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Plant-based functional foods for preschool nutrition: from nutrient density to bioavailability, sensory acceptance and translational potential

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ABSTRACT

Plant-based functional foods are considered an advantageous food-based approach since they are able to combine the attributes of being nutrient-dense with those of dietary fibers and bioactive substances and even those connected with the use of potentially sustainable food sources. Nevertheless, the mere presence of nutrients or bioactive substances is not the criterion for a substance's functionality; it is stated that their functionality depends on their bioavailability, processing, flavor perception, safety, affordability and actual use. This review aims to analyze plant-based functional foods in the context of preschool nutrition with the emphasis on the following food types: grains, millet, legumes, pseudocereals, roots and tubers, seeds, fruits and vegetables, as well as probiotics, prebiotics and bioactive substances of plant origin. In the course of the study, data on production processes and implementation of preventive measures aimed at children will be analyzed in terms of the adequacy of nutrients, development, micronutrient content, health of the digestive system and diet quality. There has been a focus on *anti-nutritional* factors and processing techniques that affect nutrient bioavailability, sensory properties, food neophobia, allergies, portion size, energy density, and parental contributions to eating behavior. This review also discusses factors affecting the translation process from laboratory solutions to practical nutrition programs including regulations, economics, and sustainability. There seems to be a lot of potential for the use of locally sourced and culturally familiar foods but in terms of long-term health effects in preschoolers, evidence is still limited. There is a need for a new approach that would take into account all the variables such as nutrient efficacy, bioavailability, sensory characteristics, safety, cost, convenience, and sustainability. A model that relates ingredient selection and processing to bioavailability, acceptance, consumption, and health is suggested.

Keywords: Plant-based foods, Functional foods, Preschool children, Nutrient- dense foods, Bioactive compounds, Nutrient bioavailability, Sensory acceptability, Sustainable foods, Micronutrient, Plant-based nutrition

1. Introduction

The preschool period, generally encompassing 3-5 years of age, represents an important developmental window during which adequate nutrition supports physical growth, immune competence, neurological maturation, cognitive development and the establishment of dietary behaviours. Although the rate of growth declines compared with infancy, preschool children continue to have relatively high nutrient requirements in relation to body size (Anton-Paduraru *et al.*, 2018; Zysk *et al.*, 2020) [1, 2]. Dietary exposures during this period may also influence food preferences and eating patterns later in life.

Malnutrition during the early years of a child's life continues to be a problem around the world. There are a number of nutrients that preschoolers do not get enough of in their diets, including but not limited to iron, zinc, calcium, vitamin A, vitamin D, iodine, folate, vitamin B12 and essential fatty acids (Black *et al.*, 2021; Goyena *et al.*, 2021) [3, 4]. However, the increasing availability, consumption of energy dense and highly processed foods leads to the risk of excessive energy intake and poor diet quality. Picky eating and food neophobia can further restrict dietary diversity and reduce acceptance of vegetables, legumes and other nutrient dense foods (Kling *et al.*, 2016; Anwar *et al.*, 2023) [6, 5].

Functional foods have therefore attracted considerable interest as a complementary approach to conventional dietary diversification, supplementation and fortification. Typically, functional foods are considered as foods that they naturally present or added biologically active ingredients, offer physiological benefits and health impacts beyond basic nutritional requirements. However, the term is conceptually and regulatory diverse and a potentially bioactive component is not necessarily indicative of a health benefit.

Plant derived foods have numerous nutrients and bioactive substances, such as protein, dietary fibre, resistant starch, polyphenols, carotenoids, fatty acids, vitamins, and minerals. Therefore, millet and grain beans,

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pseudocereals, fruits, vegetables, tubers, etc., can be considered as raw materials for the creation of special foods for young children (Dinu *et al.*, 2017; Tusso *et al.*, 2013) [7]. Their potential contribution to sustainable diets is particularly relevant in the case of locally adapted and culturally familiar crops.

However, the nutritional capability of plant-based functional foods should not be conflated with their proven efficacy. The nutrient content of a food product is not always an indication of its bioavailability, while the bioactive components isolated in vitro might exhibit different behaviour in vivo in children (Badia-Olmos *et al.*, 2023; Chiranthika *et al.*, 2022; Vishwakarma *et al.*, 2024) [8, 9, 10]. Likewise, even the best formula, nutrition-wise, would hardly prove helpful if children refuse to consume it owing to its taste, smell, or anything else.

