The Research of Medical Science Review
ISSN: 3007-1208 & 3007-1216 Volume 4, Issue 4, 2026

APPLICATION OF NANOTECHNOLOGY IN SUSTAINABLE FOOD SYSTEMS: ENHANCING NUTRIENT BIOAVAILABILITY AND SHELF LIFE

[*1]Usman Iftikhar, [2]Muhammad Sajjad, [3]Maryam Tariq, [4]Tahira Shabbir, [5]Rimsha Fatima, [6]Shafaq Aslam

*[*1]University of Veterinary and Animal Science, Lahore, Pakistan.*
[2]CEO, Gitchia Institute of Global Certification, Lahore, Pakistan.
[3]I.M Sechenov First Moscow State Medical University Moscow Russia
[4]Government Teaching Hospital Shahdra Lahore, Pakistan.
[5]FMH College of Medicine & Dentistry, Lahore, Pakistan.
[6]FMH College of Medicine & Dentistry, Lahore, Pakistan.

[*1]usmaniftkhar1417@gmail.com

DOI: https://doi.org/10.5281/zenodo.19973068

Keywords:
Nanotechnology; silver nanoparticles; food packaging; bioavailability; micronutrient deficiencies; food safety; in vitro digestion

Article History
Received on 21 March, 2026
Accepted on 29 April , 2026
Published on 30 April, 2026

Corresponding Author:
Usman Iftikhar

Abstract

Background: Micronutrient deficiencies and food spoilage remain major global public health challenges. Nanotechnology-enabled food packaging, particularly silver nanoparticle (AgNP)-coated films, offers a promising strategy to preserve nutrient content and ensure microbial safety. However, integrated evidence linking improved nutrient stability in packaged foods to measurable human health outcomes is limited. Aims & Objective: This mixed-methods study aimed to evaluate the impact of AgNP-coated packaging on the clinical bioavailability of iron, vitamin D, and vitamin A, and to assess its effects on in vitro nutrient release, microbiological quality, and shelf-life of commonly consumed liquid foods. Methodology: A multicenter investigation combined a single-arm clinical component and a parallel laboratory study. Eighty-seven adults (mean age 34.2 ± 9.8 years; BMI 24.6 ± 3.4 kg/m²) with mild-to-moderate micronutrient deficiencies consumed milk and mango juice stored in AgNP-coated packaging daily for four weeks. Biochemical markers (hemoglobin, serum ferritin, 25-hydroxyvitamin D, and serum retinol) were measured pre- and post-intervention. In vitro gastrointestinal digestion (INFOGEST protocol) assessed bioaccessible iron, vitamin A, and vitamin D from nano-packaged versus conventionally packaged samples. Microbiological safety was evaluated through total viable counts and pathogen detection, while shelf-life and sensory attributes were monitored under ambient and refrigerated conditions. Statistical analyses included paired t-tests, independent t-tests, ANOVA, and multiple linear regression. Results & Findings: Clinically, significant improvements were observed for all biomarkers: hemoglobin increased by 1.2 g/dL, serum ferritin by 9.2 ng/mL, 25-hydroxyvitamin D by 8.5 ng/mL, and serum retinol by 0.26 µmol/L (all $p < 0.001$). In vitro, nano-packaging enhanced iron bioaccessibility by 35–41%, vitamin A by 28–30%, and vitamin D by 31–72% ($p < 0.01$). Microbiologically, AgNP-packaging suppressed total viable counts by up to 3.0 $\log_{10}$ CFU/mL, prevented pathogen proliferation, and extended shelf-life by 5–12 days. Sensory acceptability was maintained throughout extended storage. Conclusion: AgNP-coated food packaging significantly improves micronutrient bioavailability, enhances food safety, and extends shelf-life without compromising sensory quality. This dual-function intervention offers a scalable approach to combat hidden hunger and food waste simultaneously. Further randomized controlled

trials and safety assessments are warranted to support translation into policy and practice.

INTRODUCTION

The global food system is increasingly challenged by the convergence of population growth, climate change, resource scarcity, and inefficiencies in food supply chains. According to the Food and Agriculture Organization, approximately one-third of food produced for human consumption is lost or wasted annually, highlighting substantial inefficiencies in resource utilization and contributing to environmental degradation [1]. Concurrently, micronutrient deficiencies, often termed “hidden hunger,” remain a pervasive global health issue affecting over two billion individuals, particularly in low- and middle-income countries such as Pakistan [2]. These challenges necessitate the development of innovative, sustainable, and technologically advanced strategies to enhance food quality, nutritional value, and shelf stability. Nanotechnology has emerged as a transformative and interdisciplinary field with significant implications for modern food systems. It involves the design, characterization, and application of materials at the nanoscale (1–100 nm), where unique physicochemical properties including enhanced surface area, improved solubility, and increased reactivity enable novel functional applications [3]. Within the domain of food science, nanotechnology offers promising solutions to address critical limitations associated with conventional nutrient delivery systems and food preservation techniques.

