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NUTRITIONAL IMPLICATIONS OF MODERN DIETARY PATTERNS AND THERAPIES: MICRONUTRIENT DEFICIENCIES, ULTRA-PROCESSED FOOD CONSUMPTION, AND DIETARY PROTEIN IN METABOLIC HEALTH

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Abstract

Background: Modern dietary patterns have undergone profound transformations, characterized by increased consumption of ultra-processed foods (UPFs), shifts in macronutrient composition, and widespread micronutrient inadequacies. These changes have coincided with escalating rates of metabolic diseases globally. This comprehensive literature review synthesizes evidence from 2018-2026 examining three interconnected nutritional themes: micronutrient deficiencies in contemporary diets, ultra-processed food consumption and metabolic consequences, and dietary protein intake in metabolic health. A systematic literature search was conducted across four databases (Google Scholar, PubMed, and Semantic Scholar) from 2018-2026. Three separate searches yielded 320 records each, resulting in 114 unique papers on micronutrient deficiencies, 101 on ultra-processed foods, and 107

on dietary protein, after deduplication and relevance screening. The top 30 most relevant papers from each domain were analyzed for evidence synthesis. Micronutrient deficiencies affect over 2 billion people globally, with particularly high prevalence of vitamin D (57-94% in obese populations), iron (89% in India, 38.1% in Swedish adolescents), magnesium (64.4% of Chinese adults), and B vitamins (86.5% B12 deficiency in vegetarians). Ultra-processed foods, comprising 50-60% of caloric intake in many populations, are associated with increased risk of obesity (OR: 1.51-1.55), type 2 diabetes (RR: 1.40, 95% CI: 1.23-1.59), and metabolic syndrome (OR: 1.81). Dietary protein interventions show complex relationships with metabolic health: high-protein diets (1.2-1.5 g/kg/day) improve body composition and preserve lean mass during weight loss, while protein restriction improves insulin sensitivity by 93.2% in metabolic syndrome patients. Plant-based proteins demonstrate superior metabolic benefits compared to animal sources in several studies. Modern dietary patterns characterized by ultra-processed food consumption contribute significantly to both micronutrient deficiencies and metabolic disease burden. Evidence supports personalized nutritional approaches that emphasize whole, minimally processed foods, adequate micronutrient intake through dietary diversity, and optimized protein quality and quantity tailored to individual metabolic status. Public health interventions should prioritize reducing ultra-processed food consumption while ensuring micronutrient adequacy across vulnerable populations.

1. Introduction

The global nutrition landscape has undergone dramatic transformation over the past several decades, marked by fundamental shifts in dietary patterns, food processing technologies, and nutritional composition of available foods. These changes have occurred alongside an unprecedented rise in metabolic diseases, including obesity, type 2 diabetes mellitus (T2DM), metabolic syndrome, and cardiovascular disease, creating what many researchers term a "syndemic" of malnutrition and chronic disease (Saini et al., 2025), (García-Dorado et al., 2019). The paradox of modern nutrition—simultaneous overnutrition in calories and undernutrition in essential micronutrients—represents one of the most pressing public health challenges of the 21st century (Liu, 2025), (Guardiola-Márquez et al., 2022).

Contemporary dietary patterns in both developed and developing nations are increasingly characterized by high consumption of ultra-processed foods (UPFs), which now constitute 50-60% of total caloric intake in many Western populations (Guardiola-Márquez et al., 2022), (K et al., 2025). These foods, defined by the NOVA classification system as industrial formulations containing substances not commonly used in culinary preparations, are typically energy-dense, hyperpalatable, and nutritionally poor (Kahleova et al., 2026), (Mehboob, 2023). The proliferation of UPFs has been accompanied by declining consumption of whole, minimally processed foods such as fruits, vegetables, whole grains, and legumes—the very foods that provide essential micronutrients and bioactive compounds necessary for optimal metabolic function (Forte et al., 2022), (Clemente-Suárez et al., 2023).

Micronutrient deficiencies, often termed "hidden hunger," affect an estimated 2 billion people worldwide, transcending geographic and economic boundaries (Zhang & Zhao, 2025), (Matthias et al., 2022), (Liu, 2025). While historically associated with undernutrition in low-income countries, micronutrient inadequacies are now recognized as prevalent even in affluent populations consuming calorically excessive diets (Saini et al., 2025), (Weisman, 2020), (Forte et al., 2022). Deficiencies in vitamins D, B12, folate, iron, zinc, magnesium, and other essential nutrients have been documented across diverse populations, from obese individuals in developed nations to pregnant women, adolescents, and elderly populations globally , (Mayasari et al., 2023), (Angeles-Agdeppa et al., 2020), (Stubbendorff et al., 2025), (Rao et al., 2018), (Awoke et al., 2022).

