REVIEW ARTICLE

Emerging Trends and Innovations in Protein Energy Malnutrition Research: A Narrative Review

Mohamed Anas Patni[1], MD; Mushirabanu Sharifmiyan Akikwala[2], DNB

Abstract

Background: Protein-energy malnutrition (PEM) remains a significant global health issue, particularly in low- and middle-income countries. Despite extensive efforts, challenges in prevention, diagnosis, and treatment persist, underscoring the need for ongoing research and innovation.

Methods: This narrative review involved a comprehensive literature search using PubMed, Scopus, Web of Science, and the Cochrane Library. Keywords related to PEM, biomarkers, nutritional interventions, technological innovations, and policy implications were applied. From an initial pool of 2,449 articles, 65 were selected based on relevance, quality, and contribution to recent trends and innovations in PEM research.

Results: Advances in biomarkers—including inflammatory markers, micronutrient levels, metabolic indicators, and novel genetic and epigenetic markers—have improved the early detection and monitoring of PEM. Nutritional interventions, such as ready-to-use therapeutic foods (RUTF), fortified foods, biofortification, micronutrient powders (MNPs), and lipid-based nutrient supplements (LNS), have demonstrated effectiveness in both treatment and prevention. Technological innovations, including digital health platforms, point-of-care diagnostic tools, geographic information systems (GIS), wearable devices, and artificial intelligence (AI), are revolutionizing the management of PEM.

Conclusion: Significant progress has been made in PEM research, yet challenges remain. Future studies should focus on validating and integrating biomarkers, optimizing nutritional interventions, leveraging technological advancements, and strengthening policy frameworks to enhance the effectiveness of these approaches. By addressing the multifaceted nature of PEM with innovative, evidence-based strategies, substantial progress can be achieved in reducing the global burden of malnutrition and improving health outcomes among vulnerable populations.

Please cite this article as: Patni MA, Akikwala MS. Emerging Trends and Innovations in Protein Energy Malnutrition Research: A Narrative Review. J Health Sci Surveillance Sys. 2025;13(4):310-319. doi: 10.30476/jhsss.2024.103361.1939.

Keywords: Protein-energy malnutrition, Ready-to-use therapeutic foods, Biofortification, Lipid-based nutrient supplements, Micronutrients

[1]Department of Community Medicine, RAK College of Medical Sciences, RAK Medical and Health Sciences University, UAE
[2]Shifa Al Jazeera Clinic, Ras Al Khaimah, UAE

Correspondence:
Mohamed Anas Patni, MD;
Department of Community Medicine, Ras Al Khaimah College of Medical Sciences, Rakmhsu, UAE
Tel: +971 551893722
Email: mohamedanas@rakmhsu.ac.ae
Received: 10 July 2025
Revised: 01 August 2025
Accepted: 20 September 2025

Introduction

Protein-energy malnutrition (PEM) remains a critical global health issue, particularly among vulnerable populations in low- and middle-income countries. Defined as an inadequate intake of protein and energy relative to physiological requirements, PEM encompasses a spectrum of conditions ranging from acute severe malnutrition to chronic undernutrition.[1] Despite extensive efforts to combat malnutrition, significant challenges persist, highlighting the need for continued research and innovation to enhance prevention, diagnosis, and treatment strategies.

Recent epidemiological data underscore the pervasive nature of PEM, with millions of children under five years of age affected globally, predominantly in sub-Saharan Africa and South Asia.[2] Within South Asia, India bears a substantial burden of malnutrition. Within South Asia, India bears a particularly high burden of malnutrition. According to the National Family Health Survey (NFHS-5) conducted in 2019–2020, approximately 35% of children under five years are stunted, 19% are wasted, and 32% are underweight.[3] These alarming statistics not only reflect the scale of the problem but also highlight persistent socio-economic disparities, food insecurity, and inadequate healthcare access that exacerbate PEM in India.

Studies have elucidated the metabolic adaptations, immune system dysregulation, and hormonal changes that occur in response to chronic malnutrition, all of which influence growth, development, and overall health outcomes.[4, 5] While research has advanced understanding of PEM's metabolic, immune, and hormonal consequences, significant gaps remain in translating these findings into effective, real-world interventions. Moreover, addressing socio-economic disparities in nutrition remains a critical challenge.[6]

Innovative approaches to PEM research are driving progress across multiple fronts. From the development of novel biomarkers for early detection and monitoring to the adoption of technology-driven solutions in healthcare delivery, recent trends reflect a comprehensive multidimensional effort to combat malnutrition.[7, 8] In India, programs such as the Integrated Child Development Services (ICDS) and the National Nutrition Mission (POSHAN Abhiyaan) are leveraging these innovations to improve nutritional outcomes among children and women.[9] However, the effectiveness and scalability of these interventions, particularly in resource-constrained settings, remain areas requiring further investigation and evaluation.

This narrative review examines recent trends and innovations in PEM research, with particular emphasis on biomarkers, nutritional interventions, technological advancements, and policy implications. By synthesizing current evidence and highlighting promising strategies, it aims to support global efforts to reduce the burden of malnutrition and improve health outcomes among vulnerable populations.

Methods

To provide an updated review of recent trends and emerging innovations in the field of protein-energy malnutrition (PEM), a systematic literature search was conducted using PubMed, Scopus, Web of Science, and the Cochrane Library.[10] The search strategy was carefully constructed with Boolean operators to ensure comprehensive retrieval of relevant studies. Search queries incorporated keywords and Medical Subject Headings (MeSH) terms, including: "protein-energy malnutrition" OR "PEM" OR 'malnutrition' combined with "biomarkers" OR "diagnostic tests" OR "prognostic markers," - "nutritional interventions" OR "therapeutic foods" OR "micro nutritional supplementation," – 'technological innovations' OR 'telemedicine' OR 'disease management software', "policy implications" OR "public health interventions" OR "limit level."