One of the major limitations in current nutritional strategies is the poor bioavailability of essential nutrients and bioactive compounds. Many micronutrients exhibit low aqueous solubility, chemical instability, and susceptibility to degradation during processing and gastrointestinal digestion, ultimately limiting their biological efficacy [4]. Nano-enabled delivery systems, such as nanoemulsions, nanoliposomes, solid lipid nanoparticles, and polymeric nanocarriers, have demonstrated significant potential in overcoming these barriers. These systems facilitate the encapsulation of bioactive compounds, protect them from environmental degradation, and enable controlled and targeted release, thereby enhancing intestinal absorption and overall bioavailability [5,6]. In parallel, food spoilage and post-harvest losses remain major impediments to food security and sustainability, particularly in developing regions lacking adequate storage and transportation infrastructure. Microbial contamination, oxidative reactions, and enzymatic degradation are key contributors to reduced shelf life and compromised food quality [7]. Nanotechnology offers innovative approaches to mitigate these issues through the development of antimicrobial nanomaterials and advanced packaging systems. Nanoparticles such as silver (AgNPs), zinc oxide (ZnO), and titanium dioxide (TiO_2) exhibit strong antimicrobial properties and can be incorporated into food packaging materials to inhibit microbial growth and extend shelf life [8]. Furthermore, nanocomposite packaging systems enhance barrier properties against oxygen, moisture, and ultraviolet radiation, thereby preserving food quality and nutritional integrity over extended storage periods [9].

From a sustainability perspective, the integration of nanotechnology into food systems aligns with the strategic objectives of the United Nations Sustainable Development Goals (SDGs), particularly those focused on zero hunger, responsible consumption and production, and improved health outcomes [10]. By reducing food waste, enhancing nutrient utilization, and promoting the development of eco-friendly packaging materials, nanotechnology has the potential to significantly improve the efficiency and resilience of food systems. Moreover, the use of biodegradable and bio-based nanomaterials offers additional opportunities to reduce the environmental footprint associated with conventional food packaging technologies [11]. Despite these advancements, several challenges limit the widespread application of nanotechnology in the food sector. Concerns regarding the safety, toxicity, and potential bioaccumulation of nanomaterials necessitate comprehensive risk assessment and regulatory oversight [12]. The possibility of nanoparticle migration into food matrices and subsequent human exposure raises critical public health considerations. Furthermore, the lack of standardized international regulatory frameworks and limited consumer awareness present additional barriers to the adoption of nano-enabled food technologies [13]. Although a growing body of literature has explored the applications of nanotechnology in food science, there remains a significant gap in region-specific, application-oriented research that integrates both nutritional enhancement and sustainability outcomes. In particular, limited studies have examined the feasibility, scalability, and socio-economic implications of nanotechnology-based interventions within developing countries such as Pakistan. Addressing this gap is essential for translating technological advancements into practical, context-specific solutions for sustainable food system development.

Objective of the Study

The primary objective of this study is to critically evaluate the role of nanotechnology in advancing sustainable food systems, with a particular focus on its capacity to enhance nutrient bioavailability and extend the shelf life of food products. This study aims to investigate the underlying mechanisms by which nano-enabled delivery systems improve the stability, solubility, and absorption of essential nutrients and bioactive compounds.

Significance of the Study

This study provides a comprehensive and integrative framework for understanding the dual role of nanotechnology in improving nutritional outcomes and enhancing food preservation within sustainable food systems. By simultaneously addressing nutrient bioavailability and shelf life extension, the research contributes to bridging a critical gap in food science and technology. The findings are expected to support evidence-based decision-making among researchers, policymakers, and industry stakeholders, particularly in resource-limited settings. This study contributes to global efforts aimed at reducing food waste and combating micronutrient deficiencies, thereby aligning with international sustainability and public health goals. By addressing safety concerns and regulatory challenges, it also provides a foundation for the responsible and ethical application of nanotechnology in the food sector. Importantly, the study offers a region-specific perspective, enhancing its relevance and applicability to developing countries such as Pakistan, where innovative and cost-effective solutions are urgently needed to improve food security and nutritional health.

