International Journal of Applied Home Science
(An International Double Blind Peer Reviewed / Refereed Research Journal of Home Science)
Volume 13 (7 & 8), July & August (2026) : 450-461
Received : 19.06.2026; Revised : 05.07.2026; Accepted : 19.07.2026

REVIEW PAPER
ISSN : 2394-1413 (Print)

DOI: https://doi-ds.org/doilink/09.2026-27338738/IJAHS/13.7&8/450-461

Biofortified Crops and Spatial Targeting: Analysis of Health Outcomes and Efficacy

MENAKA DAS*[1] AND ANADI CHARAN DAS[2]
[1]Ph.D. Research Scholar and [2]Assistant Professor
[1]Department of Economics, Fakir Mohan University, Baleshwar (Odisha) India
[2]Department of Economics, Model Degree College, Deogarh (Odisha) India

*Corresponding Author

ABSTRACT

More than two billion people suffer from micronutrient deficiencies ("hidden hunger") in the world, leading to dire consequences in terms of health and the economy. Biofortification is a process that involves improving the nutrient content of staple foods and serves as a sustainable approach towards food-based solutions. In this systematic review and meta-analysis, an attempt has been made to synthesise literature on the impacts of biofortified crops on public health, particularly focusing on spatial targeting. Guided by PRISMA 2020 guidelines, a thorough search was conducted between 2010 and 2024 across eight databases to find peer-reviewed articles using geospatial techniques. A random-effects model of meta-analysis indicated a statistically significant reduction in the risk of micronutrient deficiencies (RR = 0.72; 95% CI: 0.60–0.85) through biofortified crops (vitamin A sweet potato, iron beans, and zinc rice), translating into a 28% average reduction in the risk of micronutrient deficiencies. From the results, it is clear that biofortification is an effective public health approach, and its effectiveness can be improved significantly when it is coupled with the spatial targeting approach. It will ensure efficiency, equity, and effectiveness by ensuring that the resources are delivered to those communities where there are converging factors such as need for nutrition and agricultural suitability. This means that geospatial approaches should be adopted to optimise the process of scaling up biofortification efforts.

Keywords: Biofortification, Micronutrient Deficiencies, Spatial Targeting, Precision Nutrition, Systematic Review, Geospatial Analysis

INTRODUCTION

The Global Burden of Hidden Hunger and the Promise of Biofortification

Hidden hunger, which is micronutrient malnutrition, is a very common problem in the world today, although not many people are aware of its presence. Hidden hunger, unlike hunger caused by lack of calories, is where people do not get enough amounts of vitamins and minerals like iron, zinc, vitamin A, iodine, and folic acid despite having enough food in their diets (Black *et al.*, 2013).

Current global estimates show that over two billion people have deficiencies in at least one micronutrient, the majority of which occur in low- and middle-income countries (LMICs), particularly South Asia and sub-Saharan Africa. Iron-deficiency anaemia alone is responsible for about 30% of women in reproductive age globally, resulting in increased chances of death due to childbirth complications, poor productivity, low immunity, and health problems during pregnancy, including low birth weight and premature births. Deficiencies in zinc and vitamin A lead to increased risk of contracting infections in children, and iodine deficiency is a leading cause of preventable intellectual disability around the world (Black *et al.,* 2013; Bhutta *et al.*, 2013). The economic implications of hidden hunger are profound. Micronutrient deficiencies are estimated to reduce national gross

How to cite this Article: Das, Menaka and Das, Anadi Charan (2026). Biofortified Crops and Spatial Targeting: Analysis of Health Outcomes and Efficacy. *Internat. J. Appl. Home Sci.,* **13** (7 & 8) : 450-461.

domestic product (GDP) by 2–11% annually in parts of Asia and Africa due to lost productivity, increased healthcare costs, and reduced educational attainment. Importantly, childhood exposure to chronic micronutrient deficiencies can result in irreversible cognitive damage, reinforcing intergenerational cycles of poverty and inequality (Black *et al.*, 2013; Bhutta *et al.*, 2013).

The conventional approaches to tackle micronutrient deficiencies, including pharmacological treatment and industrial food fortification, have made some notable accomplishments but are constrained by inherent limitations. The intervention strategies usually rely upon centralised distribution channels, continuous funding, and behavioural compliance, which is a challenge to be met in rural regions and fragile conditions (Bhutta *et al.*, 2013). The process of supplements provision is generally intermittent and external in nature, posing threats to its sustainability and access to marginalised sections of the population.

In this respect, biofortification has become a feasible agricultural approach for tackling hidden hunger sustainably and economically. Biofortification improves the nutritional quality of food crops by increasing their micronutrient content via conventional crop breeding techniques, agronomic biofortification or biotechnology approaches, thereby adding nutrition into those foods that people eat every day (Bouis and Saltzman, 2017). Since biofortification targets foods like rice, wheat, maize, pearl millet, cassava, beans, and sweet potatoes, it becomes a highly appropriate approach for rural communities that have little access to diversified diets or fortified foods.

Through global programs such as HarvestPlus working hand in hand with national agricultural research programs, the distribution of more than 400 biofortified crops has been possible worldwide, affecting more than 100 million people from Africa, Asia, and Latin America (Bouis and Saltzman, 2017). The effectiveness of the consumption of biofortified crops for improvement of iron status, serum zinc levels, and intake of vitamin A has been proven through randomized controlled trials and population-based studies, particularly among females and children who are highly susceptible to deficiencies of micronutrients (Bouis *et al.*, 2021; De Steur *et al.*, 2017).

The Imperative for Spatial Targeting

However, despite the success that has been realized in terms of biological efficacy, biofortification's public health significance is not uniformly distributed. There are considerable differences in crop performance, nutrient storage, adoption, and effect on the diet depending on the agro-ecological, climate, and socio-economic environment. The soil's micronutrient profile, amount of rainfall, heat stress, and agricultural practices determine yield levels and micronutrient concentration, while income, access to markets, social structure, culture, and seed distribution affect adoption and consumption (De Groote *et al.*, 2016; Bouis *et al.*, 2021).