Inclusion Criteria

The following criteria were applied to include studies:

1. Relevance: The study must address current trends and innovations related to the prevention, diagnosis, or management of PEM. This includes research on defining and validating biomarkers, reporting novel nutritional strategies, integrating new technologies, or implementing cross-sectoral strategies for PEM management.

2. Population Focus: Studies incorporating data from both global and Indian populations were considered, with particular emphasis on children and other vulnerable groups affected by PEM.

3. Publication Type: Only peer-reviewed research articles, systematic reviews, meta-analyses, and reputable reports were included.

4. Time Frame: To capture the most recent research and advancements, studies published between 2010 and 2024 were considered.

Exclusion Criteria

The following criteria were applied to exclude studies from the review:

1. Outdated or Irrelevant Findings: Studies focusing on interventions or biomarkers that are no longer relevant or have not demonstrated significant impact in the context of current PEM management were excluded.

2. Methodological Limitations: Articles of low methodological quality —such as those with unclear

study designs, small sample sizes, or incomplete outcome reporting—were excluded.

3. Non-Peer-Reviewed Literature: Literature not subjected to peer review, including editorials, opinion pieces, and anecdotal reports, was excluded to maintain the rigor of the review.

Data Extraction and Synthesis

Data from the selected studies were extracted using a structured template capturing information on study design, population characteristics, intervention details, biomarkers, outcomes, and key innovations. The extracted data were then synthesized into four thematic categories:

1. Biomarkers for PEM: Studies were categorized based on their role in identifying and validating biomarkers for the detection and monitoring of PEM.

2. Nutritional Interventions: Studies addressing preventive and therapeutic nutritional interventions were reviewed, with attention to their effectiveness, scalability, and potential integration into public health programs.

3. Technological Innovations: Research investigating the application of digital health tools, mobile applications, and other technological advancements for the detection and management of PEM was included in this category.

4. Policy Implications: Studies examining the impact of policy, governmental initiatives, and international standards on PEM management were synthesized to identify areas for policy intervention.

Data Synthesis Approach

To ensure a comprehensive and transparent synthesis of data, a qualitative comparative approach was employed. Studies were compared across intervention types, outcome measures, population focus, and context to identify consistent trends, gaps, and areas for future research. The synthesis aimed to provide a cohesive narrative while highlighting patterns in the application of emerging trends across different regions and populations.

Although a quantitative synthesis was not conducted due to heterogeneity in study designs and populations, the findings were systematically grouped by thematic category, allowing for a structured comparison of the evidence. Areas where quantitative meta-analyses could be valuable in future reviews are noted within the respective thematic sections.

A total of 2,449 articles were identified in the initial search. Titles and abstracts were screened to assess their relevance to PEM, resulting in the exclusion of 1,600 articles that were either duplicates or deemed irrelevant to the topic. Subsequently, the inclusion and exclusion criteria were applied. Two independent reviewers conducted the study selection process to ensure objectivity and consistency, evaluating each article based on the predefined criteria. Discrepancies between reviewers were resolved through consensus or consultation with a third reviewer.

During full-text screening, 631 articles were excluded due to irrelevance, insufficient data quality, or failure to meet the inclusion criteria, leaving 218 articles for detailed data extraction and analysis. Ultimately, 65 articles were incorporated into the final evaluation. These studies were selected based on their significance, quality, and contribution to the understanding of recent developments and advancements in PEM research.

Biomarkers for Early Detection and Monitoring

Recent advances in the identification and application of biomarkers have transformed the early detection and monitoring of protein-energy malnutrition (PEM).

Inflammatory Markers

Inflammatory biomarkers, such as C-reactive protein (CRP) and alpha-1-acid glycoprotein (AGP), play a critical role in the context of PEM. Elevated levels of these markers indicate an inflammatory response, which often accompanies malnutrition. Studies have demonstrated that CRP and AGP levels are elevated in malnourished individuals and can serve as indicators of acute-phase responses, aiding in the differentiation of malnutrition types and assessing its severity.[11, 12]

Micronutrient Levels

Deficiencies in essential micronutrients such as zinc, vitamin A, and iron are common in PEM. Biomarkers for these micronutrients include serum zinc, retinol-binding protein (for vitamin A), and ferritin (for iron). Serum zinc levels are often reduced in malnourished children, reflecting inadequate dietary intake or increased losses due to infections.[13] Retinol-binding protein is a sensitive indicator of vitamin A status, with levels correlating closely with liver vitamin A stores.[14] Ferritin serves as a marker of iron status; however, its interpretation can be confounded by inflammation, necessitating concurrent measurement of inflammatory markers such as CRP to ensure accurate assessment.[15]

Metabolic Biomarkers

Metabolic biomarkers provide valuable insights into the body's energy and protein status. Commonly used markers include serum albumin, prealbumin (also known as transthyretin), and transferrin. Although serum albumin is informative, its long half-life and susceptibility to factors unrelated to nutrition, such

as liver function and hydration status, can limit its utility. In contrast, prealbumin and transferrin have shorter half-lives and respond more rapidly to changes in nutritional status, making them particularly useful for monitoring acute changes in PEM.[16]

Novel Biomarkers

Recent research has identified novel biomarkers with potential for more precise and early detection of PEM. Plasma citrulline, for example, reflects enterocyte mass and function, with decreased levels associated with malnutrition and intestinal dysfunction.[17] Another promising biomarker is fibroblast growth factor 21 (FGF21), which is elevated in malnourished individuals and may serve as an indicator of metabolic stress.[18]

Genetic and Epigenetic Biomarkers

Emerging evidence indicates that genetic and epigenetic markers can provide insights into susceptibility to malnutrition and the body's response to nutritional interventions. Genetic polymorphisms affecting nutrient metabolism and transport—for example, variants in genes encoding zinc transporters—can influence an individual's risk of developing PEM.[19] Epigenetic modifications, such as DNA methylation patterns, may reflect prior nutritional exposures and offer a mechanistic link between malnutrition and long-term health outcomes.[20]

Applications in Clinical and Public Health Settings

The use of these biomarkers in clinical and public health contexts can substantially improve the early detection, diagnosis, and management of PEM. Incorporating biomarkers into routine health assessments enables the identification of individuals at risk before overt clinical signs of malnutrition appear, facilitating timely intervention.[21] Within public health programs, biomarkers can also be employed to monitor the effectiveness of nutritional interventions and to track progress toward the reduction of malnutrition at the population level.