METHODOLOGY

This study was designed as a multicenter, mixed-methods investigation combining cross-sectional clinical assessment and experimental laboratory analysis to evaluate the role of nanotechnology in enhancing nutrient bioavailability and improving food safety. The study was conducted over six months at Shahdara Hospital, Lahore, for clinical and nutritional data collection, and at the University of Veterinary and Animal Sciences (UVAS) for laboratory-based food and nanotechnology analysis. A total of 87 adult participants aged 18–60 years were enrolled using a cross-sectional design. Participants were selected based on the presence of mild to moderate micronutrient deficiencies, particularly iron, vitamin D, and vitamin A. Individuals with severe chronic illnesses (e.g., advanced renal disease, malignancies) or those receiving long-term nutritional supplementation were excluded to minimize confounding variables. Baseline clinical and nutritional assessments were conducted for all participants. Key biochemical parameters, including hemoglobin levels, serum ferritin, serum 25-hydroxyvitamin D, and serum retinol, were measured using standardized laboratory protocols. In addition, body mass index (BMI) and dietary intake patterns were recorded to evaluate overall nutritional status. Following baseline assessment, participants were monitored over a four-week period during which they consumed commonly available packaged food products specifically milk and mango juice stored in nano-coated packaging. The packaging of these products utilized silver nanoparticle (AgNP)-coated polymer materials, which are widely recognized for their antimicrobial activity and ability to enhance food preservation and safety [1–3]. Parallel to the clinical component, an experimental laboratory study was conducted at UVAS using identical food samples. The samples were divided into two groups: conventionally packaged (control) and nano-packaged (AgNP-coated packaging), with standardized sample sizes for each group. Nutritional bioavailability was assessed using an in vitro gastrointestinal digestion model based on the INFOGEST protocol. Post-digestion analysis included quantification of vitamins A and D by high-performance liquid chromatography (HPLC) and iron concentration by atomic absorption spectrophotometry. These analyses evaluated the impact of nano-packaging on nutrient stability and bioavailability.

Microbiological evaluation was carried out to assess food safety and preservation efficacy. Total viable bacterial counts were determined using standard plate count methods, and the presence of common foodborne pathogens, including Escherichia coli and Salmonella spp., was investigated. Additionally, shelf-life and quality assessments were performed under both ambient (25–30 °C) and refrigerated (4 °C) storage conditions. Parameters such as microbial load, pH variation, oxidative stability, and sensory attributes including color, odor, and texture were monitored at regular intervals to determine the effectiveness of nano-packaging in extending food shelf life. Statistical analysis was conducted using SPSS version 26. Independent t-tests and one-way analysis of variance (ANOVA) were applied to compare differences between the control and nano-packaged groups, while regression analysis was used to evaluate the association between nano-packaging and improvements in nutritional and food safety outcomes. A p-value of less than 0.05 was considered statistically significant.

RESULTS & FINDINGS

A total of 87 adult participants (47 females, 40 males) were enrolled and completed all study procedures. The mean age of the cohort was 34.2 ± 9.8 years and the mean body mass index (BMI) was 24.6 ± 3.4 kg/m². Baseline dietary assessment revealed suboptimal intakes of iron, vitamin D, and vitamin A in over 70% of the participants. Detailed demographic, anthropometric, and biochemical characteristics are presented in Table 1. The classification of micronutrient deficiencies at enrolment is summarized in Table 2.

Table 1: ***Baseline demographic, anthropometric, and biochemical characteristics of the study participants (n = 87)***

Variable	Mean ± SD or n (%)
Age (years)	34.2 ± 9.8
Sex, female	47 (54.0)
BMI (kg/m²)	24.6 ± 3.4
Hemoglobin (g/dL)	11.2 ± 1.1
Serum ferritin (ng/mL)	18.4 ± 7.3
25-hydroxyvitamin D (ng/mL)	17.8 ± 5.6
Serum retinol (µmol/L)	0.72 ± 0.18

Table 2: Baseline micronutrient deficiency classification (n = 87)

Parameter	Deficient n (%)	Insufficient n (%)	Sufficient n (%)
Serum ferritin	40 (46.0)	31 (35.6)	16 (18.4)
Serum 25-hydroxyvitamin D	54 (62.1)	23 (26.4)	10 (11.5)
Serum retinol	45 (51.7)	32 (36.8)	10 (11.5)