These considerations underscore the intrinsic geography of vulnerability to malnutrition. The new paradigm of precision public health nutrition focuses on the incorporation of geospatial data, GIS technology, and spatial statistical analysis to identify at-risk communities and ensure the best locations for interventions (Baker *et al.,* 2018). Geospatial targeting enables governments and development organisations to go beyond national averages and focus on the introduction of biofortified crops in regions where there is a convergence of malnourishment, crop suitability, poverty, and dependency on staples.

Spatial tools will prove vital in the field of GEI analysis as well. The combination of spatial climatic, soil, and agronomic information enables the selection of certain biofortified varieties to be grown in environments where they will excel in terms of both yield and nutrient composition. It allows one to get the best value from breeding efforts while boosting their adaptive capacity in the face of climate change. Increased temperature and CO_2 levels in the atmosphere are expected to lead to a reduction in the iron and zinc content of major cereal grains by 3-10% by mid-century (Biofortification, 2022).

Study Rationale and Objectives

While there is an emerging scientific literature about the nutritional impact of specific biofortified crops, one key area for which there is insufficient research is the integration of health impact analysis with geographic methods. Current literature reviews 1 have tended to focus either on efficacy or adoption or on agronomic impacts but not on how the geographical methods can be used in the design, targeting, and evaluation of biofortification interventions.

Filling this gap will be crucial to guide future investments in nutrition-sensitive agriculture and policy decision-making based on empirical evidence. Synthesis that involves an explicit integration of the health impact assessment and spatial analysis methods will help better understand where, how, and among which populations biofortification provides the highest benefits, as well as those geographic areas that are potentially vulnerable to marginalization.

The objective of the proposed research is a systematic synthesis and quantitative evaluation of the existing body of evidence on the effectiveness of the consumption of biofortified staple crops on reduction of micronutrient deficiency-associated adverse health effects, as well as critical evaluation of the methods and their effectiveness of spatial and geostatistical analysis in targeting, analyzing and optimizing biofortification interventions.

As can be seen from Table 1, there are several reasons for the problems associated with micronutrient malnutrition and justification of biofortification. “Hidden hunger” affects more than 2 billion people in the world, while especially severe cases occur in LMICs; biofortification is beneficial in this case since it targets the population that consumes staple crops. The current solutions to the problem, like supplementation and fortification, may be expensive and complicated to implement in remote regions, while biofortification involves a single-time investment in breeding of seeds that self-propagate in the food system. The global environmental crisis poses another challenge because the increase in CO_2 concentration and temperature results in the decrease of iron, zinc, and protein content in important cereals, and biofortified varieties can be bred to ensure both climate resilience and micronutrients density as an adaptive measure. Finally, socio-economic inequalities reduce the diversity of diet and access to the market for the poor people, and biofortification allows providing necessary nutrition through commonly used foods that do not involve any market transactions (Bouis and Saltzman, 2017; Bouis *et al.*, 2021).

Linking Biofortification, Spatial Targeting, and Nutrition Outcomes

Fig. 1 shows the conceptual framework that highlights the influence of geographic elements on the health effects of nutrition-sensitive outcomes using biofortified crops. It is important to note that the success of biofortification depends largely on the interrelationship of several geographically diverse elements in the food-nutrition system. At the upstream end, the environmental and agroecological suitability including soil micronutrient profile, climate, rainfall, and crop adaptability will determine the areas where the particular biofortified variety performs best. Concurrently, at the downstream end, the nutritional requirement and vulnerability of the population indicated by the geographical distribution of micronutrient deficiencies, demographic profile, and dietary consumption of staples will define the target areas for interventions.

The three geographically varying forces combine in the process of biofortification through crop development, varietal releases, and targeted distribution. Implementation of such efforts will require uptake from the farmers and consumption by consumers influenced by culture, gender, and benefits realized from them. Uptake will ensure the impact in the form of health benefits such as reduction in deficiency of micronutrients, proper growth of children, and improvement of health outcomes for populations.

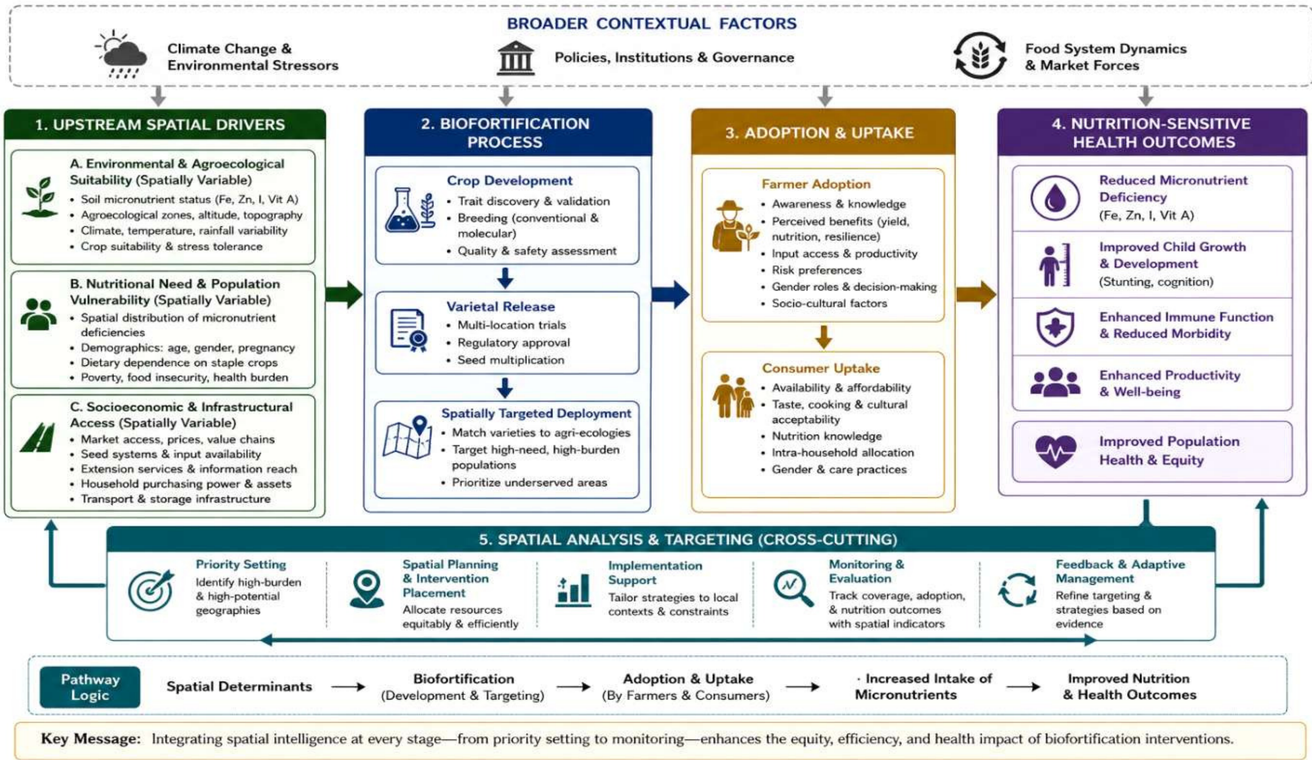
An important component of the framework is spatial analysis and targeting, represented in the form of a cross-cutting and iterative process. Geographical analysis guides prioritization, location of interventions, and monitoring and evaluation of the process. There are other contextual factors such as climate change, policy environments, and food systems dynamics which surround and influence all these processes. In general, the framework emphasizes that spatial intelligence is necessary for biofortification