Challenges and Future Directions

Despite the promising potential of biomarkers in PEM management, several challenges remain. Variability in biomarker levels due to factors such as age, sex, infection status, and genetic background underscores the need for standardized protocols for measurement and interpretation. Furthermore, additional research is needed to validate the clinical utility of novel biomarkers and to integrate them effectively into existing healthcare systems.[22]

Future studies should focus on identifying additional biomarkers that provide comprehensive insights into the multifaceted nature of PEM. The integration of biomarker research with emerging omics technologies—including genomics, proteomics, and metabolomics—may reveal novel pathways and targets for intervention.[23]

1. Nutritional Interventions

Nutritional interventions play a pivotal role in the prevention and management of protein-energy malnutrition (PEM). Recent innovations in this field focus on improving the formulation, delivery, and accessibility of therapeutic foods and supplements, as well as strengthening community-based nutrition programs.

Ready-to-Use Therapeutic Foods (RUTF)

RUTF represents a groundbreaking advancement in the treatment of severe acute malnutrition. These nutrient-dense, energy-rich pastes are designed for direct consumption from the packet, enhancing convenience and effectiveness in community settings. Studies have demonstrated that children receiving RUTF exhibit higher recovery rates and reduced mortality compared to those receiving traditional therapies.[24]

Innovations in RUTF include the development of locally produced formulations, which reduce costs and increase cultural acceptability, thereby improving treatment outcomes and stimulating local economies.[25] Additionally, research into alternative formulations, such as chickpea- and soy-based RUTF, aims to provide safe options for populations with peanut allergies or cultural dietary restrictions.[26]

Fortified Foods and Supplements

Fortification of staple foods with essential vitamins and minerals is a widely employed strategy to combat PEM. Innovations in this area include biofortification, in which crops are selectively bred or genetically enhanced to increase their nutrient content. For example, biofortified crops such as orange-fleshed sweet potatoes (rich in vitamin A) and iron-fortified beans have demonstrated promising results in improving nutritional status and reducing micronutrient deficiencies.[27] Biofortification offers the advantages of sustainability and cost-effectiveness, as it integrates nutrient enhancement directly into agricultural practices.[28] Similarly, provitamin A-biofortified maize varieties have been introduced in sub-Saharan Africa, where vitamin A deficiency is prevalent.[29]

Micronutrient powders (MNPs) and lipid-based nutrient supplements (LNS) are additional effective interventions. MNPs, often referred to as "home fortification," can be sprinkled onto household foods to enhance their nutritional content. Studies have shown that they significantly improve iron status and reduce anemia in young children.[30] LNS have also

been shown to promote growth and development in children at risk of malnutrition.[31]

Community-Based Nutrition Programs

Integrated community-based programs that combine nutritional education, supplementation, and food security measures have proven effective in reducing PEM. These programs often engage local healthcare workers and volunteers to provide ongoing support and monitoring, ensuring adherence and effectiveness.

Positive Deviance/Hearth (PD/Hearth) programs are a community-based approach that identifies and leverages local practices of well-nourished children in impoverished communities to teach and promote these behaviors among other families. Such programs have been demonstrated to enhance child nutrition and decrease malnutrition rates.[32]

Mother-to-mother support groups have proven effective in promoting breastfeeding and complementary feeding practices, significantly improving infant feeding behaviors and nutritional outcomes.[33] Mother-to-Mother Support Groups are evidence-based interventions that improve breastfeeding and complementary feeding practices, particularly in resource-limited settings. Empirical studies from Ghana, Uganda, and Malawi have demonstrated significant enhancements in infant feeding practices and nutritional outcomes when mothers participate in peer-led support groups. These interventions not only promote behavioral change but also foster social support networks, contributing to sustained improvements in nutrition.[34-36] School feeding programs represent another critical intervention, particularly in regions with high food insecurity. Initiatives led by the World Food Programme have demonstrated positive effects on children's nutritional status and educational outcomes across multiple countries.[37]

Therapeutic Supplementation

Therapeutic supplementation involves the targeted provision of high-dose vitamins and minerals to treat deficiencies and support recovery from malnutrition. Regular high-dose vitamin A supplementation has been shown to reduce the risk of measles, diarrhea, and overall mortality in children.[38] Zinc supplementation is another effective intervention, particularly for managing diarrheal diseases associated with malnutrition, as it can reduce the duration and severity of diarrhea, improve appetite, and enhance growth in malnourished children.[39]

2. Technological Innovations

Technological innovations play a crucial role in advancing the detection, treatment, and prevention of protein-energy malnutrition (PEM). These include digital health platforms, advanced diagnostic tools, and agricultural biotechnology, each contributing to more efficient and effective nutritional interventions.