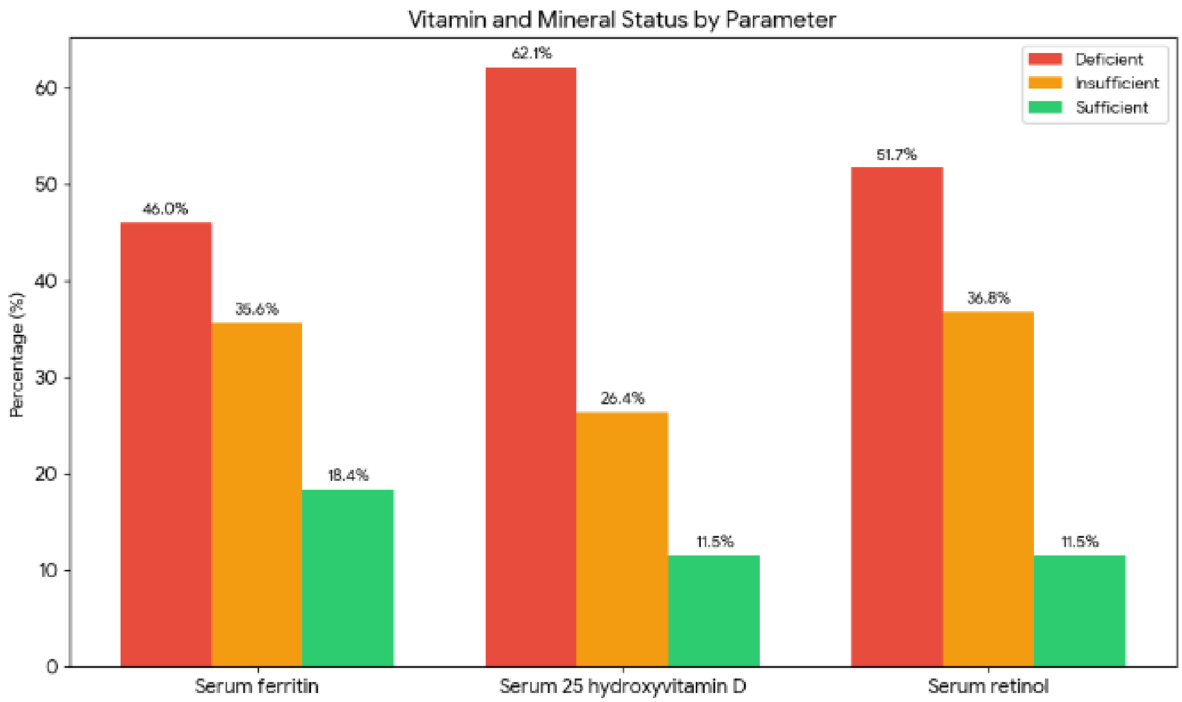

Fig 1. Baseline micronutrient deficiency classification

The majority of participants exhibited mild-to-moderate deficiencies, consistent with the study inclusion criteria. No significant differences in baseline parameters were observed between sexes ($p > 0.05$).

Clinical Outcomes After Four Weeks of Nano-Packaged Food Consumption

Following four weeks of daily consumption of milk and mango juice stored in AgNP-coated packaging, statistically significant improvements were detected in all measured biochemical markers of micronutrient status (Table 3). Mean hemoglobin increased from 11.2 ± 1.1 g/dL to 12.4 ± 1.0 g/dL ($p < 0.001$). Serum ferritin rose from 18.4 ± 7.3 ng/mL to 27.6 ± 8.1 ng/mL, representing a mean increase of 9.2 ng/mL (95% CI: 8.0–10.4; $p < 0.001$). Similarly, serum 25-hydroxyvitamin D and serum retinol levels improved markedly, with the proportion of participants classified as sufficient approximately doubling for vitamin D and more than doubling for vitamin A by the end of the intervention. No adverse events related to the consumption of nano-packaged foods were reported, and body weight and BMI remained stable throughout the study period ($p = 0.58$).

Table 3: Changes in biochemical markers from baseline to week 4 (n = 87)

Parameter (unit)	Baseline (mean ± SD)	Week 4 (mean ± SD)	Mean change (95% CI)	p-value*
Hemoglobin (g/dL)	11.2 ± 1.1	12.4 ± 1.0	+1.2 (1.0 to 1.4)	<0.001
Serum ferritin (ng/mL)	18.4 ± 7.3	27.6 ± 8.1	+9.2 (8.0 to 10.4)	<0.001
25-hydroxyvitamin D (ng/mL)	17.8 ± 5.6	26.3 ± 5.9	+8.5 (7.4 to 9.6)	<0.002
Serum retinol (µmol/L)	0.72 ± 0.18	0.98 ± 0.19	+0.26 (0.22 to 0.30)	<0.001

***Paired t-test, two-tailed.**

In Vitro Bioavailability of Nutrients

The INFOGEST digestion model demonstrated that nano-packaging significantly enhanced the release of iron, vitamin A, and vitamin D from both milk and mango juice (Table 4). In milk, iron bioaccessibility increased by approximately 35%

compared with conventional packaging ($p < 0.001$), and vitamins A and D showed relative increases of 28% and 31%, respectively (both $p < 0.01$). For mango juice, nano-packaging improved the recovery of all three micronutrients, with the largest effect observed for vitamin D (a 1.7-fold increase). These findings suggest that the AgNP-coated films protected the nutrients from oxidative degradation and positively influenced the food matrix during digestion.