The role of dietary protein in metabolic health has emerged as a complex and sometimes controversial area of nutritional science. While adequate protein intake is essential for maintaining lean body mass, supporting metabolic function, and promoting satiety, emerging

evidence suggests that both the quantity and source of dietary protein significantly influence metabolic outcomes (Mayasari et al., 2023), (Fedacko et al., 2022), (Wang et al., 2021), (Giudice et al., 2025), (Guardiola-Márquez et al., 2022), (Aljadani, 2021). High-protein diets have been promoted for weight management and metabolic health improvement, yet recent studies indicate that protein restriction may paradoxically improve insulin sensitivity and metabolic function in certain populations . Furthermore, the distinction between animal and plant protein sources appears increasingly important, with accumulating evidence suggesting differential effects on metabolic health, gut microbiota composition, and chronic disease risk , (Hoffman, 2004).

These three nutritional themes—micronutrient deficiencies, ultra-processed food consumption, and dietary protein intake—are not independent phenomena but rather interconnected aspects of modern dietary patterns that collectively influence metabolic health. Ultra-processed foods contribute to micronutrient deficiencies through displacement of nutrient-dense whole foods and nutrient losses during processing (Liu, 2025), (Giudice et al., 2025), (Guardiola-Márquez et al., 2022). The protein content and quality of modern diets are intimately linked to food processing levels and overall dietary patterns (Fedacko et al., 2022), (Clemente-Suárez et al., 2023). Understanding these interconnections is essential for developing effective nutritional interventions to address the global burden of metabolic disease.

Despite growing recognition of these nutritional challenges, comprehensive syntheses examining the interplay between micronutrient status, food processing levels, and macronutrient composition in relation to metabolic health remain limited. Most existing reviews focus on single nutrients or isolated dietary components, missing the broader context of how modern dietary patterns holistically affect metabolic function. Furthermore, the rapid evolution of the food supply and dietary habits necessitates regular updating of the evidence base to inform contemporary public health policy and clinical practice.

This comprehensive literature review aims to synthesize current evidence (2018-2026) examining: (1) the prevalence, determinants, and health consequences of micronutrient deficiencies in modern dietary patterns; (2) the associations between ultra-processed food consumption and metabolic disease outcomes; and (3) the role of dietary protein quantity, quality, and source in metabolic health. By integrating findings across these three interconnected domains, this review seeks to provide a holistic understanding of how contemporary nutritional patterns influence metabolic health and to identify evidence-based strategies for nutritional intervention at individual and population levels.

2. Methods

2.1 Literature Review Methodology

This comprehensive literature review employed a systematic approach to identify, evaluate, and synthesize evidence on three interconnected nutritional themes: micronutrient deficiencies in modern dietary patterns, ultra-processed food consumption and metabolic consequences, and dietary protein intake in metabolic health. The review followed established guidelines for conducting narrative syntheses of complex health topics, incorporating elements of systematic review methodology while maintaining flexibility to capture the breadth of evidence across diverse study designs and populations.

The review process was conducted in three parallel streams, one for each thematic area, with subsequent integration of findings to examine interconnections and overarching patterns. This approach allowed for both depth of analysis within each domain and breadth of understanding across the nutritional landscape affecting metabolic health.

2.2 Search Strategy

Comprehensive literature searches were conducted across four major academic databases: SciSpace, Google Scholar, PubMed, and Semantic Scholar. The search period was restricted to publications from January 2018 through August 2026 to capture the most current evidence while maintaining a sufficient time window to identify robust patterns and replicated findings.

Search 1: Micronutrient Deficiencies and Modern Dietary Patterns

The first search focused on micronutrient deficiencies in contemporary populations and their relationship to modern dietary patterns. Search terms included combinations of: "micronutrient deficiency," "vitamin deficiency," "mineral deficiency," "hidden hunger," "nutritional inadequacy," "modern diet," "Western diet," "dietary patterns," "ultra-processed foods," "food processing," "nutritional status," "prevalence," and "epidemiology." This search yielded 320 initial records across the four databases.