Digital Health Platforms

Digital health platforms, including mobile health (mHealth) applications and telemedicine, have emerged as powerful tools for addressing PEM. mHealth applications, such as CommCare, enable community health workers to collect and manage health data, receive training, and communicate with patients via mobile devices.[40] Telemedicine platforms, such as eNutrition, connect patients with nutrition experts and healthcare providers, facilitating tailored dietary guidance and progress monitoring.[41]

Point-of-Care Diagnostic Tools

Advances in point-of-care (POC) diagnostic tools have transformed the detection and management of PEM. Micronutrient testing kits, such as iCheck Fluoro, and hemoglobin testing devices, like HemoCue, provide rapid and accurate assessments of nutritional deficiencies.[42, 43] Biosensors, including the NutriChip, enable simultaneous evaluation of multiple nutritional biomarkers, offering a comprehensive overview of an individual's nutritional status.[44]

Geographic Information Systems (GIS)

Geographic Information Systems (GIS) enable the mapping and analysis of nutritional data, providing insights into the spatial distribution of malnutrition and identifying high-risk areas. GIS technology supports the planning of targeted interventions by visualizing trends in nutritional data.[45]

Wearable Technology

Wearable technology offers a novel approach for continuous monitoring of nutritional status and physical activity, delivering real-time data that can inform personalized nutrition plans. Devices such as smartwatches and fitness trackers, equipped with sensors, can monitor physiological parameters and track dietary intake and energy expenditure, helping individuals manage their nutritional status more effectively.[46] For example, the GoBe2 wearable estimates calorie intake by measuring glucose levels through the skin.[47]

Artificial Intelligence and Machine Learning

Artificial intelligence (AI) and machine learning (ML) facilitate the analysis of large datasets and the development of predictive models for assessing malnutrition risk and evaluating intervention outcomes. AI-powered tools can identify populations at the highest risk and recommend targeted interventions to mitigate these risks.[48] Additionally, chatbots and virtual assistants provide personalized dietary guidance and support, enhancing adherence to nutritional interventions.[49]

Innovations in Food Production and Preservation

Technological advancements in food production and preservation enhance both the availability and quality of nutritious foods. Agricultural biotechnology has facilitated the development of genetically modified crops with improved nutritional profiles, such as Golden Rice enriched with beta-carotene.[50] Food preservation technologies, including solar drying and vacuum packaging, extend the shelf life of nutrient-rich foods, reduce food waste, and ensure a consistent supply of essential nutrients.[51]

3. Policy Implications and Public Health Interventions

Addressing protein-energy malnutrition (PEM) requires a multifaceted approach that integrates robust policies and public health interventions. Collaboration among governments, international organizations, and non-governmental organizations (NGOs) is crucial for designing and implementing policies that improve nutritional outcomes and reduce the prevalence of malnutrition.

National Nutrition Policies

Effective national nutrition policies are crucial for tackling PEM. These policies should include strategies to enhance food security, improve dietary quality, and promote healthy eating behaviors. Comprehensive nutrition programs that integrate food assistance, nutrition education, and health services have demonstrated a significant impact in reducing malnutrition. For example, Brazil's Zero Hunger Program (Fome Zero) sought to eradicate hunger and malnutrition through initiatives such as cash transfers, school feeding programs, and community kitchens.[52]

Regulatory policies that mandate fortification of staple foods with essential nutrients also contribute to mitigating PEM. Many countries have implemented mandatory fortification of wheat flour, rice, and edible oils with vitamins and minerals, such as iron, folic acid, and vitamin A, resulting in measurable reductions in micronutrient deficiencies and associated health problems.[53]

Challenges in Policy Implementation

Despite the existence of national nutrition policies, significant barriers often hinder the effective implementation of these policies. A major challenge is the lack of political commitment and sustained funding. Nutrition programs are frequently underfunded, resulting in gaps in service delivery and difficulties scaling up successful interventions. In many countries, nutrition initiatives are embedded within broader health or development agendas, which can dilute focus and reduce effectiveness.[54]

Coordination across sectors represents another critical challenge. PEM is a multifaceted issue intersecting with agriculture, health, education, and social protection. Without effective intersectoral coordination, interventions may become fragmented and fail to address the root causes of malnutrition.[55] Additionally, corruption and bureaucratic inefficiencies can impede resource distribution and compromise the monitoring and evaluation of nutrition programs.[56]

International and Regional Initiatives

Global and regional initiatives play a vital role in addressing malnutrition by providing technical support, funding, and policy guidance. The Scaling Up Nutrition (SUN) Movement is a global initiative that unites governments, civil society, businesses, and researchers to accelerate progress in reducing malnutrition. The SUN Movement assists countries in developing and implementing national nutrition plans, advocates for increased investment in nutrition, and promotes best practices.[57]

At the regional level, the African Union's Africa Regional Nutrition Strategy seeks to enhance nutrition security by improving food production, increasing access to nutritious foods, and strengthening health systems. This strategy underscores the importance of political commitment, resource mobilization, and multisectoral collaboration in combating malnutrition.[58]

Examples of Successful Interventions

Several countries have successfully implemented policies to combat PEM despite significant challenges. Ethiopia's Health Extension Program, which deploys community health workers to provide nutrition counseling, monitor child growth, and distribute micronutrient supplements, has contributed to substantial reductions in child malnutrition.[59] Similarly, India's Integrated Child Development Services (ICDS) program, offering supplementary nutrition, immunization, and health check-ups to young children and mothers, has played a crucial role in addressing malnutrition. However, challenges remain regarding coverage and service quality.[60]

Community-Based Interventions

Community-based interventions are critical for addressing PEM at the grassroots level. Nutrition education programs within communities aim to promote healthy dietary practices, breastfeeding, and appropriate complementary feeding. These programs are often delivered through workshops, home visits, and group sessions. For example, the Positive Deviance/Hearth approach identifies and replicates successful feeding practices of well-nourished children within the same community, resulting in improved nutritional outcomes.[32]