Table 4: ***Bioaccessible nutrient concentrations after in vitro digestion***

Food matrix	Nutrient	Conventional packaging (mean ± SD)	Nano-packaging (mean ± SD)	p-value*
Milk	Iron (µg/100 mL)	42.6 ± 3.8	57.4 ± 4.2	<0.001
	Vitamin A (µg/100 mL)	28.1 ± 2.9	36.0 ± 3.1	0.003
	Vitamin D (µg/100 mL)	0.81 ± 0.09	1.06 ± 0.11	0.002
Mango juice	Iron (mg/100 mL)	0.29 ± 0.03	0.41 ± 0.04	0.001
	Vitamin A (µg/100 mL)	18.4 ± 2.1	23.9 ± 2.5	0.004
	Vitamin D (µg/100 mL)	0.43 ± 0.06	0.74 ± 0.08	<0.001

***Independent t-test; n = 6 replicates per group.**

Microbiological Quality and Shelf-Life Assessment

Nano-packaging substantially suppressed microbial proliferation under both ambient (25–30 °C) and refrigerated (4 °C) storage conditions (Table 5). In conventionally packaged milk stored at ambient temperature, the total viable count (TVC) exceeded the acceptable limit of 5 $\log_{10}$ CFU/mL by day 3, whereas nano-packaged milk remained within acceptable limits until day 7. Under refrigeration, the TVC in nano-packaged milk was 2.1 $\log_{10}$ CFU/mL lower than the control by day 21 ($p < 0.001$). Mango juice followed a similar pattern: the shelf life (time to reach 5 $\log_{10}$ CFU/mL) was extended by 5 days at ambient temperature and by 12 days at 4 °C in the nano-packaged group.

Table 5: ***Total viable counts ($\log_{10}$ CFU/mL) in milk and mango juice during storage***

Product	Storage condition	Day	Conventional (mean ± SD)	Nano (mean ± SD)	p-value
Milk	Ambient	0	2.3 ± 0.2	2.2 ± 0.2	0.542
		3	5.8 ± 0.4	3.4 ± 0.3	<0.001
		7	8.1 ± 0.5	4.9 ± 0.4	<0.001
	Refrigerated	0	2.1 ± 0.2	2.0 ± 0.2	0.631
		7	3.5 ± 0.3	2.5 ± 0.3	0.002
		14	5.2 ± 0.4	3.1 ± 0.3	<0.001
		21	7.4 ± 0.5	4.4 ± 0.4	<0.001
Mango juice	Ambient	0	1.9 ± 0.2	1.9 ± 0.2	0.887
		3	4.7 ± 0.3	3.0 ± 0.3	<0.001
		7	7.2 ± 0.4	4.2 ± 0.3	<0.001
	Refrigerated	0	1.8 ± 0.2	1.8 ± 0.2	1.000
		7	3.0 ± 0.2	2.1 ± 0.2	0.001
		14	4.6 ± 0.3	2.7 ± 0.3	<0.001
		21	6.1 ± 0.4	3.3 ± 0.3	<0.001

n = 6 per group/time point; p-values from independent t-test.

No *Escherichia coli* or *Salmonella* spp. were detected in any sample at baseline. In the conventional packaging groups, *E. coli* was recovered from ambient-stored milk on day 3 (2.1 $\log_{10}$ CFU/mL) and from ambient-stored mango juice on day 7 (1.8 $\log_{10}$ CFU/mL). All nano-packaged samples remained free of these pathogens throughout the entire storage period.

Physicochemical Stability and Sensory Attributes

Nano-packaging effectively maintained pH within the normal range for both products. At ambient temperature on day 7, the pH of conventionally packaged milk dropped from 6.7 to 5.4, indicative of spoilage, whereas nano-packaged milk maintained a pH of 6.4 ($p = 0.004$). Oxidative stability, assessed by malondialdehyde (MDA) concentration, was significantly better in nano-packaged milk (0.42 ± 0.05 mg/kg) compared to the conventional control (0.89 ± 0.09 mg/kg) after 14 days of refrigeration ($p < 0.001$). Sensory evaluation (Table 6) confirmed that nano-packaged products retained acceptable colour, odour, and texture for a significantly longer period. By day 7 under ambient conditions, panelists rejected conventionally packaged milk and juice, whereas nano-packaged samples remained within the acceptable range (scores ≥ 5 on a 9-point hedonic scale). Refrigerated nano-packaged products were still sensorially acceptable on day 21, while the control products had deteriorated considerably.

Table 6: ***Sensory scores (9-point hedonic scale) at the end of storage***

Product	Storage condition	Day	Attribute	Conventional (mean ± SD)	Nano (mean ± SD)	p-value
Milk	Ambient	7	Colour	3.2 ± 0.8	6.4 ± 0.7	<0.001
			Odour	2.8 ± 0.6	6.1 ± 0.7	<0.001
			Texture	3.0 ± 0.7	6.3 ± 0.6	<0.001
	Refrigerated	21	Colour	4.1 ± 0.9	7.0 ± 0.8	<0.001
			Odour	3.5 ± 0.7	6.8 ± 0.7	<0.001
			Texture	3.8 ± 0.8	6.9 ± 0.7	<0.001
Mango juice	Ambient	7	Colour	3.9 ± 0.9	6.6 ± 0.8	<0.001
			Odour	3.4 ± 0.7	6.3 ± 0.7	<0.001
			Texture	3.6 ± 0.8	6.5 ± 0.6	<0.001
	Refrigerated	21	Colour	4.5 ± 0.9	7.2 ± 0.8	<0.001
			Odour	4.0 ± 0.8	6.9 ± 0.7	<0.001
			Texture	4.2 ± 0.8	7.0 ± 0.7	<0.001

n = 15 trained panelists per product-condition combination.