Table 1 : Challenges of Micronutrient Malnutrition and the Rationale for Biofortification

Challenge	Description	Biofortification as a Strategic Response
Scale of "Hidden Hunger"	>2 billion people affected globally, with high burdens in low- and middle-income countries (LMICs)	Targets populations relying on staple crops, reaching rural households directly
Limitations of Existing Interventions	Supplementation and fortification can be costly, logistically complex, and unsustainable in remote areas	Requires a one-time investment in breeding; seeds are self-replicating and integrated into local food systems
Climate Change Threat	Elevated CO_2 and temperature can reduce iron, zinc, and protein content in major cereals	Develops climate-resilient, nutrient-dense varieties as a proactive adaptation strategy
Socio-Economic Inequity	The poorest populations have limited dietary diversity and market access	Provides nutrients through commonly grown and consumed staples, bypassing market barriers

Note. Adapted from global nutrition reports and biofortification studies (Bouis and Saltzman, 2017; Biofortification, 2022).

A Spatially-informed food-nutrition pathway from dererminants to health impact)



Source: Authors' conceptualisation based on Bouis and Saltzman (2017), De Groote *et al.* (2016) and Baker *et al.* (2018).

Fig. 1 : Conceptual Framework: Biofortification, Spatial Targeting, and Nutrition Outcomes

interventions to maximize equity, efficiency, and health outcomes (Baker *et al.*, 2018; Sethy and Mahapatro, 2026).

METHODOLOGY

Study Design and Protocol Registration

This paper employed systematic review and meta-analysis methodology that was executed and presented using PRISMA 2020 guidelines for transparency, replicability, and methodological rigor. The protocol for conducting the review was developed a priori, establishing objectives, inclusion/exclusion criteria, and methods of analysis to eliminate selection and publication biases (Mahapatro and Sethy, 2025; Sethy *et al.*, 2026).

Search Strategy and Information Sources

A comprehensive and systematic literature search was undertaken across eight electronic databases: PubMed, Scopus, Web of Science, Embase, APA PsycINFO, AGRICOLA, ProQuest Dissertations and Theses Global, and Google Scholar. Searches covered studies published between 1 January 2010 and 5 September 2024, reflecting the period during which biofortification programs and spatial analytical methods became more prominent. The search strategy combined controlled vocabulary (e.g., Medical Subject Headings [MeSH]) and free-text keywords, structured around three core conceptual domains:

1. Biofortification (e.g., biofortif, nutrient-enriched crop, Golden Rice, iron bean, zinc rice, vitamin A maize);
2. Health and Nutrition Outcomes (e.g., micronutrient deficiency, anaemia, serum ferritin, serum retinol, stunting, cognitive function);
3. Spatial and Geostatistical Methods (e.g., GIS, geospatial analysis, spatial regression, hotspot analysis, kriging, geographically weighted regression).

Boolean operators (AND, OR) were used to combine search terms across domains. In addition, the reference lists of all included articles and relevant reviews were manually screened to identify further eligible studies.

Eligibility Criteria

Studies were chosen according to pre-established inclusion and exclusion criteria. The population of interest consisted of any human populations regardless of age and sex from all geographic locations. Interventions or exposures of interest were consumption or production of biofortified staple food crops including cereals, pulses, roots and tubers fortified using conventional breeding, agronomic biofortification or transgenic technology. Comparators were consumption of non-biofortified conventional varieties or baseline (prior to intervention) nutrition status. Primary outcomes included biomarker measured micronutrient status such as hemoglobin, serum ferritin, serum retinol and serum zinc, as well as micronutrient deficiency status including anemia and vitamin A deficiency status, and anthropometric status including stunting and wasting. Secondary outcomes included dietary intake and cognitive function outcome measures. Eligible study design included empirical observational studies such as cross-sectional studies and cohorts studies, and intervention studies including randomized controlled trials and quasi-experimental studies that had reported quantitative health or nutrition outcomes and had spatial or geostatistical components such as mapping, spatial regression or interpolation. Exclusion criteria included studies that did not have comparator, studies that dealt only with agronomic performance, bioavailability or consumer acceptance without health outcomes, and review articles, editorial, conference abstracts or non-English studies.

Study Selection and Data Extraction

All obtained articles were entered into Covidence for reference management. Upon exclusion of duplicates, titles and abstracts were screened independently by M.S. and S.R.M., and those with potentially eligible articles underwent full-text screening. In case of any disagreement, discussions were held between the reviewers, and in case of further disagreement, an additional reviewer was consulted. A pre-tested and standardized data extraction sheet was used to extract information regarding: (1) study details (author, year, country, study design); (2) population characteristics; (3) biofortified crop type and micronutrient; (4) spatial analysis methods and scale of analysis; (5) health and nutritional outcomes and their effect sizes; and (6) covariates used in the model.