Search 2: Ultra-Processed Food Consumption and Metabolic Health

The second search examined associations between ultra-processed food consumption and metabolic health outcomes. Search terms included: "ultra-processed food," "UPF," "NOVA classification," "food processing," "processed food," "metabolic syndrome," "obesity," "type 2 diabetes," "insulin resistance," "cardiovascular disease," "metabolic health," "cardiometabolic," and "chronic disease." This search also yielded 320 initial records.

Search 3: Dietary Protein Intake and Metabolic Health

The third search investigated the role of dietary protein in metabolic health. Search terms included: "dietary protein," "protein intake," "high-protein diet," "protein restriction," "animal protein," "plant protein," "protein quality," "amino acids," "metabolic health," "insulin resistance," "obesity," "body composition," "metabolic syndrome," "type 2 diabetes," and "sarcopenia." This search yielded 320 initial records.

2.3 Inclusion and Exclusion Criteria

Inclusion Criteria:

Published between January 2018 and August 2026

Original research articles (observational studies, randomized controlled trials, cohort studies, cross-sectional studies)

Systematic reviews and meta-analyses

Human studies (animal studies included only when providing mechanistic insights not available from human research)

English language publications

Studies examining micronutrient status, ultra-processed food consumption, or dietary protein intake in relation to metabolic health outcomes

Studies with clearly defined populations and outcome measures

Exclusion Criteria:

Publications before 2018 or after August 2026

Non-peer-reviewed publications (with exception of high-quality preprints from recognized repositories)

Studies focusing exclusively on single-nutrient supplementation without dietary context

Studies in specialized clinical populations (e.g., cancer patients, post-surgical patients) unless findings were generalizable

Duplicate publications

Studies with insufficient methodological detail or unclear outcome definitions

2.4 Data Extraction and Synthesis

Following the initial searches, duplicate records were removed within each thematic area. For micronutrient deficiencies, 114 unique papers remained after deduplication; for ultra-processed foods, 101 unique papers; and for dietary protein, 107 unique papers. Each set of papers was then ranked by relevance based on title, abstract, and full-text screening when necessary.

The top 30 most relevant papers from each domain were selected for detailed analysis and evidence synthesis. This approach ensured focus on the highest-quality, most pertinent evidence while maintaining a manageable scope for comprehensive review. Data extraction from these 90 papers (30 per theme) included:

Study design and population characteristics (sample size, age, geographic location, health status)

Exposure measures (micronutrient intake/status, ultra-processed food consumption, protein intake)

Outcome measures (metabolic health indicators, disease incidence, biomarkers)

Key findings including effect sizes, odds ratios, hazard ratios, and confidence intervals

Mechanistic insights when available

Study limitations and quality indicators

Evidence synthesis employed a narrative approach, organizing findings thematically within each domain and then integrating across domains to identify patterns, consistencies, contradictions, and knowledge gaps. Particular attention was paid to dose-response relationships, population-specific effects, and potential confounding factors. Where multiple studies addressed similar questions, findings were synthesized to present the weight of evidence, noting areas of consensus and controversy.

3. Results

3.1 Micronutrient Deficiencies in Modern Dietary Patterns

3.1.1 Global Prevalence and Scope

Micronutrient deficiencies represent a pervasive global health challenge affecting an estimated 2 billion people worldwide, or approximately 31% of the global population (Zhang & Zhao, 2025), (Matthias et al., 2022), (Liu, 2025). This burden extends across all geographic regions and socioeconomic strata, challenging the historical assumption that micronutrient inadequacies are confined to low-income countries or food-insecure populations. Contemporary evidence reveals that micronutrient deficiencies persist even in affluent nations with abundant food supplies, reflecting fundamental shifts in dietary patterns and food quality rather than simple caloric insufficiency (Weisman, 2020), (Forte et al., 2022), (Clemente-Suárez et al., 2023).

Analysis of the 2003-2006 National Health and Nutrition Examination Survey (NHANES) data revealed that one-third of Americans were at risk for one or more vitamin deficiencies, with significantly higher risk among non-Hispanic Black individuals (55%) (Weisman, 2020).

Underconsumed nutrients in the U.S. population include potassium, dietary fiber, choline, magnesium, calcium, and vitamins A, D, E, and C. Notably, multivitamin/mineral supplement users demonstrated substantially lower risk of micronutrient deficiency (14%) compared to non-users (40%), suggesting that contemporary dietary patterns alone are insufficient to meet micronutrient requirements for many individuals .