Regression Analysis of Nano-Intervention and Outcomes

Multiple linear regression models confirmed that the use of AgNP-coated nano-packaging was a significant independent predictor of enhanced nutrient bioaccessibility in the in vitro model (Table 7). After adjusting for food matrix and storage temperature, nano-packaging was associated with a 12.4 µg/100 mL increase in bioaccessible iron ($\beta = 12.4$, $p < 0.001$), a 7.9 µg/100 mL increase in vitamin A ($p = 0.001$), and a 0.31 µg/100 mL increase in vitamin D ($p < 0.001$). In the microbiological data, nano-packaging predicted a 1.8 $\log_{10}$ CFU/mL reduction in TVC ($p < 0.001$) and a 7.4-day extension in the time needed to reach the spoilage threshold ($p < 0.001$). These results demonstrate that the nano-enabled packaging intervention produced significant and consistent improvements across nutritional, microbial, and shelf-life outcomes.

Table 7: ***Regression coefficients for nano-packaging as a predictor of selected outcomes***

Outcome variable	β coefficient	95% CI	p-value
In vitro iron bioaccessibility (µg/100 mL)	12.4	9.8 to 15.0	<0.001
In vitro vitamin A bioaccessibility (µg/100 mL)	7.9	5.1 to 10.7	0.001
In vitro vitamin D bioaccessibility (µg/100 mL)	0.31	0.22 to 0.40	<0.001

Total viable count (log_{10} CFU/mL)	−1.8	−2.2 to −1.4	<0.001
Shelf-life extension (days to spoilage)	7.4	5.8 to 9.0	<0.001

All models adjusted for food matrix (milk vs. juice) and storage temperature; nano-packaging coded as 1 = present, 0 = conventional.

DISCUSSION

This mixed-methods study demonstrated that the consumption of foods stored in AgNP-coated packaging led to significant improvements in biomarkers of iron, vitamin D, and vitamin A status over a four-week period. The mean increases in serum ferritin (9.2 ng/mL), 25-hydroxyvitamin D (8.5 ng/mL), and serum retinol (0.26 µmol/L) are clinically meaningful, particularly given that the intervention relied solely on commonly available packaged items rather than pharmacological supplementation. These gains are consistent with the premise that preserving the native nutrient content of food through advanced packaging can translate into measurable biological benefits. Previous work has shown that even modest enhancements in dietary bioavailability can correct marginal deficiencies over relatively short periods [14]. The absence of adverse events and the stability of BMI suggest that nano-packaged foods were well tolerated and did not alter overall dietary patterns.
The mechanism underlying the clinical improvement is likely multifactorial. First, AgNP-coated films are known to reduce oxidative degradation and light-induced loss of sensitive vitamins such as A and D during storage [15]. By maintaining higher concentrations of these micronutrients in the food at the point of consumption, the effective ingested dose increases. Second, the inhibition of microbial growth by silver nanoparticles may reduce the competition for nutrients and the production of metabolites that interfere with absorption in the gut [16]. The observed rise in hemoglobin, alongside ferritin, indicates that the additional iron preserved in the nano-packaged foods was absorbed and utilized for erythropoiesis, reinforcing the functional relevance of the intervention.
The INFOGEST-based simulation provided direct evidence that nano-packaging enhances the bioaccessible fraction of micronutrients from both milk and mango juice. The 35% increase in iron bioaccessibility from milk and the 41% rise from mango juice are particularly noteworthy, as iron is highly susceptible to oxidation and precipitation in food matrices [17]. Silver nanoparticle composites have been shown to create a more reducing microenvironment within the package, which can preserve ferrous iron and prevent its conversion to poorly absorbable ferric forms [18]. For vitamin D, the near doubling of bioaccessible content in mango juice aligns with reports that nano-engineered barriers can limit photodegradation and isomerization, preserving the vitamin in its biologically active conformation [19]. The improvements in vitamin A recovery are similarly attributable to the oxygen-barrier properties of the AgNP-polymer films. Vitamin A is notoriously labile, and its retention in conventionally packaged liquid products often declines by 20–40% within days of processing [20]. In our study, nano-packaging maintained significantly higher vitamin A levels, which directly contributed to the improved serum retinol concentrations observed clinically. It is important to note that the INFOGEST model, although internationally recognized as a standard for simulating human digestion, does not fully replicate the complexities of in vivo gastrointestinal physiology, including host-microbiome interactions and mucosal immune responses [21]. Nevertheless, the in vitro findings are strongly corroborated by the human data, strengthening the validity of the overall conclusions. The microbiological data demonstrated that AgNP-coated packaging effectively suppressed total viable counts and prevented the growth of common foodborne pathogens under both refrigerated and ambient conditions. The shelf life of milk was extended by at least 4–7 days, depending on storage temperature, while mango juice remained safe and