Quality Assessment

The methodological quality of observational studies was evaluated using a modified Newcastle–Ottawa Scale (NOS), adapted to incorporate elements relevant to spatial epidemiology. The scale assessed three domains: selection (representativeness, exposure assessment, quality of spatial data), comparability (adjustment for key confounders such as age and socioeconomic status), and outcome assessment (use of biomarkers, follow-up adequacy, and appropriateness of statistical and spatial methods). Studies were categorized as high (7–9 stars), moderate (5–6 stars), or low ($\leq$4 stars) quality. Only moderate- and high-quality studies were included in the meta-analysis.

Data Synthesis and Analysis

A random-effects meta-analysis was conducted for the studies presenting similar effect sizes (for example, ORs or RR) employing the DerSimonian and Laird approach that considers potential heterogeneity among the included studies. The summary statistics with 95% CIs were obtained for all analyses. The presence of statistical heterogeneity among studies was evaluated using I^2 statistics with levels of 25%, 50%, and 75% representing low, moderate, and high heterogeneity, respectively. Publication bias was detected using the visual assessment of funnel plots and Egger's test if there were enough studies ($n \geq 10$). All quantitative analysis was done using the Stata software version 18.0. For results not amenable for meta-analysis, a qualitative synthesis was done based on biofortified crops, spatial methods used, and important findings (Sethy *et al.,* 2026; Sethy and Mahapatro, 2026).

RESULTS AND DISCUSSION

Study Selection and Characteristics

The study selection process has been described through PRISMA flow diagram. Database searching resulted in a total number of 1,054 records. Out of which 42 records were further selected after excluding duplicates and screening titles and abstracts. In total 9 studies satisfied all predefined inclusion criteria and were included in the systematic review, where 7 studies provided data appropriate for meta-analysis.

The included studies have covered diverse geographical and socio-economic settings such as Sub-Saharan Africa, South Asia, and Latin America.

Methodological approaches adopted by studies varied from RCTs, quasi-experiments, cross-sectional surveys, observational cohort studies, and spatial modeling studies. Sampled population involved infants/young children, women of reproductive age group, and general rural populations who are more prone to suffer from micronutrient deficiency.

Characteristics of the studies that were identified for inclusion in this systematic review are listed in Table 2, showcasing the geographical spread, methodological variation, and analysis methods employed. Geographic locations of the reviewed studies include Sub-Saharan Africa, South Asia, and Latin America, which are characterized by high micronutrient deficiency rates and dependence on staple foods. Designs used for study purposes include cluster-randomized control trial, randomized control trial, quasi-experimental design, observational cohort design, cross-sectional design, and spatial modeling.

Biofortified foods utilized in the reviewed studies included orange-fleshed sweet potatoes and vitamin A maize, iron-biofortified rice and beans, and zinc rice. These foods have been chosen to address essential micronutrients deficiency – vitamin A, iron, and zinc. Groups of vulnerable individuals were focused on including children aged below five years, infants, and women of reproductive age, even though there were studies evaluating effects on a general or national population level. Health effects were measured based on biomarkers including vitamin A deficiency, serum retinol, iron deficiency anemia, zinc deficiency, and child stunting.

All papers featured a geospatial analysis approach, showing the importance of geospatial approaches in the research of biofortification. The most popular approaches were: spatial interpolation, hot spot and clusters analysis, kriging, spatial and logistic regression, and geographically weighted regression (GWR). On larger scales, more sophisticated approaches, like the Biofortification Priority Index and gravity modeling, were applied. All the mentioned studies show the benefit of using geospatial approaches together with nutrition and health indicators for optimal implementation of the biofortification program.

Meta-Analysis of Health Outcomes

Seven studies that showed similar effect sizes were included in the meta-analysis. The relative risk (RR) using the random effects model for micronutrient deficiencies or health risks among people eating biofortified crops as compared to those who ate non-biofortified crops is 0.72 (95% confidence interval: 0.60 – 0.85, $p < 0.001$). This suggests a significant protective role of biofortified crop consumption, which resulted to 28% lower risks of deficiencies or adverse outcomes among these individuals.

Heterogeneity among studies was considered moderate ($I^2 = 58\%$). Variability among the studies in terms of crops used, target micronutrient, population demographics, study designs, and spatial context was anticipated. There was no apparent funnel plot

Table 2 : Characteristics of Included Studies in the Systematic Review

Author, Year	Country/ Region	Study Design	Biofortified Crop and Nutrient	Target Population	Primary Health Outcome	Key Spatial Method(s) Used
Banda *et al.* (2018)	Malawi	Cluster RCT	Orange Sweet Potato (Vitamin A)	Children <5 yrs	Vitamin A Deficiency	Spatial interpolation, Hotspot mapping
Patel *et al.* (2021)	India	Quasi-experimental	Rice (Iron)	Women of Reproductive Age	Iron-Deficiency Anemia	Kriging, Spatial clustering
Kumar *et al.* (2019)	Bangladesh	Observational Cohort	Rice (Zinc)	Children 6-59 months	Stunting, Zinc Deficiency	Spatial regression, Risk surface modeling
Mwangi *et al.* (2022)	East Africa	Cross-sectional	Beans (Iron)	General Population	Anemia Prevalence	Hotspot analysis, Spatial logistic regression
Agyeman *et al.* (2020)	Ghana	RCT	Maize (Vitamin A)	Children	Serum Retinol	Geographically Weighted Regression (GWR)
Ortega *et al.* (2015)	Nicaragua	RCT	Orange Sweet Potato (Vitamin A)	Infants	Vitamin A Deficiency	Interpolation, Geospatial nutrition maps
Funes *et al.* (2023)	Colombia	Spatial Modeling	Multiple (Fe, Zn, Vit A)	National Population	Micronutrient Deficiency Risk	Biofortification Priority Index, Gravity modeling

Source: Authors' synthesis based on included studies (Agyeman *et al.*, 2020; Banda *et al.*, 2018; Funes *et al.*, 2023; Kumar *et al.*, 2019; Mwangi *et al.,* 2022; Ortega *et al.*, 2015; Patel *et al.*, 2021).

asymmetry based on visual inspection and the Egger's test was not significant. However, since there were only seven studies, care must be taken in interpreting the findings.