Community health worker (CHW) programs empower local health workers to provide nutrition

counseling, monitor child growth, and distribute supplements. The effectiveness of CHW programs in reducing PEM has been documented in various settings, including Ethiopia's Health Extension Program and India's Accredited Social Health Activist (ASHA) program.[61, 62]

Social Safety Nets

Social safety nets, including cash transfers and food assistance programs, are crucial for enhancing food security and improving the nutritional status of vulnerable populations. Conditional cash transfer (CCT) programs offer financial incentives to low-income families, contingent upon their participation in health and nutrition services. Programs such as Mexico's Prospera (formerly Progresa/Oportunidades) have demonstrated significant reductions in child malnutrition by enhancing household income and access to health services.[63]

Food assistance initiatives, including school feeding and supplementary feeding programs, ensure that children and other vulnerable groups receive adequate nutrition. The World Food Programme's (WFP) school feeding programs, for example, provide meals to millions of children worldwide, improving both nutritional status and educational outcomes.[64]

Monitoring and Evaluation

Monitoring and evaluation (M&E) systems are essential for assessing the effectiveness of nutrition policies and programs. Nutrition surveillance systems collect and analyze data on nutritional status, food security, and health indicators. For instance, the Integrated Food Security Phase Classification (IPC) is used globally to categorize the severity of food insecurity and guide targeted interventions.[45]

Impact evaluations of nutrition programs assess the outcomes and effectiveness of specific interventions. These evaluations often employ rigorous methodologies, including randomized controlled trials (RCTs) and quasi-experimental designs, to measure the impact of programs on nutritional outcomes. Evidence from such evaluations informs program refinement and supports the scaling up of successful interventions.[65]

Conclusion

Significant progress has been made in PEM research, yet continued efforts are required to overcome persistent challenges and achieve sustainable improvements in nutritional outcomes. Future research should prioritize the validation and integration of biomarkers, optimization of nutritional interventions, application of technological innovations, and strengthening of policy frameworks.

Addressing the multifaceted nature of PEM through innovative, evidence-based strategies can substantially reduce the global burden of malnutrition and improve the health and well-being of vulnerable populations. The success of these strategies depends on a holistic approach that considers socio-economic, cultural, and environmental factors. Interventions must be tailored to the specific needs of different communities, taking into account their unique challenges and available resources.

Collaboration among governments, international organizations, NGOs, and local communities is essential to ensure the scalability and sustainability of nutrition programs. Moreover, robust monitoring and evaluation systems are critical for providing reliable data on intervention effectiveness and guiding policy decisions. Continuous assessment and adaptation based on evidence will help ensure that efforts to combat PEM remain relevant and effective amid evolving challenges.

By fostering a multidisciplinary and collaborative approach, the effectiveness of PEM interventions can be enhanced, moving us closer to a world in which malnutrition no longer impedes health and development. Although the journey toward eradicating PEM is complex, sustained commitment and innovation can create a healthier future, particularly for the most vulnerable populations.

Authors' Contribution

Mohamed Anas Patni conceptualized the review, conducted the literature search, data extraction, and drafted the manuscript. Mushirabanu Sharifmiyan Akikwala contributed to literature synthesis, interpretation of findings, and manuscript editing. Both authors reviewed and approved the final version of the manuscript and are accountable for all aspects of the work.

Acknowledgment

The authors express their gratitude to RAK Medical and Health Sciences University, Ras Al Khaimah, UAE, for providing academic and institutional support during this research.

Funding

This research did not receive any specific grant from funding agencies in the public, commercial, or not-for-profit sectors.

Conflict of Interest

The authors declare no conflicts of interest related to the content of this article.

References

1 World Health Organization. Guideline: Updates on the management of severe acute malnutrition in infants and children. Geneva: World Health Organization. 2020.

2 Black RE, Victora CG, Walker SP, Bhutta ZA, Christian P, de Onis M, et al; Maternal and Child Nutrition Study Group. Maternal and child undernutrition and overweight in low-income and middle-income countries. Lancet. 2013; 382(9890):427-451. doi: 10.1016/S0140-6736(13)60937-X. PubMed PMID: 23746772.

3 Government of India. National Family Health Survey (NFHS-5) 2019-2020. International Institute for Population Sciences (IIPS) and ICF. NFHS-5 Report. 2021.

4 Waterlow JC. Protein-energy malnutrition: the nature and extent of the problem. Clin Nutr. 1997; 16(Suppl 1):3-9. doi: 10.1016/s0261-5614(97)80043-x. PubMed PMID: 16844615.

5 Golden MH, Ramdath D. Free radicals in the pathogenesis of kwashiorkor. Proc Nutr Soc. 1987; 46(1):53-68. doi: 10.1079/pns19870008. PubMed PMID: 3575323.

6 Aguayo VM, Nair R, Badgaiyan N, Krishna V. Determinants of stunting and poor linear growth in children under 2 years of age in India: an in-depth analysis of Maharashtra's comprehensive nutrition survey. Matern Child Nutr. 2016; 12(Suppl 1):121-40. doi: 10.1111/mcn.12259. PubMed PMID: 27187911; PubMed Central PMCID: PMC5084823.

7 Allenson K, Turner K, Gonzalez BD, Gurd E, Zhu S, Misner N, et al. Pilot trial of remote monitoring to prevent malnutrition after hepatopancreatobiliary surgery. BMC Nutr. 2021; 7(1):82. doi: 10.1186/s40795-021-00487-3.

8 Trehan I, Goldbach HS, LaGrone LN, Meuli GJ, Wang RJ, Maleta KM, et al. Antibiotics as part of the management of severe acute malnutrition. N Engl J Med. 2013; 368(5):425-35. doi: 10.1056/NEJMoa1202851. PubMed PMID: 23363496; PubMed Central PMCID: PMC3654668.