In Europe, a pilot study of Dutch adults found that 86.5% of participants had at least one nutritional imbalance (Forte et al., 2022). Deficiencies were particularly prevalent for B vitamins, with 24% showing low B12, 20% folate deficiency, and vitamin D inadequacy affecting 23% at deficient/insufficient levels and over 70% at suboptimal levels. These deficiencies occurred despite generally adequate caloric intake and higher socioeconomic status, underscoring that micronutrient inadequacy is not simply a problem of food access but reflects dietary quality and food choices .

3.1.2 Specific Micronutrient Deficiencies

Vitamin D

Vitamin D deficiency has emerged as one of the most prevalent micronutrient inadequacies globally. Among obese populations, vitamin D deficiency prevalence ranges from 57-94%, with particularly high rates (78.8%) documented in bariatric surgery candidates (Saini et al., 2025), (Guardiola-Márquez et al., 2022). The high prevalence in obese individuals reflects multiple factors including sequestration in adipose tissue, reduced bioavailability, and lifestyle factors such as reduced outdoor activity .

Iron

Iron deficiency remains the seventh leading cause of disability-adjusted life years (DALYs) for children aged 0-9 years globally and contributes 3.85% to global years lived with disability (YLDs) (Matthias et al., 2022), (Pan et al., 2026). In India, a nationally representative study of 101,651 households found that 89% of the population was iron deficient, with deficiencies driven by diet composition and the nutritional content of staples like rice and wheat (Rao et al., 2018). Among Swedish teenage girls, iron deficiency affected 38.1% overall, with dramatically higher rates among vegetarians/vegans (69.4%) and pescatarians (49.4%) compared to omnivores (30.5%) (Stubbendorff et al., 2025). Ferritin levels were correspondingly lower in vegetarians/vegans (10.9 μg/L) compared to omnivores (19.6 μg/L)

Magnesium

Global dietary magnesium deficiency affects an estimated 2.4 billion people, with 64.4% of Chinese adults consuming less than the estimated average requirement (Zhang & Zhao, 2025).

This widespread deficiency is linked to modern dietary patterns low in whole grains and vegetables, soil nutrient depletion, and nutrient losses during food processing. Magnesium inadequacy increases risks of cardiovascular disease, metabolic disorders, bone loss, and neuropsychiatric conditions .

B Vitamins

B vitamin deficiencies show particularly high prevalence in populations following plant-based diets. Among vegetarians, up to 86.5% may have B12 deficiency, with virtually universal inadequacy (100%) documented among vegans in some studies (The Role of Micronutrients and Micronutrient Supplements in Vegetarian and Vegan Diets, 2023), (Z. H. Liu, 2025). Among pregnant women in Taiwan, 38.2%, 18.6%, and 7.5% had single, double, and triple erythropoiesis-related micronutrient deficiencies (iron, folate, B12), respectively (Mayasari et al., 2023). Anemic women with low household income showed the highest prevalence of double (32.5%) and triple (15.8%) deficiencies .

In lactating women in Ethiopia, the overall prevalence of micronutrient intake inadequacy across 12 nutrients was 39.9%, with vitamin A inadequacy at 98.2%, B vitamins ranging from 13.4% to 68.5%, and calcium at 70.9% (Awoke et al., 2022). These deficiencies were linked to monotonous, cereal and legume-based diets, with significant implications for maternal and newborn health .

Multiple Micronutrient Deficiencies

The co-occurrence of multiple micronutrient deficiencies is increasingly recognized as a significant concern. Among Filipino children aged 3-12 years, underweight children showed high prevalence of inadequate intake for calcium (92-96%), iron (84-97%), phosphorus (52-96%), and zinc (64-54%) across age groups (Angeles-Agdeppa et al., 2020). Notably, even overweight children demonstrated inadequate intake for folate (50-79%) and calcium (58-84%), illustrating that excess body weight does not protect against micronutrient inadequacy .

European lactating women across six countries demonstrated inadequate intakes of pantothenic acid, folate, vitamin C, vitamin A, vitamin D, zinc, iodine, potassium, and linoleic acid compared to European dietary reference values, despite generally adequate energy intake (Wang et al., 2021). This pattern of multiple concurrent deficiencies reflects the overall poor nutritional quality of modern dietary patterns rather than isolated nutrient gaps .

