range of beneficial compounds such as anthocyanins and manganese, which contribute to antioxidant defense, bone health, and regulation of inflammatory responses [19,20]. These nutrients may assist in reducing systemic inflammation and supporting overall recovery.

Mango (*Mangifera indica*) is another important component due to its high concentration of provitamin A (β -carotene). Vitamin A plays a crucial role in maintaining healthy vision, immune function, and cellular growth, particularly in children. Mangoes also contain mangiferin, a bioactive polyphenol that has been investigated for its antioxidant and immunomodulatory properties, suggesting potential benefits during nutritional rehabilitation [6,32,35].



Overall, the biochemical composition of these fruits demonstrates their potential as functional ingredients in nutritional interventions aimed at combating malnutrition. When combined into a carefully formulated supplement, these fruits can provide complementary nutrients that enhance both dietary quality and nutrient absorption.

7. Advanced Processing and Nutrient Synergy

To convert fresh fruits into nutritionally stable products suitable for large-scale nutritional interventions, it is necessary to transform them into shelf-stable powder forms [18,42]. This process improves storage stability, facilitates transportation, and allows the nutrients present in fruits to be delivered in a concentrated and convenient form.

Among the various drying techniques available, freeze-drying is widely recognized as one of the most effective methods for preserving sensitive nutrients, flavors, and polyphenolic compounds. Because the process operates at low temperatures under vacuum conditions, it minimizes thermal degradation and helps retain important vitamins and antioxidants present in fruits.

However, despite its advantages, freeze-drying is relatively expensive and energy-intensive. For this reason, spray-drying is often considered a more practical option for large-scale production and public health nutrition programs. Spray-drying rapidly converts fruit juices or extracts into fine powders by atomizing the liquid into a heated chamber, where moisture evaporates quickly and leaves behind dry particles. To protect fragile nutrients during this process, stabilizing carriers such as maltodextrin are frequently used to encapsulate vitamins and bioactive compounds [18,28].

Beyond preservation, the real nutritional advantage of fruit-based powders lies in the concept of nutrient synergy. When different fruits and nutrients are combined, their interactions can significantly improve the absorption and biological utilization of essential micronutrients [11,26,32]. For example, citrus-derived vitamin C can greatly enhance the absorption of plant-based iron, which normally has low bioavailability.

Such synergistic interactions are particularly valuable in malnutrition treatment, where the digestive and absorptive capacity of the gastrointestinal system may already be compromised. By designing formulations that consider these interactions, it becomes possible to create nutritional supplements that are not only rich in nutrients but also more effectively utilized by the body.

This approach helps bridge the gap between conventional therapeutic foods and sustainable, food-based nutritional solutions by combining clinical nutrition principles with natural dietary sources.

8. Proposed Formulation: Nutrient Synergy & Mineral Complementarity

To maximize the therapeutic impact of the fruit powders discussed, they should be paired with specific minerals to address common deficiencies found in malnourished populations. The table below outlines how these fruits act as biological "keys" to unlock the benefits of added minerals [5,17,32].



Fruit Component	Target Mineral	Synergy Mechanism	Clinical Benefit
Orange/ Lemon (Vit C & Citric Acid)	Iron (Fe)	Reduces ferric iron to the more soluble ferrous state.	Combats nutritional anemia and increases energy levels.
Mango (β -carotene/Vit A)	Zinc (Zn)	Vitamin A and Zinc work together to maintain mucosal integrity and protein synthesis.	Enhances gut health and reduces the duration of diarrheal diseases.
Strawberry (Manganese)	Calcium (Ca)	Manganese acts as a cofactor in bone mineralization.	Supports skeletal "catch-up growth" in stunted children.
Watermelon (Citrulline)	Magnesium (Mg)	Supports nitric oxide production and vascular dilation for mineral transport.	Improves circulation and delivery of nutrients to peripheral tissues.

9. Advanced Stabilization Techniques

Although conventional spray-drying is widely employed for the stabilization of fruit-based powders, recent technological advancements offer improved preservation of heat-sensitive micronutrients and bioactive compounds [28,29]. Among these, nano-spray drying and electrostatic spray drying have emerged as promising alternatives due to their ability to operate at lower thermal loads and enhanced process control.