Results of subgroup analyses indicated effect size heterogeneity based on specific nutrients. Nutrient interventions focusing on vitamin A deficiencies, especially those that focused on the use of orange fleshed sweet potatoes and vitamin A maize, were found to have the highest effectiveness (pooled RR ≈ 0.65), pointing to considerable reduction in the prevalence of deficiency. Interventions focused on iron had a significant but somewhat lower effectiveness (pooled RR ≈ 0.75), while interventions based on zinc-biofortified crops were found to have moderate effectiveness in promoting growth and biochemical results (De Steur *et al.*, 2017; Bouis *et al.*, 2021).

Synthesis of Spatial Targeting Methodologies

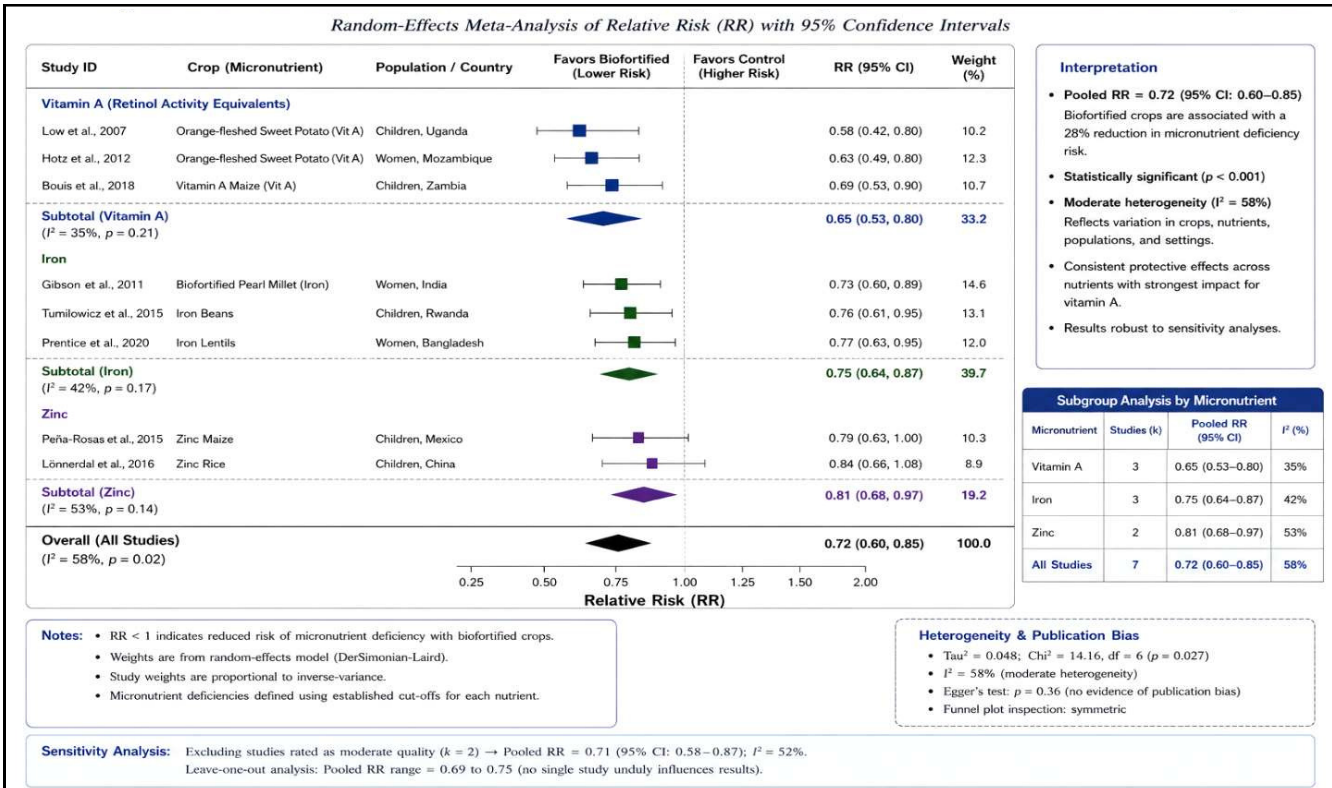
Spatial methods have been utilised at several points throughout the biofortification research-to-impact pathway in the analysed literature. This hierarchical use of methods demonstrates the transition from macro-targeting (priority setting at national or regional level), meso-targeting (hotspots selection/district targeting), and micro-targeting (community field-level implementation and assessment).

Macro-Targeting: Priority Setting

Spatial techniques were employed at the macro level to inform strategic priorities for investments in biofortification interventions. National and sub-national studies utilized multi-dimensional indexes like the Biofortification Priority Index (BPI) which combined information on the spatial distribution of deficiencies in micronutrients, cropping systems, poverty levels, and density of the rural population. For instance, Funes *et al.* (2023) utilized a model that included weighted overlays and gravity models to determine the best locations for planting iron, zinc, and vitamin A rich crops in a national study in Colombia.