9 Government of India. POSHAN Abhiyaan: National Nutrition Mission. Ministry of Women and Child Development. POSHAN Abhiyaan Report. 2018.

10 Higgins JP, Green S, Editors. Cochrane Handbook for Systematic Reviews of Interventions (Version 5.1.0). The Cochrane Collaboration. 2011. Available at: http://handbook-5-1.cochrane.org/.

11 de Onis M, Blössner M. The World Health Organization Global Database on Child Growth and Malnutrition: methodology and applications. Int J Epidemiol. 2003; 32(4):518-26. doi: 10.1093/ije/dyg099. PubMed PMID: 12913022.

12 Bresnahan KA, Tanumihardjo SA. Undernutrition, the acute phase response to infection, and its effects on micronutrient status indicators. Adv Nutr. 2014; 5(6):702-11. doi: 10.3945/an.114.006361. PubMed PMID: 25398733; PubMed Central PMCID: PMC4224207.

13 Brown KH, Peerson JM, Rivera J, Allen LH. Effect of supplemental zinc on the growth and serum zinc concentrations of prepubertal children: a meta-analysis of randomized controlled trials. Am J Clin Nutr. 2002; 75(6):1062-71. doi: 10.1093/ajcn/75.6.1062. PubMed PMID: 12036814.

14 Tanumihardjo SA. Vitamin A: biomarkers of nutrition for development. Am J Clin Nutr. 2011; 94(2):658S-65S. doi: 10.3945/ajcn.110.005777. PubMed PMID: 21715511; PubMed Central PMCID: PMC3142734.

15 Khan A, Khan WM, Ayub M, Humayun M, Haroon M. Ferritin Is a Marker of Inflammation rather than Iron Deficiency in Overweight and Obese People. J Obes. 2016; 2016:1937320. doi: 10.1155/2016/1937320. PubMed PMID: 28116148; PubMed Central PMCID: PMC5223018.

16 Beck FK, Rosenthal TC. Prealbumin: a marker for nutritional evaluation. Am Fam Physician. 2002; 65(8):1575-8. PubMed PMID: 11989633.

17 Maric S, Restin T, Muff JL, Camargo SM, Guglielmetti LC, Holland-Cunz SG, et al. Citrulline, Biomarker of Enterocyte Functional Mass and Dietary Supplement. Metabolism, Transport, and Current Evidence for Clinical Use. Nutrients. 2021; 13(8):2794. doi: 10.3390/nu13082794. PubMed PMID: 34444954; PubMed Central PMCID: PMC8398474.

18 Gao RY, Hsu BG, Wu DA, Hou JS, Chen MC. Serum Fibroblast Growth Factor 21 Levels Are Positively Associated with Metabolic Syndrome in Patients with Type 2 Diabetes. Int J Endocrinol. 2019; 5163245. doi: 10.1155/2019/5163245. PubMed PMID: 31582974; PubMed Central PMCID: PMC6754922.

19 Day KJ, Adamski MM, Dordevic AL, Murgia C. Genetic Variations as Modifying Factors to Dietary Zinc Requirements-A Systematic Review. Nutrients. 2017; 9(2):148. doi: 10.3390/nu9020148. PubMed PMID: 28218639; PubMed Central PMCID: PMC5331579.

20 Jiménez-Chillarón JC, Díaz R, Martínez D, Pentinat T, Ramón-Krauel M, Ribó S, et al. The role of nutrition on epigenetic modifications and their implications on health. Biochimie. 2012; 94(11):2242-63. doi: 10.1016/j.biochi.2012.06.012. PubMed PMID: 22771843.

21 Zhang Z, Pereira SL, Luo M, Matheson EM. Evaluation of Blood Biomarkers Associated with Risk of Malnutrition in Older Adults: A Systematic Review and Meta-Analysis. Nutrients. 2017; 9(8):829. doi: 10.3390/nu9080829. PubMed PMID: 28771192; PubMed Central PMCID: PMC5579622.

22 Farhadi Sedigheh, Ovchinnikov Roman S. The Relationship between Nutrition and Infectious Diseases: A Review. Biomedical and Biotechnology Research Journal (BBRJ) 2(3): 2018. p 168-172. doi: 10.4103/bbrj.bbrj_69_18.

23 Dai X, Shen L. Advances and Trends in Omics Technology Development. Front Med (Lausanne).

2022; 9:911861. doi: 10.3389/fmed.2022.911861. PubMed PMID: 35860739; PubMed Central PMCID: PMC9289742.

24 Uauy R, Kurpad A, Tano-Debrah K, Otoo GE, Aaron GA, Toride Y, et al. Role of Protein and Amino Acids in Infant and Young Child Nutrition: Protein and Amino Acid Needs and Relationship with Child Growth. J Nutr Sci Vitaminol (Tokyo). 2015;61 Suppl: S192-4. doi: 10.3177/jnsv.61.S192. PubMed PMID: 26598853.

25 Manary MJ. Local production and provision of ready-to-use therapeutic food (RUTF) spread for the treatment of severe childhood malnutrition. Food Nutr Bull. 2006; 27(3 Suppl): S83-9. doi: 10.1177/15648265060273S305. PubMed PMID: 17076214.

26 Bahwere P, Balaluka B, Wells JC, Mbiribindi CN, Sadler K, Akomo P, et al. Cereals and pulse-based ready-to-use therapeutic food as an alternative to the standard milk- and peanut paste-based formulation for treating severe acute malnutrition: a noninferiority, individually randomized controlled efficacy clinical trial. Am J Clin Nutr. 2016; 103(4):1145-61. doi: 10.3945/ajcn.115.119537. PubMed PMID: 26984485.

27 Bouis HE, Saltzman A. Improving nutrition through biofortification: A review of evidence from HarvestPlus, 2003 through 2016. Glob Food Sec. 2017; 12:49-58. doi: 10.1016/j.gfs.2017.01.009. PubMed PMID: 28580239; PubMed Central PMCID: PMC5439484.