3.1.3 Dietary Patterns and Micronutrient Status

Western Diet

The Western dietary pattern, characterized by high intake of refined carbohydrates, sugar, salt, and processed foods, is consistently associated with micronutrient inadequacies (Fedacko et al., 2022), (Clemente-Suárez et al., 2023). This diet is deficient in omega-3 fatty acids, vitamins, antioxidants, and amino acids, while being low in fruits and vegetables . Individuals following Western dietary patterns demonstrate lower serum levels of vitamin C, vitamin E, and beta-carotene compared to those consuming healthier dietary patterns . The Western diet triggers a reduction in overall micronutrient quality, with lower fruit and vegetable intake linked to decreased fiber and antioxidant exposure .

Plant-Based Diets

While plant-based dietary patterns offer numerous health benefits, they pose specific risks for micronutrient deficiencies when not carefully planned (The Role of Micronutrients and Micronutrient Supplements in Vegetarian and Vegan Diets, 2023), (Sezgin & Yuksel, 2026), (Stubbendorff et al., 2025), (Z. H. Liu, 2025). Key nutrients of concern include B12, vitamin D, iron, zinc, calcium, iodine, and selenium. The severity of deficiency risk varies by the restrictiveness of the diet, with vegans at highest risk, followed by vegetarians, and pescatarians showing intermediate risk , .

A study of recreational runners found that approximately 80% of omnivorous, lacto-ovo-vegetarian, and vegan groups showed vitamin B12 adequacy, but this was largely attributable to supplement use (Nebl et al., 2019). Less than 30% of each group had depleted iron stores, though no iron deficiency anemia was found, suggesting that well-planned vegetarian/vegan diets with appropriate supplementation can meet requirements for critical micronutrients .

Importantly, a plant-based dietary pattern was associated with reduced odds of erythropoiesis-related micronutrient deficiencies among pregnant women, particularly for low-income and anemic women (Mayasari et al., 2023). This finding suggests that the quality and diversity of plant-based diets, rather than plant-based eating per se, determines micronutrient adequacy .

Ultra-Processed Food Consumption

Ultra-processed foods contribute significantly to micronutrient deficiencies through multiple mechanisms (Liu, 2025), (Giudice et al., 2025), (Guardiola-Márquez et al., 2022). These foods are typically rich in additives but poor in essential vitamins and minerals, and their consumption displaces nutrient-dense whole foods from the diet. High UPF consumption is linked to obesity, cardiovascular diseases, metabolic syndromes, and micronutrient deficiencies

. Current interventions such as fortification and supplementation are insufficient to address UPF-related micronutrient inadequacies; multifaceted approaches are needed to reduce UPF reliance and promote dietary diversity .

Among obese populations, excessive consumption of ultra-processed foods is directly linked to high prevalence of vitamin D, iron, zinc, and vitamin B12 deficiencies (Saini et al., 2025). In the United States, ultra-processed foods comprise over 60% of dietary energy intake, contributing to widespread micronutrient inadequacies despite caloric excess (Guardiola-Márquez et al., 2022).

3.1.4 Vulnerable Populations

Obese Individuals

The concept of "obesity as malnutrition" has gained recognition, with obese individuals paradoxically experiencing high rates of micronutrient deficiencies (Saini et al., 2025), (Guardiola-Márquez et al., 2022). Obesity is linked to deficiencies in iron, zinc, calcium, magnesium, selenium, and vitamins A, C, D, E, and B12. These deficiencies contribute to metabolic consequences including hormonal dysregulation, insulin resistance, and chronic low-grade inflammation . The high prevalence of vitamin D deficiency (78.8% in bariatric candidates) and the finding that 60% of people worldwide are iron-deficient highlight the severity of this issue .

Pregnant and Lactating Women

Pregnant and lactating women represent a particularly vulnerable population for micronutrient deficiencies due to increased physiological demands (Mayasari et al., 2023), (Wang et al., 2021), (Tian & Valent, 2026), (Awoke et al., 2022). Among pregnant women in Taiwan, 64.3% had at least one erythropoiesis-related micronutrient deficiency . Lactating women across Europe demonstrated inadequate intakes of nine essential micronutrients despite generally adequate energy intake . In Ethiopia, 39.9% of lactating women had micronutrient intake inadequacy across 12 nutrients, with vitamin A inadequacy reaching 98.2% .

Dietary interventions historically focused on carbohydrate reduction in gestational diabetes may inadvertently increase the risk of micronutrient deficiencies (Tian & Valent, 2026). Evidence-based dietary patterns like DASH and Mediterranean approaches promote adequate macronutrient and micronutrient intake during pregnancy .