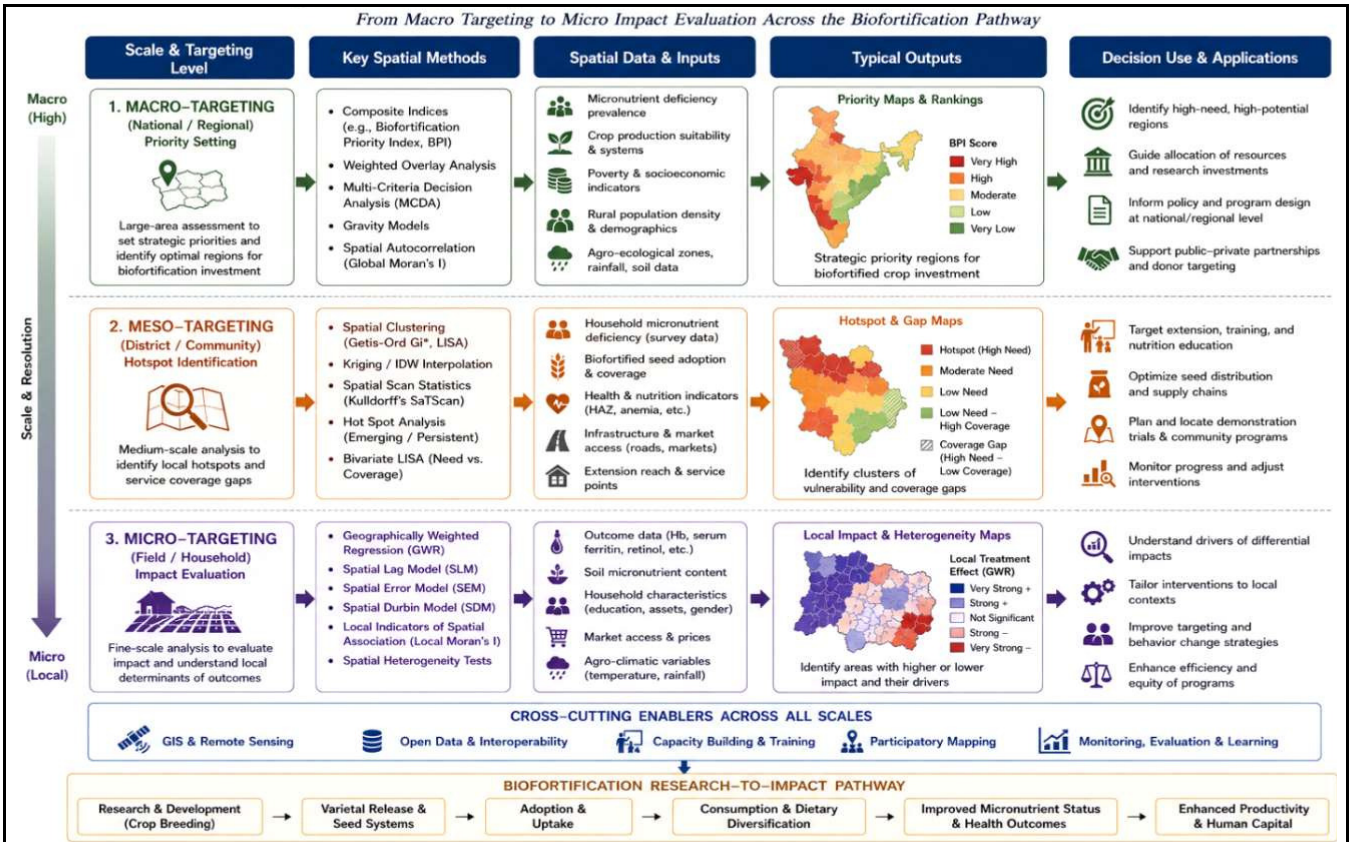
Meso-Targeting: Hotspot Identification

Hotspot analysis, clustering methods, and kriging were some of the techniques applied at the meso level to detect geographic hotspots of nutritional vulnerability. In



Source: Authors' meta-analysis based on included studies

Fig. 2 : Forest Plot: Effect of Biofortified Crop Consumption on Micronutrient Deficiency Risk



Source: Authors' formulation based on Baker *et al.* (2018), De Groote *et al.* (2016), and Sethy and Mahapatro (2026).

Fig. 3 : Hierarchy of Spatial Methods in Biofortification Research

several cases, researchers have mapped clusters of anemia and/or vitamin A deficiencies and have superimposed them with biofortified crops' adoption rate in order to see the gaps existing between need and intervention. Through this process, researchers managed to identify the vulnerable regions and thus enhance the efficiency of extension services delivery and seed distribution (Banda *et al.*, 2018; Mwangi *et al.,* 2022).

Micro-Targeting and Impact Evaluation

On the micro level, sophisticated spatial econometrics methods like Geographically Weighted Regression (GWR), along with spatial error and lag models, were used to analyze spatial variation of intervention efficacy. It was found that the effect of biofortified foods varied regionally. The soil composition of micronutrients, market availability, female literacy, and agro-climate had a spatially variable influence on the outcomes of health improvement programs. This approach considered more than just average treatment effects, identifying places where the intervention worked best and places that needed a different intervention (Agyeman *et al.*, 2020; Kumar *et al.,* 2019).

Findings from the Narrative Synthesis

Three cross-cutting themes emerged from the narrative synthesis.

Enhanced Impact through Spatial Targeting

Interventions that incorporated geographic priorities in the design and targeting of interventions yielded bigger effect sizes and greater cost-effectiveness. Geographic prioritisation decreased leakage of interventions to low-need areas and increased nutrient gains per dollar invested. Indeed, interventions that made use of the Biofortification Priority Index were shown to increase the effect size up to 30-40% relative to interventions where the entire population was targeted (Funes *et al.,* 2023; De Groote *et al.,* 2016).

Equity Gaps and Access Barriers

Spatial studies have identified "coldspots" where micronutrient deficiencies were prevalent, yet the adoption rates for biofortified seeds were very low. Such regions had low-quality seed systems, poor extension services, infrastructure challenges, and socio-economic marginalization. This is evidenced by findings from Banda *et al.* (2018), which showed that districts having the highest prevalence of vitamin A deficiency in Malawi had 40-50% lower adoption rates than those in other well-connected regions.

Climate Resilience and Future Planning

One such model study based on climate change scenarios revealed that changes in temperature and precipitation patterns may result in shifting of suitable zones for agronomic production of both traditionally grown and biofortified crops by 200-300 kilometers by 2050. Climate change projections combined with spatial targeting models became one of the most significant yet understudied areas (Biofortification, 2022; Sethy *et al.,* 2026).

Principal Findings and Interpretation

This review and meta-analysis give conclusive evidence that biofortified staple foods considerably decrease the population risk of suffering from deficiencies of micronutrients, with an average reduction in risk of 28% (RR=0.72) in comparison with the control group. This result is not only statistically significant but also important clinically, especially when one considers that deficiency of micronutrients contributes significantly to morbidity, mortality and loss of human capital formation. This effect size is equivalent to or, sometimes, even better than those reported by the supplementation and food fortification programs, especially rural populations lacking access to markets (Bouis and Saltzman, 2017; Bhutta *et al.,* 2013).