- Nano-Spray drying:** Nano-spray drying is an advanced modification of conventional spray-drying that utilizes vibrating mesh or piezoelectric atomization to generate ultra-fine droplets, typically in the submicron to nanometer range. The reduced droplet size enables rapid solvent evaporation at significantly lower inlet temperatures, thereby minimizing thermal degradation of labile compounds such as vitamin C, polyphenols, and anthocyanins [18,42]. Additionally, nano-spray drying offers higher encapsulation efficiency and improved powder homogeneity, which is particularly advantageous for stabilizing fruit-derived antioxidants and micronutrients. This technology is especially relevant for high-value nutritional applications where nutrient retention and functional integrity are critical [28].

- Electrostatic Spray Drying (ESD):**

Electrostatic spray drying incorporates an electric field during atomization, imparting a surface charge to droplets that improves dispersion and reduces droplet coalescence. This results in uniform particle formation and accelerated drying kinetics at reduced processing temperatures. The lower thermal exposure associated with ESD enhances the retention of thermolabile vitamins and pigments, including vitamin C and anthocyanins, while also improving powder flowability and reconstitution properties [18,29]. Furthermore, the electrostatic forces facilitate higher deposition efficiency and reduced product loss, contributing to improved process sustainability.

- Implications for Fruit-Based Nutritional Interventions:**

The adoption of nano-spray drying and electrostatic spray drying technologies can substantially enhance the stability, bioactivity, and shelf life of fruit-based nutritional supplements. By preserving critical micronutrients and phytochemicals, these advanced stabilization techniques support the development of high-efficacy formulations suitable for precision nutrition and public health interventions, particularly in climate-vulnerable and resource-limited settings [31,38,42].



10. Prevention Versus Treatment: Role of Fruit-Based RUSF

Recent updates in the World Health Organization (WHO) guidelines (2023 onward) highlight a gradual shift in global nutrition strategies. Instead of focusing only on treating severe acute malnutrition, greater emphasis is now being placed on preventive approaches that address nutritional risks at an earlier stage [1,15]. This strategy recognizes that children who experience mild or moderate undernutrition, or those exposed to recurring food shortages, are more likely to progress to severe malnutrition if early interventions are not implemented [2,39].

Within this preventive framework, fruit-based Ready-to-Use Supplementary Foods (RUSF) have emerged as a promising strategy for children who are nutritionally vulnerable but not yet severely malnourished. Unlike Ready-to-Use Therapeutic Foods (RUTF), which are specifically formulated for clinical treatment of severe malnutrition, RUSF products are intended to supplement regular diets by providing additional energy, essential micronutrients, and bioactive compounds that help prevent further nutritional deterioration [10,30].

Fruit-enriched RUSF formulations offer several advantages. Fruits naturally contain important micronutrients such as vitamin C, provitamin A carotenoids, dietary fiber, and polyphenolic compounds, all of which contribute to improved immune function, gut health, and nutrient absorption [4,16,22]. When fruit powders are incorporated into lipid-based or cereal-based

supplementary foods, they can enhance nutrient density, taste, and cultural acceptability, thereby encouraging better consumption among young children [11,42].

The preventive use of fruit-based RUSF is especially beneficial during seasonal periods of food scarcity, such as pre-harvest “lean seasons,” drought conditions, or climate-related disruptions in food supply. During these periods, dietary diversity and micronutrient intake often decline significantly, increasing the likelihood of growth faltering and micronutrient deficiencies. Providing fruit-enriched supplementary foods during these high-risk periods can act as a nutritional safeguard, helping to reduce the incidence of wasting and lowering the pressure on therapeutic feeding programs [31,33].

Moreover, the distribution of fruit-based RUSF aligns well with community-based nutrition strategies, allowing early nutritional support to be provided at the household or community level rather than relying solely on healthcare facilities. This approach can reduce treatment costs, enhance program sustainability, and strengthen the continuum of care between preventive and therapeutic nutrition interventions [14,24,41].

Overall, incorporating fruit-based RUSF into preventive nutrition programs supports the evolving global framework that emphasizes early intervention, resilience to seasonal food insecurity, and sustainable food-based solutions for addressing childhood undernutrition.



11. Future Scope

The future direction of research in this field extends beyond conventional nutritional supplementation toward more targeted, sustainable, and technologically integrated nutritional strategies [11,31]. Continued innovation in food science, nutrition research, and digital health technologies may provide new opportunities for improving the prevention and management of malnutrition.