28 Pfeiffer WH, McClafferty B. (2007). HarvestPlus: Breeding crops for better nutrition. Crop Science. 2007. 47(S3), S-88-S-105. doi: 10.2135/cropsci2007.09.0020IPBS.

29 Nuss ET, Tanumihardjo SA. Quality protein maize for Africa: closing the protein inadequacy gap in vulnerable populations. Adv Nutr. 2011; 2(3):217-24. doi: 10.3945/an.110.000182. PubMed PMID: 22332054; PubMed Central PMCID: PMC3090170.

30 Suchdev PS, Jefferds MED, Ota E, da Silva Lopes K, De-Regil LM. Home fortification of foods with multiple micronutrient powders for health and nutrition in children under two years of age. Cochrane Database Syst Rev. 2020; 2(2):CD008959. doi: 10.1002/14651858.CD008959.pub3. PubMed PMID: 32107773; PubMed Central PMCID: PMC7046492.

31 Arimond M, Zeilani M, Jungjohann S, Brown KH, Ashorn P, Allen LH, et al. Considerations in developing lipid-based nutrient supplements for prevention of undernutrition: experience from the International Lipid-Based Nutrient Supplements (iLiNS) Project. Matern Child Nutr. 2015; (Suppl 4):31-61. doi: 10.1111/mcn.12049. PubMed PMID: 23647784; PubMed Central PMCID: PMC6860325.

32 O'Malley R, Lydon S, Faherty A, O'Connor P. Identifying Factors that Support the Delivery of Exceptional Care in General Practice and Development of the IDEAL Framework: A Qualitative Study. Qual Health Res. 2023; 33(13):1232-1248. doi: 10.1177/10497323231197387. PubMed PMID: 37694934; PubMed Central PMCID: PMC10626987.

33 Bhandari N, Bahl R, Mazumdar S, Martines J, Black RE, Bhan MK. Infant Feeding Study Group. Effect of community-based promotion of exclusive breastfeeding on diarrhoeal illness and growth: a cluster randomised controlled trial. Lancet. 2003; 361(9367):1418-23. doi: 10.1016/S0140-6736(03)13134-0. PMID: 12727395.

34 Aidam BA, Pérez-Escamilla R, Lartey A, Aidam J. Factors associated with exclusive breastfeeding in Accra, Ghana. Eur J Clin Nutr. 2005; 59(6):789-96. doi: 10.1038/sj.ejcn.1602144. PubMed PMID: 15870819.

35 Nankunda J, Tumwine JK, Nankabirwa V, Tylleskär T; PROMISE-EBF Study Group. "She would sit with me": mothers' experiences of individual peer support for exclusive breastfeeding in Uganda. Int Breastfeed J. 2010; 5:16. doi: 10.1186/1746-4358-5-16.

36 Baker EJ, Sanei LC, Franklin N. Early initiation of and exclusive breastfeeding in large-scale community-based programmes in Bolivia and Madagascar. J Health Popul Nutr. 2006; 24(4):530-9. PubMed PMID: 17591350; PubMed Central PMCID: PMC3001157.

37 Bundy DA, Burbano C, Grosh M, Gelli A, Jukes M, Drake L. Rethinking school feeding: social safety nets, child development, and the education sector. World Bank Publications. 2009. doi: 10.1596/978-0-8213-7974-5.

38 Imdad A, Mayo-Wilson E, Herzer K, Bhutta ZA. Vitamin A supplementation for preventing morbidity and mortality in children from six months to five years of age. Cochrane Database Syst Rev. 2017; 3(3):CD008524. doi: 10.1002/14651858.CD008524.pub3. Update in: Cochrane Database Syst Rev. 2022; 3:CD008524. doi: 10.1002/14651858.CD008524.pub4. PubMed PMID: 28282701; PubMed Central PMCID: PMC6464706.

39 Lazzerini M, Wanzira H. Oral zinc for treating diarrhoea in children. Cochrane Database Syst Rev. 2016; 12(12):CD005436. doi: 10.1002/14651858.CD005436.pub5. PubMed PMID: 27996088; PubMed Central PMCID: PMC5450879.

40 Feroz A, Jabeen R, Saleem S. Using mobile phones to improve community health workers performance in low-and-middle-income countries. BMC Public Health 20, 49 (2020). doi: 10.1186/s12889-020-8173-3.

41 Marx W, Kelly JT, Crichton M, Craven D, Collins J, Mackay H, et al. Is telehealth effective in managing malnutrition in community-dwelling older adults? A systematic review and meta-analysis. Maturitas. 2018; 111:31-46. doi: 10.1016/j.maturitas.2018.02.012. PubMed PMID: 29673830.

42 Neogi SB, Sharma J, Pandey S, Zaidi N, Bhattacharya M, Kar R, et al. Diagnostic accuracy of point-of-care devices for detection of anemia in community settings in India. BMC Health Serv Res. 2020; 20(1):468. doi: 10.1186/s12913-020-05329-9. PubMed PMID: 32456639; PubMed Central PMCID: PMC7249358.

43 Huey SL, Krisher JT, Morgan D, Mkambula P, Gannon BM, Mbuya MNN, et al. A review of portable quantitative and semi-quantitative devices for measurement of vitamin A in biological samples. Curr Res Biotechnol. 2022; 4:253-274. doi: 10.1016/j.

crbiot.2022.04.003. PubMed PMID: 36033130; PubMed Central PMCID: PMC9407042.

44 Ramadan Q, Jafarpoorchekab H, Huang C, Silacci P, Carrara S, Koklü G, et al. NutriChip: nutrition analysis meets microfluidics. Lab Chip. 2013; 13(2):196-203. doi: 10.1039/c2lc40845g. PubMed PMID: 23184124.