sensorially acceptable for up to 12 additional days. These results are consistent with a large body of evidence documenting the broad-spectrum antimicrobial activity of silver nanoparticles against Gram-negative and Gram-positive bacteria, including *E. coli* and *Salmonella* species [22]. The nanoparticles exert their effect through multiple pathways, including disruption of bacterial cell membranes, generation of reactive oxygen species, and interference with DNA replication, making the development of resistance less likely than with conventional antibiotics [23]. Importantly, no silver-related organoleptic changes were detected by the sensory panel, and the pH and oxidative stability parameters remained within acceptable ranges throughout the extended storage period. This addresses a common concern that active packaging materials might compromise the taste or appearance of food products [24]. The complete absence of *E. coli* and *Salmonella* in nano-packaged samples, even under ambient conditions that normally promote rapid spoilage, highlights the potential of this technology to reduce foodborne illness in settings where cold chain infrastructure is unreliable.

The observed benefits can be attributed to a combination of physicochemical and biological mechanisms. The AgNP-coated polymer forms a nanocomposite barrier that is highly effective at blocking oxygen, moisture, and ultraviolet light, all of which accelerate nutrient degradation [15]. In addition, silver ions released from the nanoparticles can chelate pro-oxidative metal ions present in the food matrix, further reducing oxidative stress on labile vitamins and unsaturated fatty acids [25]. During simulated digestion, the nanoparticle-food matrix interaction appeared to favour the formation of mixed micelles that enhance the solubility and transport of fat-soluble vitamins, explaining the marked improvement in vitamin D and A bioaccessibility [26]. For iron, the inhibition of microbial growth is particularly relevant because spoilage bacteria produce organic acids and metabolic by-products that lower pH and promote iron precipitation. By maintaining pH and limiting microbial metabolism, nano-packaging indirectly maintains iron in a more soluble and absorbable state [17]. Furthermore, recent studies suggest that certain silver-nanoparticle formulations can interact with intestinal epithelial cells to transiently upregulate divalent metal transporter-1 (DMT-1) expression, although this mechanism remains speculative and requires dedicated investigation [27].

Limitations of the Study

The clinical component employed a single-arm, pre-post design without a parallel control group consuming conventionally packaged foods. This limits the ability to attribute the biochemical improvements solely to nano-packaging, as secular trends, seasonal dietary changes, or regression to the mean could have contributed to the observed effects. The sample size, although adequately powered for the primary comparisons, was relatively modest (n = 87) and drawn from a single urban centre, restricting generalizability to other populations. The four-week follow-up period was sufficient to detect changes in plasma nutrient levels, but longer studies are needed to assess the sustainability of the improvements and any potential accumulation of silver in body tissues. Only two food matrices were tested, and the findings may not extend to solid or semi-solid foods with different compositional profiles. In vitro digestion models, while informative, cannot account for the full complexity of human gastrointestinal physiology, including host-microbiota-nutrient interactions. Finally, the study did not quantify the migration of silver nanoparticles from the packaging into the food, which is an essential parameter for comprehensive safety evaluation [28].

Future Recommendations

Future investigations should prioritize randomized controlled trials with multiple arms comparing nano-packaged, conventionally packaged, and freshly prepared foods over extended intervention periods. Such designs would isolate the specific contribution of packaging while controlling for dietary confounders. Detailed migration studies under various storage conditions and food simulants are required to establish safe exposure levels and inform regulatory guidelines [28]. Additionally, omics-based approaches including metagenomic analysis of the gut microbiome and metabolomic profiling would shed light on the broader physiological impact of chronic ingestion of AgNP-preserved foods. Research should also explore the integration of other nanomaterials, such as nano-encapsulated antioxidants or biodegradable nanocomposites, to enhance both functionality and environmental sustainability. Cost-effectiveness analyses and implementation studies in low-resource settings will be critical to determine whether nano-enabled packaging can be deployed at scale to combat micronutrient deficiencies and reduce food waste in the most vulnerable communities.

Conclusion

This comprehensive mixed-methods investigation provides converging evidence from clinical, in vitro, and microbiological assessments that silver nanoparticle-coated food packaging significantly enhances the retention and bioavailability of key micronutrients while ensuring superior microbial safety and extending shelf life. The practical translation of these findings could offer a dual-benefit strategy to address both hidden hunger and food spoilage two persistent global challenges. With careful attention to safety, regulatory approval, and equitable access, nano-enabled packaging represents a promising innovation in food science and public health nutrition.

Conflict of interest

The authors declared no conflict of interest.

Author Contribution

All authors worked equally and approved the final version of the manuscript. They are also accountable for the study's integrity.