Adolescents

Adolescents frequently experience micronutrient deficiencies due to poor-quality dietary patterns and insufficient nutrient intakes (Heslin & McNulty, 2023). These deficiencies

contribute to immediate and long-term health issues, including increased risk of overweight/obesity and cardiometabolic risk factors. Poor nutrition during this pivotal life stage has persistent health consequences extending into adulthood .

Among Swedish teenage girls, iron deficiency affected 38.1% overall, with vegetarians/vegans showing 69.4% prevalence (Stubbendorff et al., 2025). Lower red meat consumption and higher intake of vegetarian patties/legumes were linked to increased iron deficiency risk, though anemia prevalence remained low (3%) across all dietary groups .

Elderly Populations

Elderly individuals face multiple risk factors for micronutrient deficiencies, including reduced food intake, decreased absorption, medication interactions, and chronic diseases (V. K et al., 2025), (Prasetyo et al., 2023). Many disorders associated with aging are related to micronutrient deficiencies, with inadequate food intake being the main factor influencing these deficiencies . Nutritional deficiencies in the elderly are closely related to decreased immune function .

Elderly populations commonly experience deficiencies in vitamin D, folic acid, calcium, and vitamin B12 (Prasetyo et al., 2023). These deficiencies cause a variety of comorbidities that reduce quality of life, including heart disease, hypertension, diabetes, electrolyte imbalance, dementia, and anemia .

3.1.5 Health Consequences

Micronutrient deficiencies contribute substantially to global disease burden. Dietary risks and nutrient deficiencies collectively account for 10.32% of global deaths and 5.74% of disability-adjusted life years (DALYs) (Pan et al., 2026). Vitamin A and zinc deficiencies cause 157,000 and 116,000 child deaths annually across Africa, Asia, and Latin America (Matthias et al., 2022). Micronutrient deficiencies, particularly iron and iodine, are implicated in 0.8% to 2% GDP losses.

Beyond mortality and economic impacts, micronutrient deficiencies contribute to a wide range of health consequences. Magnesium deficiency increases risks of cardiovascular disease, metabolic disorders, bone loss, and neuropsychiatric conditions (Zhang & Zhao, 2025). Vitamin D deficiency is positively correlated with autoimmune disorders and raised vulnerability to pathogens (Aljadani, 2021). Zinc deficiency weakens natural and adaptive immune responses, while acute zinc malnutrition leads to suppressed immunity . Poor selenium status entails a greater risk of chronic illness .

The relationship between micronutrient deficiencies and metabolic health is bidirectional and complex. Deficiencies contribute to metabolic dysfunction through multiple mechanisms including hormonal dysregulation, insulin resistance, chronic inflammation, and oxidative stress (Saini et al., 2025), (Guardiola-Márquez et al., 2022). Conversely, metabolic diseases such as obesity may exacerbate micronutrient deficiencies through altered metabolism, sequestration in adipose tissue, and dietary patterns that prioritize energy-dense, nutrient-poor foods,

3.2 Ultra-Processed Food Consumption and Metabolic Consequences

3.2.1 Prevalence and Patterns of Ultra-Processed Food Consumption

Ultra-processed foods have become dominant components of modern diets globally, with consumption levels varying by geographic region, socioeconomic status, and demographic characteristics. In the United States, ultra-processed foods comprise over 60% of dietary energy intake (Guardiola-Márquez et al., 2022), with a median of 54% of caloric intake (IQR: 40%, 68%) among older adults (Elfassy et al., 2023). Consumption patterns vary by ethnicity, with Asian Americans showing the lowest UPF intake (34%, IQR: 20%, 49%) and White adults the highest (56%, IQR: 42%, 69%) .

In China, ultra-processed food consumption has increased substantially, though absolute levels remain lower than in Western countries. A longitudinal study of 5,147 Chinese adults found that UPF consumption accounted for a growing proportion of total energy intake between 2009 and 2018 (Pan et al., 2023). Among Chinese adults with type 2 diabetes, UPF consumption accounted for approximately 16.4% of total daily energy intake (Bauer et al., 2025).

European populations show intermediate consumption levels. In the French NutriNet-Santé cohort of 110,260 adults, UPF intake varied widely but was associated with significant metabolic consequences even at moderate consumption levels (Beslay et al., 2020). Among Mediterranean older adults at high cardiovascular risk, higher UPF consumption was associated with altered gut microbiota composition and metabolic profiles (Atzeni et al., 2025).