Recent studies in children have emphasized the importance of being cautious. It has been found that planned and consumption of plant-based diets can help maintain good growth but insufficient concern about the intake of various nutrients like iron, vitamin B12, vitamin D, iodine and omega-3 fatty acids can create nutritional deficiencies in children. Therefore, the idea is not to promote the consumption of plant-based diets blindly, but to find out plant-based food items that can provide nutritional benefits.

This review critically evaluates plant-based functional foods for preschool nutrition, emphasizing the relationship between nutrient density, bioavailability, food functionality, sensory acceptance, safety, affordability, sustainability and scalability.

2. Nutritional priorities during the preschool period

The dietary needs of preschool children include sufficient energy and protein for growth and actively as well as adequate intake of micronutrients to support development of brains, bones and immune system.

Key micronutrients include iron, zinc, iodine, vitamin A, folate, vitamin B12, calcium, vitamin D and essential fatty acids.

Iron is required for haemoglobin formation and brain development, while zinc helps with growth, immunity, and metabolism. Calcium and vitamin D play important roles in bone formation, while iodine and vitamin B12 are needed for the development of the brain. Vitamin A is needed for vision and immunity, while essential fatty acids play an important role in the development of the brain and vision.

Reference: WHO/FAO/UNU (2007) [11]; Roberts *et al.* (2022) [12]; Zysk *et al.* (2020) [2]; Zimmermann *et al.* (2012) [13]; Black *et al.* (2013); Lauritzen *et al.* (2016) [14].

A key consideration is that plant-based dietary sources do not provide all nutrients in equivalent forms or with equivalent bioavailability. For example, vitamin B12 requires particular attention in diets with limited animal-source foods, whereas plant-derived iron is predominantly non-haem iron and is influenced by dietary inhibitors and enhancers of absorption. Therefore, functional food development should address both nutrient content and nutritional availability.

3. Plant-based functional foods: conceptual considerations

The same distinction holds true in the case of biofortified foods. In biofortification, the nutrient content of crops is increased by means of breeding or agronomic methods, while with conventional fortification nutrients are added during food processing. Although both methods can contribute to the development of functional foods, their nutritional effects and the evidence base for them is different.

Table 1. Nutritional components of particular relevance to preschool children

Nutrient/component	Major physiological relevance	Potential plant-based sources or vehicles
Protein	Growth, tissue synthesis and immunity	Pulses, legumes, millets, pseudocereals, seeds
Iron	Haemoglobin synthesis and neurodevelopment	Millets, legumes, green leafy vegetables, fortified foods
Zinc	Growth and immune function	Legumes, seeds, nuts
Calcium	Bone and dental development	Finger millet, sesame, fortified foods
Vitamin A/provitamin A	Vision, immunity and growth	Green leafy vegetables, carotenoid rich fruits and vegetables
Folate	Cell division and development	Legumes and green leafy vegetables
Vitamin B12	Neurological function and erythropoiesis	Fortified foods; supplementation where required
Vitamin D	Bone mineralisation and calcium metabolism	Fortified foods; sunlight exposure
Omega-3 fatty acids	Neurological and visual development	Flaxseed, chia and other oilseeds
Dietary fibre/prebiotic substrates	Gastrointestinal health	Whole grains, legumes, fruits and vegetables

For preschool nutrition, three concepts should be distinguished.

Plant-based food refers broadly to food derived predominantly from plant sources.

Fortified food refers to food to which nutrients have been deliberately added.

Functional food refers to food intended to provide a physiological benefit beyond basic nutritional adequacy.

These categories can overlap but should not be considered synonymous. For example, a millet based snack is plant-based and may be nutrient dense, but it should not automatically be described as a functional food unless a scientifically reasonable functional benefit is established.

The same distinction applies to biofortified foods. Biofortification increases the nutrient content of crops through breeding or agronomic approaches, whereas conventional fortification adds nutrients during food processing. Both may contribute to functional food development but their nutritional effects and evidence bases are different.

For a preschool functional food, the relevant sequence should therefore be:

Ingredient → nutrient/bioactive composition → processing → bioavailability → sensory acceptance → consumption → physiological/nutritional outcome.

This evidence pathway provides a more meaningful basis for evaluating functionality than nutrient composition alone.

4. Plant-based ingredients with potential for functional food development

4.1 Millets and cereal-based ingredients

The growing trend of focusing on millets arises mainly from the nutritional benefits along with their good fiber, mineral, and phytochemical contents and the potential of those grains to help in building climate smart food systems. Specifically, finger millet is particularly noted for its high calcium content so as different forms of millet vary

in the amounts of iron, zinc, proteins, and other compounds they contain.