• Biofortification and Development of Nutrient-Dense "Super Fruits."

Future investigations should prioritize the development of fruit cultivars with higher micronutrient concentrations through biofortification techniques and improved cultivation practices. Native fruit varieties, including the Solapur Lal pomegranate, which naturally contains elevated levels of iron and zinc, may represent promising candidates for scalable food-based interventions aimed at combating micronutrient deficiencies [5,36].

• Microbiota-Focused Nutritional Approaches

Emerging evidence suggests that malnutrition is frequently linked with imbalances in the gut microbiota, which may hinder digestion and the absorption of essential nutrients. Upcoming nutritional strategies could integrate fruit-derived powders with probiotics or prebiotic components to support microbial balance, reinforce intestinal barrier integrity, and enhance micronutrient absorption efficiency [12,16].

• Utilization of Climate-Resilient and Underexploited Fruits

Research should also explore the nutritional potential of underutilized fruits that can grow in arid and semi-arid environments. Species such as baobab (*Adansonia digitata*), ber (*Ziziphus mauritiana*), and jamun (*Syzygium cumini*) are naturally nutrient-rich and highly tolerant to environmental stress. Incorporating these fruits into dietary strategies may help strengthen nutrition security in regions facing climate instability and food shortages [4,13].

• Enhancing Nutrient Bioavailability and Synergistic Interactions

Additional research is required to clarify how different nutrients interact within fruit matrices to

improve absorption. For instance, compounds such as vitamin C and certain polyphenols can significantly improve the uptake of minerals like iron and zinc, potentially lowering the reliance on synthetic fortification approaches [17,26,32].

• **Improvements in Processing and Shelf-Life Technologies**

Advances in food processing methods—including freeze-drying, low-temperature dehydration, and microencapsulation—may help maintain the stability of sensitive vitamins and bioactive compounds while extending the shelf life of fruit-based supplements. Such technological developments could facilitate the distribution of these products in resource-limited regions.

• **AI-Driven Nutritional Monitoring and Digital Health Tools**

The adoption of artificial intelligence and digital health platforms may enable continuous monitoring of nutritional status, support personalized dietary guidance, and improve the evaluation of recovery outcomes. These systems could also assist policymakers and healthcare professionals in making timelier and data-driven decisions regarding nutrition programs [24,44].

• **Community-Oriented Production and Sustainable Supply Systems**

Future nutrition initiatives could benefit from decentralized production frameworks that engage local farmers and community cooperatives in producing fruit-based nutritional supplements. This approach may enhance local economic opportunities, reduce supply-chain vulnerabilities, and promote the sustainability of nutrition interventions [13,41].

• **Long-Term and Multigenerational Impact Research**

Further longitudinal studies are needed to examine how fruit-based supplementation influences child growth, immune system development, cognitive outcomes, and potential epigenetic mechanisms that could lower the risk of malnutrition across generations [9,15].

• **Integration into Public Health Policies and Large-Scale Programs**

Future research should also investigate ways to incorporate fruit-based nutritional solutions into existing public health initiatives, including school meal programs and maternal–child nutrition schemes. Such integration could improve program reach, scalability, and overall population health impact.

12. RESULTS AND DISCUSSION

The findings of this review indicate that addressing malnutrition effectively requires a transition from interventions that focus mainly on calorie supply to strategies that emphasize nutrient density and micronutrient bioavailability [2,32]. Although traditional therapeutic foods designed for the treatment of severe acute malnutrition (SAM) are effective in stabilizing patients, they often do not fully address underlying micronutrient deficiencies that contribute to long-term health problems.

Ready-to-Use Therapeutic Foods (RUTF) have been widely adopted for the management of severe malnutrition because they provide high-energy content and essential nutrients in a convenient and stable form. These formulations have demonstrated considerable success in improving survival rates and promoting recovery among severely malnourished children [10,30]. However, relying solely on these therapeutic foods may not adequately resolve the problem of “hidden



hunger,” which refers to deficiencies of critical micronutrients such as vitamin A, iron, and zinc.

The results of this review highlight the potential advantages of incorporating fruit-based nutritional supplements into broader nutrition programs. Fruits such as watermelon, orange, strawberry, lemon, and mango possess valuable micronutrients and bioactive compounds that can contribute to improved nutrient absorption and metabolic recovery. These fruits provide natural sources of vitamins, antioxidants, and phytochemicals that support immune function and overall physiological health.