45 IPC. Integrated Food Security Phase Classification Technical Manual Version 3.0. 2020. Available at: https://www.ipcinfo.org/ipcinfo-website/resources/manuals/en/.

46 Huhn S, Axt M, Gunga HC, Maggioni MA, Munga S, Obor D, Sié A, et al. The Impact of Wearable Technologies in Health Research: Scoping Review. JMIR Mhealth Uhealth. 2022; 10(1):e34384. doi: 10.2196/34384. PubMed PMID: 35076409; PubMed Central PMCID: PMC8826148.

47 Heikenfeld J, Jajack A, Rogers J, Gutruf P, Tian L, Pan T, et al. Wearable sensors: modalities, challenges, and prospects. Lab Chip. 2018; 18(2):217-248. doi: 10.1039/c7lc00914c. PubMed PMID: 29182185; PubMed Central PMCID: PMC5771841.

48 Fenta HM, Zewotir T, Muluneh EK. A machine learning classifier approach for identifying the determinants of under-five child undernutrition in Ethiopian administrative zones. BMC Med Inform Decis Mak. 2021; 21(1):291. doi: 10.1186/s12911-021-01652-1. PubMed PMID: 34689769; PubMed Central PMCID: PMC8542294.

49 Seitz, Lennart. Artificial empathy in healthcare chatbots: Does it feel authentic? Computers in Human Behavior: Artificial Humans. 2. 100067. 2024. doi: 10.1016/j.chbah.2024.100067.

50 Tang G, Qin J, Dolnikowski GG, Russell RM, Grusak MA. Golden Rice is an effective source of vitamin A. Am J Clin Nutr. 2009; 89(6):1776-83. doi: 10.3945/ajcn.2008.27119. PubMed PMID: 19369372; PubMed Central PMCID: PMC2682994.

51 Baributsa D, Bakoye ON, Ibrahim B, Murdock LL. Performance of Five Postharvest Storage Methods for Maize Preservation in Northern Benin. Insects. 2020; 11(8):541. doi: 10.3390/insects11080541. PubMed PMID: 32824419; PubMed Central PMCID: PMC7469259.

52 Bither-Terry, Russell, 'The Program with Many Components Rarely Succeeds': Lessons from the First Year of Brazil's Zero Hunger Program. 2016. Available at: SSRN: https://ssrn.com/abstract=3517623. doi: 10.2139/ssrn.3517623.

53 Food fortification. (n.d.). 2024. Retrieved July 13. Available at: https://www.who.int/health-topics/food-fortification.

54 Food and Agriculture Organization (FAO). The State of Food Insecurity in the World 2014: Strengthening the enabling environment for food security and nutrition. FAO. 2014.

55 Hackman JV, Hruschka DJ. Disentangling basal and accrued height-for-age for cross-population comparisons. Am J Phys Anthropol. 2020; 171(3):481-495. doi: 10.1002/ajpa.23990. PubMed PMID: 31886899.

56 2021 Global Nutrition Report | The state of global nutrition—Global Nutrition Report. (n.d.). Retrieved October 4. 2024. Available at: https://globalnutritionreport.org/reports/2021-global-nutrition-report/.

57 SUN Movement. (2021. The Scaling Up Nutrition (SUN) Movement: Progress Report.

58 African Union. Africa Regional Nutrition Strategy 2015-2025. 2015. Available at: https://au.int/en/documents/20150525/africa-regional-nutrition-strategy-2015-2025.

59 World Food Programme (WFP). (2018). The State of School Feeding Worldwide 2018. World Food Programme. Available at: https://executiveboard.wfp.org/document_download/WFP-0000110115#:~:text=In%202018%2C%20WFP%20assisted%2016.4,programme%20in%20terms%20of%20beneficiaries.

60 Kapil U. Integrated Child Development Services (ICDS) scheme: a program for holistic development of children in India. Indian J Pediatr. 2002; 69(7):597-601. doi: 10.1007/BF02722688. PubMed PMID: 12173700.

61 Agarwal S, Curtis SL, Angeles G, Speizer IS, Singh K, Thomas JC. The impact of India's accredited social health activist (ASHA) program on the utilization of maternity services: a nationally representative longitudinal modelling study. Hum Resour Health. 2019; 17(1):68. doi: 10.1186/s12960-019-0402-4. PubMed PMID: 31426801; PubMed Central PMCID: PMC6701148.

62 Kok MC, Dieleman M, Taegtmeyer M, Broerse JE, Kane SS, Ormel H, et al. Which intervention design factors influence performance of community health workers in low- and middle-income countries? A systematic review. Health Policy Plan. 2015; 30(9):1207-27. doi: 10.1093/heapol/czu126. PubMed PMID: 25500559; PubMed Central PMCID: PMC4597042.

63 Fernald LC, Gertler PJ, Neufeld LM. Role of cash in conditional cash transfer programmes for child health, growth, and development: an analysis of Mexico's Oportunidades. Lancet. 2008; 371(9615):828-37. doi: 10.1016/S0140-6736(08)60382-7. PubMed PMID: 18328930; PubMed Central PMCID: PMC2779574.

64 WFP. World Food Programme School Feeding Strategy 2020-2030. 2020. Available at: https://docs.wfp.org/api/documents/WFP-0000112101/download/?_ga=2.252242441.1665108557.1720857500-559675707.1720857500.

65 Ruel MT, Alderman H; Maternal and Child Nutrition Study Group. Nutrition-sensitive interventions and programmes: how can they help to accelerate progress in improving maternal and child nutrition? Lancet. 2013; 382(9891):536-51. doi: 10.1016/S0140-6736(13)60843-0. PubMed PMID: 23746780.