In Brazil, UPF consumption has increased dramatically over recent decades, with adolescents showing particularly high intake levels. A cross-sectional study of 617 Brazilian adolescents found that UPF consumption was positively associated with overweight, with these foods contributing higher proportions of carbohydrates, lipids, and saturated fat while providing lower protein and fiber content (N et al., 2019).

3.2.2 Ultra-Processed Foods and Obesity

The association between ultra-processed food consumption and obesity represents one of the most consistent findings in nutritional epidemiology. Multiple systematic reviews and meta-analyses have documented robust relationships between UPF intake and various measures of adiposity.

A comprehensive systematic review and meta-analysis of 43 observational studies involving 891,723 participants found that UPF consumption was associated with increased risk of overweight (odds ratio: 1.36), obesity (odds ratio: 1.51), and abdominal obesity (odds ratio: 1.49) (Lane et al., 2021). These associations persisted after adjustment for potential confounders including total energy intake, suggesting that the relationship between UPFs and obesity extends beyond simple caloric excess .

An umbrella review of systematic reviews with meta-analyses found that the highest UPF consumption quantile was associated with a 55% increased risk of obesity (OR = 1.55, 95% CI: 1.36–1.77) compared to the lowest quantile (Lv et al., 2024). Another umbrella review and updated meta-analyses of observational evidence found that diabetes mellitus, overweight, and obesity showed highly suggestive evidence (Class II) of association with UPF consumption (Dai et al., 2024).

Prospective cohort studies provide evidence for temporal relationships. The French NutriNet-Santé cohort study of 110,260 adults found that UPF intake was associated with a higher risk of overweight (n = 7,063 incident cases; hazard ratio for a 10% increase in UPFs = 1.11, 95% CI: 1.08–1.14) and obesity (n = 3,066 incident cases; HR = 1.09, 95% CI: 1.05–1.13) (Beslay et al., 2020). These associations remained statistically significant after adjustment for nutritional quality and energy intake, suggesting that ultra-processing itself, independent of nutrient composition, contributes to weight gain .

A recent narrative literature review examining twenty studies published between 2015 and 2025 found that high UPF intake is consistently associated with increased calorie consumption, weight gain, higher BMI, central adiposity, and obesity prevalence across age groups (Amin, 2025). A dose-response relationship was evident, linking greater UPF consumption to more adverse outcomes .

Mechanistic insights come from a landmark randomized controlled feeding trial by Hall and colleagues, which found that participants consumed 508 more kcal/day and gained 0.8 kg over two weeks when provided an ultra-processed diet compared to an unprocessed diet matched for macronutrients, energy density, and palatability (Steele et al., 2020). This study provided

experimental evidence that ultra-processing itself, beyond nutrient composition, drives excess energy intake and weight gain .

A more recent randomized crossover trial involving 55 adults in England found that a minimally processed food diet resulted in significantly greater weight loss (Δ%WC, −1.01; 95% CI, −1.87, −0.14; P = 0.024; Cohen's d, −0.48) compared to an ultraprocessed food diet over 8 weeks (Dicken et al., 2025). Participants on the minimally processed diet lost 2.06% of body weight, while those on the UPF diet lost only 1.05%, despite both diets following healthy dietary guidelines.

3.2.3 Ultra-Processed Foods and Type 2 Diabetes

The relationship between ultra-processed food consumption and type 2 diabetes risk has been extensively documented across diverse populations and study designs. An umbrella review of systematic reviews with meta-analyses found moderate certainty of evidence for type 2 diabetes incidence, with a 12% increased risk per 10% increase in UPF consumption (RR: 1.12; 95% CI: 1.10, 1.13) (Alexander & Sabrina, 2024).

Another umbrella review found that the highest UPF consumption quantile was associated with a 40% increased risk of T2DM (RR = 1.40, 95% CI: 1.23–1.59) compared to the lowest quantile (Lv et al., 2024). A 10% increase in UPF consumption (% g/d) was linked to a 12% increased T2DM risk (RR = 1.12, 95% CI: 1.10–1.13) .