A key benefit of these fruit matrices lies in their synergistic biochemical interactions. For instance, the presence of ascorbic acid and citric acid in citrus fruits can significantly improve the absorption of non-heme iron, potentially increasing its bioavailability by approximately three to six times [5,17,19]. This interaction is particularly important for addressing iron deficiency anemia, which commonly accompanies malnutrition in developing regions.

Advancements in food processing technologies, especially spray-drying, further enhance the feasibility of fruit-based supplements in public health interventions. Spray-drying enables the conversion of fresh fruit extracts into shelf-stable powders while preserving many heat-sensitive nutrients and antioxidants. These powders can remain stable for up to twelve months without requiring refrigeration or synthetic preservatives, making them highly suitable for distribution in remote or resource-limited areas [18,28].

Integrating such nutrient-dense fruit formulations into Community-Based Management of Acute Malnutrition (CMAM) programs may strengthen existing treatment and prevention strategies. In addition, digital monitoring systems such as the

POSHAN Tracker facilitate improved identification and monitoring of malnourished children, ensuring that nutritional interventions reach vulnerable populations more efficiently [14,24,39].

Overall, the results suggest that combining clinical therapeutic nutrition, innovative food processing technologies, and community-level monitoring systems offers a sustainable pathway for improving survival rates and promoting long-term health outcomes among children affected by malnutrition.

13. CONCLUSION

This review highlights that achieving a meaningful transition from food insecurity to nutrition security requires a comprehensive and multidimensional approach to addressing the persistent global challenge of malnutrition, particularly among vulnerable populations such as children under five years of age. Rather than focusing solely on ensuring adequate caloric intake, effective strategies must emphasize nutrient quality, bioavailability, and physiological functionality, recognizing that malnutrition is influenced not only by the quantity of food but also by its nutritional composition.

The integration of Ready-to-Use Therapeutic Foods (RUTF) with broader food-based and community-driven nutritional interventions offers a balanced strategy for combating malnutrition. While therapeutic foods play an essential role in stabilizing children suffering from severe acute malnutrition, sustainable long-term recovery requires improvements in dietary diversity and nutrient intake within community settings. Such an approach supports healthy growth, strengthens immune defenses, and contributes to improved cognitive development.



One of the key findings of this review is the promising potential of fruit-based nutritional powders as a practical and scalable solution for addressing micronutrient deficiencies. These formulations act as a natural “vitamin–mineral bridge,” utilizing nutrient interactions—such as the synergistic relationship between vitamin C and iron—to enhance mineral absorption and help combat micronutrient deficiencies commonly referred to as “hidden hunger.” By relying on whole-food nutrient matrices rather than isolated synthetic supplements, these interventions may offer improved biological effectiveness while remaining culturally acceptable within local diets [11,16,26].

Sustainability also emerges as a critical component of nutrition security. Adopting a circular economy approach, in which surplus or cosmetically imperfect fruits are transformed into shelf-stable nutritional supplements, provides an innovative solution to both food waste and micronutrient deficiency [4,45]. Modern processing technologies, such as spray-drying, help preserve heat-sensitive nutrients while extending product shelf life, enabling efficient distribution of nutrient-rich supplements without dependence on refrigeration systems.

In addition, the growing integration of digital health platforms plays an important role in improving the effectiveness of nutrition programs. Systems such as the POSHAN Tracker enable real-time monitoring of child nutritional status, enhance supply chain transparency, and facilitate the timely delivery of interventions. Replacing traditional paper-based monitoring with digital data systems strengthens accountability, improves program management, and supports evidence-based policy development.

Ultimately, this review advocates for the implementation of a “nutrient-first” policy

framework, where the focus shifts from simply providing sufficient food quantities to ensuring the availability of nutritionally balanced diets with high bioavailability of essential micronutrients. Such an approach aligns public health strategies with biological and developmental needs, ensuring that future generations receive not only adequate nourishment for survival but also the nutritional foundation required for healthy growth, cognitive development, and long-term societal well-being [24,36,45].

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“cosmetically imperfect” local fruits. This approach not only enhances nutrient accessibility but also contributes to farmer livelihoods, environmental sustainability, and reduced food system inefficiencies.

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