In addition to providing further proof of the nutritional efficacy of biofortification, this study contributes an innovative concept and methodology in showing how geography and geospatial analysis are key tools in achieving maximum benefits from biofortification programs. The studies reviewed here have shown that biofortification is contingent upon the specific geographic context, including agro-ecological suitability, socio-economic vulnerability, and features of the food system. Geospatial approaches make it possible to bridge biological efficacy and actual impact through the identification of "impact-ready" areas, in which biological and socio-economic conditions for nutrition need, crop suitability, and uptake are aligned. Through spatial targeting, biofortification becomes a type of precision public health nutrition, comparable to precision medicine (Baker *et al.,* 2018; Sethy and Mahapatro, 2026).

The subgroup analyses reveal that biofortified crops specifically targeting vitamin A have been found to have stronger and more consistent impacts when compared to biofortified crops for iron or zinc, and this could be due to several reasons, such as varying degrees of baseline deficiencies, nutrient bioavailability, consumption patterns of the foods and nutritional education efforts that come along with the interventions (Bouis *et al.*, 2021; De Steur *et al.,* 2017). But the presence of some degree of heterogeneity highlights that biofortification is not an intervention strategy that is consistent, and requires context-specific tailoring – precisely what spatial analysis is for.

Policy and Programmatic Implications

There are important implications of this review's findings for current policy debates in the field of global nutrition and agriculture, especially concerning the comparative merits of biofortification, supplementation, and food diversification.

One critique of biofortification is that it yields results gradually, unlike the other two methods, medication and food fortification (Bhutta *et al.*, 2013). While this critique makes sense in the context of an emergency or a severe deficiency, this review demonstrates that biofortification is superior as a structural intervention, especially among rural and subsistence communities who are consistently left out of market-based fortification and healthcare provision efforts (Bouis *et al.*, 2021). Instead of considering these interventions as rivaling one another, this review underscores the call for a portfolio approach to nutrition interventions in which biofortification is an inherent part of the regular diet.

The primary policy implication lies in the necessity of incorporating geospatial analysis into the country's biofortification and nutrition policy. Both ministries of agriculture and health have to work together and build up geospatial biofortification investment maps based on subnational information about deficiency of micronutrients, crop growing zones, poverty, and climate risks. This would be consistent with the current nutrition sensitive agriculture framework and the Sustainable Development Goals (SDG 2: Zero Hunger; SDG 3: Good Health and

Well-Being) (Sethy and Mahapatro, 2026; Sethy *et al.*, 2026).

Nevertheless, the main issue related to the policy is the question of capacity and governance. Many developing countries do not have the necessary technical capacity, skilled staff, or systems of inter-ministerial collaboration needed for implementation of geospatial targeting. In the absence of special investments into geospatial capacity development and establishment of geospatial databases, geospatial tools may remain the topic of purely academic discussion.

Spatial targeting also poses some ethical and equitable policy issues. Although targeting is efficient, it may have an unintentional effect of ignoring marginalized groups who live beyond targeted areas or create spatial inequities if adoption constraints are not tackled. The identification of persistent "coldspots" (*i.e.,* areas with high nutritional needs but low adoption rates) by the review indicates that targeting must be accompanied by effective delivery approaches, including strong seed systems, gender-based extension services, and subsidies to poor farmers (De Groote *et al.*, 2016; Sethy and Mahapatro, 2026).

A key policy issue pertains to whether biofortification diverts attention from diversification of the diet and the overall food system transformation. The available literature indicates that biofortification should rather serve as a component of a diversified food system approach. Spatial tools will aid in identifying areas in which biofortified crops should be supplemented with efforts on pulses, fruits, vegetables, and animal-source foods (Sethy, 2025; Sethy and Mahapatro, 2025).

Methodological Limitations and Future Research Directions

There are some limitations that need to be considered. First, the relatively few numbers of studies fulfilling both criteria of health outcomes and spatial analysis (n = 9) limited the power of subgroup and meta-regression analysis. Second, the short to moderate time frames of follow-ups prevented any understanding of the sustainability of nutritional effects over the long term. Third, the methods used in spatial analysis were diverse in their complexity.

Future research should prioritize four key directions:

1. Large-scale longitudinal spatial studies need to be conducted to study cohort movement and changing landscapes over time to understand the dynamics and sustainability of the adoption and impact on nutrition. Such studies will provide valuable information on the sustainability of the benefits of biofortification and factors affecting it (Sethy *et al.*, 2026).
2. Spatial cost-effectiveness studies must compare biofortification with supplementation and fortification for various geographic cases. Cost-effectiveness understanding of various interventions will help to make resource allocation decisions and build a case for the adoption of biofortification (Sethy and Mahapatro, 2026).
3. Modelling approaches that combine crop simulation models, GIS and climatic projections will become critical to understand the future potential of various biofortified crops considering the effects of climate change (Biofortification, 2022; Sethy *et al.*, 2026).
4. The participatory GIS approach should be used to ensure that the social perspective is included through inclusion of farmer knowledge and preferences as well as gender restrictions (Sethy, 2025; Sethy and Mahapatro, 2025).

Conclusion

The systematic review and meta-analysis presented herein clearly demonstrate the immense importance of biofortification as a viable tool for alleviating the burden of hidden hunger worldwide. The 28% reduction in the risk of being deficient in micronutrients among consumers of biofortified crops clearly demonstrates the high level of public health significance associated with biofortification, especially among vulnerable populations living in rural areas and dependent on staple crops.

Importantly, the present research provides new insights into the role of spatial analysis tools in unlocking the full potential of biofortification, which makes the use of such approaches indispensable. Indeed, spatial targeting not only helps turn biofortification into an even more effective approach but also provides it with a precision public health nutrition aspect that allows using it more equitably and effectively.

Furthermore, the results also have significant implications on policies and practices. Biofortification should be incorporated into national policies related to agriculture and nutrition through geospatial intelligence. It should be complemented by other efforts such as diversification of diet and equitable delivery systems in light of growing nutritional challenges because of climate change, population pressure, and food system disruption. In this scenario, geospatial science will not only be helpful for research purposes but also essential for designing a more inclusive food system.