Blending of cereals, pulses or oilseeds enhances the nutritive value of the formulations through complementary amino acid profile as well as higher protein and micronutrient content. A 2024 study among tribal preschool children in Telangana involving millet, pulse and groundnut formulations indicated improvement in anthropometric parameters and haemoglobin levels (Mazumdar *et al.*, 2024) [15]. This study gives direct proof for child nutrition compared to compositional analyses only.

At the same time, millet formulations exemplify the difference between nutrient content and functional effectiveness. Phytate and other components can affect the availability of minerals, as well as processing and formulation affect texture, flavor and acceptability. Therefore, the use of one millet variety requires specific processing and formulation approaches.

4.2 Legumes and pulses

Legumes are great source of protein, fibre, minerals, bioactive compounds and possess important technological properties including water absorption, emulsification, foaming and gel formation. Chickpea, lentil, pea, soybean and other legumes can therefore be incorporated into cereal based snacks, porridges and baked products (Badia-Olmos *et al.*, 2023) [8].

Blending cereals with legumes may provide complementary amino acid profiles. The presence of phytates, tannins and other *anti-nutritional* factors can influence nutrient availability (Guan *et al.*, 2023) [16]. Fermentation, germination, soaking and thermal processing may improve digestibility and reduce selected *anti-nutritional* factors.

For preschool applications, gastrointestinal tolerance and sensory characteristics are also important. A formulation with high protein content may not necessarily be successful if it produces an undesirable texture or flavour.

4.3 Pseudocereals

Amaranth, quinoa and buckwheat are popular as a source of protein, fibre content, minerals and bioactive compounds. Their functional properties make them suitable for incorporation into biscuits, crackers, extruded products and other snack formulations (Saeid *et al.*, 2021) [17].

Their use in preschool nutrition should nevertheless be evaluated on the basis of child-specific evidence. Evidence derived predominantly from adult populations, in-vitro experiments or compositional studies should be regarded as supportive rather than definitive.

4.4 Roots and tubers

Roots and tubers such as sweet potato, yam, cassava, taro and potato can provide energy, starch and depending on the crop, variety, dietary fibre, resistant starch and phytochemicals. Underutilized roots and tubers may also contribute to dietary diversification and local food system resilience (Chiranthika *et al.*, 2022) [9].

Their value for preschool functional foods may be greatest when they are incorporated into culturally familiar products. This approach can reduce the barrier associated with unfamiliar ingredients while utilizing local agricultural resources.

4.5 Seeds and oilseeds

Flaxseed, chia, pumpkin, sesame and sunflower seeds provide combinations of protein, fibre, minerals, essential fatty acids and phytochemicals. Flaxseed and chia are the rich plant sources of alpha linolenic acid, while pumpkin and sesame seeds contribute protein and minerals (Gholami *et al.*, 2021) [18].

However, seed-based products require careful consideration of allergy, energy density, particle size and texture. Claims regarding disease prevention should be avoided unless supported by direct evidence.

4.6 Fruits and vegetables and their by-products

Fruits and vegetables contribute vitamins, minerals, dietary fibre, phytochemicals and can also provide opportunities for food product innovation. Fruit powders, purees and selected processing by-products may be incorporated into bakery and snack products to increase fibre or bioactive content (Dana *et al.*, 2024) [19].

The use of by-products also introduces a sustainability dimension by potentially reducing food waste and contributing to circular food systems. However, safety, contaminant accumulation, sensory effects and regulatory acceptability must be assessed before food applications are recommended.

5. Bioavailability and the role of food processing

Bioavailability is one of the most important but comparatively under-developed aspects of plant-based functional food research.

A plant food may contain considerable amounts of iron, zinc or calcium while absorption is limited by phytate, oxalate, tannins or other dietary components. Protein digestibility and amino acid availability can also vary according to the plant source and processing method.

Food processing can modify these characteristics. Germination and fermentation may reduce selected *anti-nutritional* factors and improve digestibility. Malting, soaking and thermal processing can alter nutrient availability and sensory properties. Extrusion can improve product texture and shelf stability and may modify starch digestibility and other functional characteristics.

However, processing should not be considered universally beneficial. Excessive thermal treatment may reduce heat sensitive nutrients, while certain processing conditions may alter bioactive compounds. The objective should therefore be optimization of the complete nutritional and sensory profile rather than maximization of a single nutrient.