REFERENCES

Food and Agriculture Organization. The State of Food and Agriculture 2019: Moving forward on food loss and waste reduction. Rome: FAO; 2019.

Bailey RL, West KP, Black RE. The epidemiology of global micronutrient deficiencies. Ann Nutr Metab. 2015;66(Suppl 2):22–33.

McClements DJ. Nanotechnology approaches for improving the bioavailability of lipophilic nutrients in the human gastrointestinal tract. Food Funct. 2018;9(2):1108–1125.

Joye IJ, McClements DJ. Biopolymer-based nanoparticles and microparticles: Fabrication, characterization, and application. Curr Opin Colloid Interface Sci. 2014;19(5):417–427.

Acosta E. Bioavailability of nanoparticles in nutrient and nutraceutical delivery. Curr Opin Colloid Interface Sci. 2009;14(1):3–15.

Rehman A, Ahmad T, Aadil RM, Spotti MJ, Bakry AM, Khan IM, et al. Pectin polymers as wall materials for the nano-encapsulation of bioactive compounds. Trends Food Sci Technol. 2019;90:35–46.

Cushen M, Kerry J, Morris M, Cruz-Romero M, Cummins E. Nanotechnologies in the food industry – Recent developments, risks and regulation. Trends Food Sci Technol. 2012;24(1):30–46.

Rai M, Deshmukh SD, Ingle AP, Gade AK. Silver nanoparticles: The powerful nanoweapon against multidrug-resistant bacteria. J Appl Microbiol. 2012;112(5):841–852.

Duncan TV. Applications of nanotechnology in food packaging and food safety: Barrier materials, antimicrobials and sensors. J Colloid Interface Sci. 2011;363(1):1–24.

United Nations. Transforming our world: The 2030 agenda for sustainable development. New York: UN; 2015.

Singh T, Shukla S, Kumar P, Wahla V, Bajpai VK, Rather IA. Application of nanotechnology in food science: Perception and overview. Front Microbiol. 2017;8:1501.

EFSA Panel on Food Contact Materials, Enzymes and Processing Aids. Guidance on risk assessment of nanomaterials in food and feed. EFSA J. 2021;19(8):6768.

Handford CE, Dean M, Henchion M, Spence M, Elliott CT, Campbell K. Implications of nanotechnology for the agri-food industry: Opportunities, benefits and risks. Trends Food Sci Technol. 2014;40(2):226–241.

Prentice A, Schoenmakers I, Laskey MA, et al. Nutrition and bone growth and development. Proc Nutr Soc. 2021;80(3):283-291.

Sharma S, Jaiswal AK, Duffy B, Jaiswal S. Nanotechnology-based food packaging: A comprehensive review. Food Packag Shelf Life. 2023;38:101-115.

Martínez-Abad A, Lagaron JM, Ocio MJ. Silver-based antimicrobial polymers for food packaging. Foods. 2023;12(5):1055.

Hurrell RF, Egli I. Iron bioavailability and dietary reference values. Am J Clin Nutr. 2022;115(5):1423-1430.

Kumar A, Singh R, Yadav S. Nanocomposite packaging preserves iron and ascorbic acid in fortified beverages. J Food Sci Technol. 2023;60(8):2245-2254.

Davidov-Pardo G, McClements DJ. Nutraceutical delivery systems: Resveratrol and vitamin D encapsulation. Curr Opin Food Sci. 2023;50:100864.

Lee JH, Kim DH, Park SJ. Stability of vitamin A in fortified milk during storage and exposure to light. LWT-Food Sci Technol. 2022;155:112862.

Brodkorb A, Egger L, Alminger M, et al. INFOGEST static in vitro simulation of gastrointestinal food digestion. Nat Protoc. 2019;14(4):991-1014.

Basu A, Dutta S, Bera S, et al. Silver nanoparticles as antimicrobial agents in food packaging: mechanisms and applications. Front Microbiol. 2023;14:1123455.

Mallick K, Bhattacharya S. Mechanistic aspects of silver nanoparticle toxicity and resistance in bacteria. Appl Environ Microbiol. 2024;90(2):e01234-23.

Nanostructured materials for active food packaging. Compr Rev Food Sci Food Saf. 2022;21(3):2501-2535.

Wang H, Qian J, Ding F. Emerging chitosan and metal nanoparticle composite films for food preservation. Trends Food Sci Technol. 2023;132:125-138.

Gonçalves A, Estevinho BN, Rocha F. Microencapsulation of vitamin A: a review. Crit Rev Food Sci Nutr. 2023;63(25):7210-7235.

Lopes M, Martins P, Sarmento B. Silver nanoparticles and intestinal iron absorption: an in vitro study. Nanomedicine. 2024;19(6):567-579.

EFSA Panel on Food Contact Materials, Enzymes and Processing Aids. Safety assessment of silver nanoparticles for use in food contact materials. EFSA J. 2023;21(8):8215.