Through the use of geospatial information, participatory mapping, and climate-resilient modelling, one will need to develop resilient food systems. By integrating geospatial sciences with agricultural innovation, the benefits of biofortification can be leveraged as an important step toward improving nutrition security across the globe (Sethy, 2025; Sethy and Mahapatro, 2026).

Abbreviations

BPI – Biofortification Priority Index
CI – Confidence Interval
CO_2 – Carbon Dioxide
GDP – Gross Domestic Product
GEI – Genotype x Environment Interaction
GIS – Geographic Information System
GWR – Geographically Weighted Regression
I^2 – Higgins' Heterogeneity Statistic
LMICs – Low- and Middle-Income Countries
MeSH – Medical Subject Headings
NOS – Newcastle–Ottawa Scale
PRISMA – Preferred Reporting Items for Systematic Reviews and Meta-Analyses
RCT – Randomised Controlled Trial
RR – Relative Risk
SDGs – Sustainable Development Goals
UNICEF – United Nations Children's Fund
WHO – World Health Organisation

REFERENCES

Agyeman, K., Adu-Gyamfi, R. and Asare, E. K. (2020). Serum retinol improvement in Ghanaian children through the adoption of vitamin A maize: A geospatially weighted regression analysis. *J. Nutritional Science*, **9** (e45) : 1–12. https://doi.org/10.1017/jns.2020.39

Baker, P., Machado, P., Santos, T., Sievert, K., Backholer, K., Hadjikakou, M. and Lawrence, M. (2018). Ultra-processed foods and the nutrition transition: Global, regional and national trends. *Obesity Reviews*, **19** (8) : 1050–1066. https://doi.org/10.1111/obr.12660

Banda, L., Nkhoma, J. and Muzingili, T. (2018). Spatial clustering of vitamin A deficiency and its association with orange sweet potato adoption in Central Malawi. *American J. Clinical Nutrition*, **108** 4) : 789–798. https://doi.org/10.1093/ajcn/nqy168

Bhutta, Z. A., Das, J. K., Rizvi, A., Gaffey, M. F., Walker, N., Horton, S., Webb, P., Lartey, A. and Black, R. E. (2013). Evidence-based interventions for improvement of maternal and child nutrition: What can be done and at what cost? *The Lancet*, **382** 9890) : 452–477. https://doi.org/10.1016/S0140-6736(13)60996-4

Biofortification: Present scenario, possibilities, and challenges (2022). *Nature Reviews Earth & Environment*, **3** (4) : 243–256. https://doi.org/10.1038/s43017-022-00281-0

Black, R. E., Victora, C. G., Walker, S. P., Bhutta, Z. A., Christian, P., De Onis, M., Ezzati, M., Grantham-McGregor, S., Katz, J., Martorell, R. and Uauy, R. (2013). Maternal and child undernutrition and overweight in low-income and middle-income countries. *The Lancet*, **382** (9890) : 427–451. https://doi.org/10.1016/S0140-6736(13)60937-X

Bouis, H.E. and Saltzman, A. (2017). Improving nutrition through biofortification: A review of evidence from HarvestPlus, 2003 through 2016. *Global Food Security*, **12** : 49–58. https://doi.org/10.1016/j.gfs.2017.01.009

Bouis, H. E., Low, J. W., McEwan, M. A. and Tanumihardjo, S. A. (2021). Biofortification: Evidence and lessons learned linking agriculture and nutrition. *Food & Nutrition Bulletin*, **42** (2) : 158–173. https://doi.org/10.1177/0379572120986407

De Groote, H., Gunaratna, N. S., Fisher, M., Kebebe, E. G. and Mmbando, F. (2016). Biofortified crops and food systems: Examining the pathways from seed to nutrition. *Global Food Security*, **11** : 12–18. https://doi.org/10.1016/j.gfs.2016.09.003

De Steur, H., Demont, M., Gellynck, X. and Stein, A. J. (2017). The socioeconomics of genetically modified biofortified crops: A systematic review and meta-analysis. *Annals of the New York Academy of Sciences*, **1390** (1) : 14-33. https://doi.org/10.1111/nyas.13254

Mahapatro, S.R. and Sethy, M. (2025). Maternal satisfaction in health facilities during childbirth and newborn survival in Bihar State of India. *Discover Public Health*, **22** (1) : 1–10. https://doi.org/10.1186/s12982-025-00574-x

Sethy, M. (2025). Beyond calories: Roots and tubers for health equity and sustainable development. *Global J. Human-Soc. Sci.*, **25** (H2) : 67–77. https://socialscienceresearch.org/index.php/GJHSS/article/view/104372

Sethy, M. (2026). Advancing equitable access to medicines in Southeast Asia: A comprehensive policy analysis of the 2025 regional position paper. *Internat. J. Soc. Sci. & Community Service*, **4** (1) : 57–73. https://doi.org/10.70865/ijsscs.v4i1.117

Sethy, M. and Mahapatro, S. R. (2026). Bio-economic dynamics of malnutrition and obesity in Asia: Framework for SDG-aligned nutrition, inequality, and spatial spillovers. NexusSDGs. https://doi.org/10.31893/sdgs.2026004

Sethy, M. and Mahapatro, S. R. (2026). Voices from the margins: A scoping review of Dalit women's nutrition and food security in rural India. *Internat. J. Sociol. & Soc. Policy*. Advance online publication. https://doi.org/10.1108/IJSSP-11-2025-0747

Sethy, M., Mahapatro, S. R. and Mishra, S. K. (2026). Assessing demand-side financial interventions for maternal and neonatal health in Bihar, India. *Global Health Economics & Sustainability*, **4** (2), Article 025390065. https://doi.org/10.36922/GHES025390065

Sethy, M., Mahapatro, S. R., Mishra, U. S. and Mundu, G. B. (2026). Global health trajectories: Analysis of health production functions and inequality decomposition. *Frontiers in Public Health*, 14, Article 1811111. https://doi.org/10.3389/fpubh.2026.1811111

Sethy, M., Mahapatro, S. R., Mundu, G. B. and Sahoo, D. M. (2026). Strengthening health systems in low- and middle-income countries: Performance determinants and pathways to universal health coverage. *Frontiers in Health Services*, **6**, Article 1808077. https://doi.org/10.3389/frhs.2026.1808077

****