Future studies should increasingly report:

- a. Nutrient retention after processing
- b. In-vitro or in-vivo bioaccessibility
- c. Protein digestibility
- d. Mineral bioavailability
- e. Effects of processing on phytates and tannins
- f. Storage stability
- g. Actual intake
- h. Physiological outcomes

This would help bridge the gap between food chemistry and child nutrition.

6. Evidence from child interventions and product development

The current literature contains different levels of evidence, ranging from laboratory formulation studies to controlled child interventions. These should not be treated as equivalent.

The evidence demonstrates considerable product-development potential but also reveals an important research gap. Nutritional composition and sensory acceptability are more frequently measured than clinically meaningful outcomes.

Table 2. Selected evidence relevant to plant-based functional foods for children

Study	Population/context	Intervention/product	Main findings	Evidence interpretation
Gad <i>et al.</i> (2024)	Slightly malnourished preschool children	Multistrain probiotic delivered in non-dairy food matrices	Increased recovery of viable probiotic organisms and changes in selected gut-related biomarkers	Provides child level evidence for plant/non-dairy delivery
Mazumdar <i>et al.</i> (2024)	Tribal preschool children, Telangana, India	Millet-pulse-groundnut formulations	Improvements in anthropometry and haemoglobin related outcomes	Relevant intervention evidence
Farah <i>et al.</i> (2023)	Product development study	Amaranth, quinoa and chia snack	High protein/fibre and high consumer acceptability	Product development evidence, not clinical efficacy
Lopez-Fernandez <i>et al.</i> (2021)	Children, adolescents and adults	Pineapple flour cookies	Increased selected nutritional/antioxidant properties and acceptable sensory quality	Demonstrates formulation feasibility
Kumari <i>et al.</i> (2021)	Product development context	Germinated pumpkin seed flour laddoo	Increased protein, fibre and selected minerals with acceptable sensory properties	Supports culturally familiar functional food development

The millet-pulse-groundnut intervention is particularly relevant because it evaluated a formulation in a vulnerable preschool population rather than relying solely on nutrient composition. However, a single intervention cannot establish the efficacy of plant-based functional foods as a broad category.

Similarly, probiotic studies demonstrate that non-dairy plant-based matrices can serve as delivery vehicles, but probiotic effects are strain-specific and dependent on dose, viability and product characteristics.

The evidence therefore supports potential rather than a universal claim of efficacy.

7. Sensory acceptance and child feeding behaviour

Sensory acceptance is a central determinant of whether a functional food can produce nutritional benefit.

Baker, 2014 [20] stated that children's food preferences are influenced by taste, texture, appearance, aroma, familiarity and repeated exposure. Food neophobia and picky eating may be particularly relevant during the preschool period. Consequently, a formulation that is nutritionally optimal but poorly accepted may have little practical effect. Sensory evaluation should therefore be incorporated into product development from the early stages rather than being treated as a final quality control step.

Important attributes include:

- a. Taste
- b. Sweetness and bitterness
- c. Texture and mouthfeel
- d. Aroma
- e. Colour
- f. Shape
- g. Portion size
- h. Familiarity
- i. Overall liking

Parental feeding practices and modelling also influence children's dietary behaviour. Parents determine food availability and frequently influence repeated exposure to unfamiliar foods (Mahmood *et al.*, 2021) [21]. Thus, successful functional food interventions should consider both the child and the family food environment.

Future research should combine sensory evaluation with measures of actual consumption. Acceptability scores alone do not establish sustained dietary intake.

8. Safety considerations

Safety assumes particular importance when developing foods for preschool children.

Functional foods derived from plants can include ingredients like peanuts, nuts, sesame, soy, and other seeds which can be allergens (Venter *et al.*, 2018) [22]. Functional food products made with concentrated plant extracts can also pose risks in the form of contamination, microbial safety, pesticides, mycotoxins, and heavy metals.

Portion size and energy density are another factor to consider when creating a functional snack. Large portions and energy-dense snacks may contribute to the increased energy consumption in preschoolers. Thus, a functional snack should not be used as a means for excess energy, sugar, salt, and saturated fat (Kling *et al.*, 2016) [6].

Probiotic-containing foods require strain-specific assessment, adequate viability through storage and appropriate safety evaluation. Similarly, concentrated extracts or novel bioactive ingredients require stronger safety evidence than conventional foods.

Functional claims should also be proportionate to the evidence. A product containing antioxidants should not automatically be promoted as preventing disease. Child focused functional foods require scientifically defensible claims and appropriate regulatory compliance.

9. Sustainability, affordability and cultural relevance

The sustainability potential of plant-based functional foods is important but should not be assumed solely from the plant origin of an ingredient.

Sustainability depends on:

- a. Crop production
- b. Water and land requirements
- c. Climate resilience
- d. Transportation
- e. Processing intensity
- f. Packaging
- g. Food loss
- h. Ingredient availability
- i. Local economic systems

Local millets, pulses, indigenous fruits, vegetables, roots and tubers, and neglected plants could perhaps have some benefits if they are locally available and accepted.

Nonetheless, a sustainable functional food must also be nutritious and affordable. Highly processed or imported plant materials need not always have an advantage over locally available traditional plant materials.

Therefore, cost effectiveness and implementation science must become regular features of future research.

10. Regulatory and programme-level considerations

The regulation surrounding functional foods targeting preschool children is quite a difficult process that includes food safety, nutrition labeling, and health claims. In India, the Food Safety and Standards Authority of India regulates issues related to food safety, nutrition labeling, and food products targeted at children. Programs like the National Nutrition Program, PM POSHAN, offer potential platforms for integrating functional foods into the country (GOI, 2021) [23].

However, integration into public programmes requires more than demonstrating nutrient content. Evidence should establish:

1. Nutritional efficacy
2. Safety
3. Child acceptability
4. Affordability
5. Storage stability
6. Production feasibility
7. Cultural suitability
8. Programme level scalability

A formulation developed under laboratory conditions may not be appropriate for large-scale implementation without addressing these factors.

11. Research gaps and future priorities

The literature reviewed identifies several important gaps.

11.1 Insufficient preschool specific evidence

Much of the literature on plant-based foods and bioactive ingredients is based on adults, older children, animal models or in-vitro studies. Evidence specifically involving preschool children remains limited.

11.2 Nutrient content is often prioritized over bioavailability

Studies frequently report proximate composition and micronutrient content without determining whether nutrients are absorbed or improve biochemical status.

11.3 Limited evidence linking formulation to actual consumption

Sensory acceptability does not necessarily correspond to sustained intake. Future studies should measure consumption over realistic intervention periods.

11.4 Limited long-term evidence

Short term studies cannot establish sustained effects on growth, cognition, micronutrient status or dietary behaviour.

11.5 Insufficient integration of sustainability and cost

Few studies simultaneously evaluate nutritional efficacy, affordability, environmental considerations and scalability.

11.6 Need for multidisciplinary research

Future research should integrate food science, nutrition, sensory science, child development, public health, agriculture and implementation science.

11.7 Need for integrated outcome measures

Future trials should evaluate the complete pathway:

Formulation → nutrient bioavailability → sensory acceptance → intake → nutritional status → functional outcome.

12. Conclusions

Plants-based functional foods have great potential as contributors to preschool nutrition in view of their nutrient density, diversity, presence of bioactive substances and possibly even sustainable food sources. Millets, legumes, pseudocereals, root crops, tubers, seeds, fruits, vegetables and plant-based probiotics/prebiotics can serve as sources of food innovation.

But not all plants-based functional foods can be considered beneficial without additional proof. Nutrient composition is not enough to prove functionality. Bioavailability, processability, sensory acceptability, real consumption, safety, economic and environmental sustainability decide whether formulation results in any nutritional benefit.

There is much more evidence for product development and nutritional composition than for child-specific clinical outcomes. This means that future research should shift from the studies of ingredients and their properties towards integrated interventions aimed at evaluation of nutritional status, bioavailability, sensory acceptability, consumption and functionality.

The optimal research direction may include development of locally available, culturally acceptable, nutrient dense plant-based foods processed through evidence based processes and tested in child specific intervention studies. It may connect food science and public nutrition through sustainable food production.

And the final scientific question remains the following: What plants-based formulations provide nutritional benefits to preschool children in certain amounts through which mechanisms and in what conditions?

Author contributions

Lahari: Conceptualization, literature collection, investigation, synthesis of literature and preparation of the original manuscript draft.

Beela G.K.: Supervision, editing, and overall scientific guidance.

Both authors approved the final manuscript.

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Conflicts of interest

The authors declare that they have no conflict of interest.

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Data availability

Data sharing is not applicable because this manuscript is based on previously published literature.

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