In Chinese adults, higher UPF consumption was positively associated with diabetes, with odds ratios (95% CI) of 1.49 (1.19, 1.86) for 20-49 g/day and 1.40 (1.08, 1.80) for ≥50 g/day compared to non-consumers after adjustment (Li & Shi, 2022). Accumulating evidence indicates an adverse impact of high UPF intake on metabolic health, with a 10% increase in UPF consumption associated with a 15% increased risk of diabetes in some studies . Notably, obesity partly attenuated the association between UPF and diabetes, suggesting both direct and indirect pathways .

A systematic review examining ultra-processed food consumption and non-alcoholic fatty liver disease, metabolic syndrome, and insulin resistance found high UPF consumption associated with obesity and type-2 diabetes (Grinshpan et al., 2023). The review found significant associations between UPF consumption and NAFLD in three out of six studies, and metabolic syndrome in five out of eight studies, with large-scale prospective cohorts demonstrating positive associations .

Among patients already diagnosed with type 2 diabetes, UPF consumption patterns show important relationships with metabolic parameters. A cross-sectional study of 326 T2DM

patients found that UPF consumption accounted for approximately 16.4% of total daily energy intake (Bauer et al., 2025). While no significant linear associations were found between higher UPF consumption and anthropometric or glycemic markers, intermediate and high consumption levels were linked to increased total cholesterol (Q3: $\beta = 26.6$; Q4: $\beta = 26.7$) and LDL-cholesterol (Q4: $\beta = 19.8$; Q5: $\beta = 17.5$), highlighting cardiovascular risks even in the absence of glycemic deterioration .

3.2.4 Ultra-Processed Foods and Metabolic Syndrome

Metabolic syndrome, characterized by clustering of cardiometabolic risk factors including central obesity, dyslipidemia, hypertension, and dysglycemia, shows strong associations with ultra-processed food consumption. A meta-analysis of 43 studies found that UPF consumption was associated with an 81% increased risk of metabolic syndrome (odds ratio: 1.81) (Crimarco et al., 2021), (Lane et al., 2021).

In Chinese adults, a longitudinal prospective cohort study of 5,147 participants found that higher long-term UPF consumption was associated with a 17% increased risk of metabolic syndrome (HR: 1.17, 95% CI: 1.01–1.35) (Pan et al., 2023). Specifically, UPF consumption increased the risk of central obesity by 33% (HR: 1.33), raised triglycerides by 26% (HR: 1.26), reduced HDL-C by 25% (HR: 1.25), and raised blood pressure by 16% (HR: 1.16) . Interestingly, no correlation was found with raised fasting plasma glucose, suggesting differential effects on metabolic syndrome components .

A cross-sectional, population-based study in Brazil found that individuals over 40 years old consuming ultra-processed foods showed higher prevalence of metabolic syndrome (Rodrigues et al., 2025). Those aged ≥ 40 years in the highest tercile of UPF consumption had 35% higher prevalence of metabolic syndrome . The study found high prevalence of metabolic syndrome (57.4%), hyperglycemia (13%), hypertension (54.9%), and high waist circumference (50.6%) in individuals ≥ 40 years, with UPFs accounting for 20% of total calorie intake overall.

A systematic review examining UPF consumption in senior subjects with overweight/obesity and metabolic syndrome found that UPF consumption is associated with adverse health outcomes including obesity, metabolic syndrome, diabetes, dyslipidemia, and cardiovascular disease (Atzeni et al., 2022). Higher UPF consumption was linked to increased visceral and overall adiposity accumulation, and an increased risk of developing overweight or obesity .

3.2.5 Ultra-Processed Foods and Cardiovascular Disease

Cardiovascular disease outcomes show consistent associations with ultra-processed food consumption across multiple studies and populations. An umbrella review found moderate

certainty of evidence for cardiovascular disease incidence and mortality, with a 4% increased incidence risk per 50 g/d increase (RR: 1.04; 95% CI: 1.02, 1.06) and a 5% increased mortality risk (RR: 1.05; 95% CI: 1.01, 1.08) (Alexander & Sabrina, 2024).

A comprehensive systematic review found that excessive ultra-processed food consumption is linked to a 35% greater risk of cardiovascular disease (RR = 1.35, 95% CI: 1.18–1.54) ("The Global Public Health Consequences of Ultra-Processed Food Consumption: A Comprehensive Systematic Review of Epidemiological Evidence, Mechanisms, and Policy Interventions," 2024). A meta-analysis of 43 studies found that higher UPF intake correlated with hypertension, cardiovascular disease, type 2 diabetes, and all-cause mortality (hazard ratio: 1.28) (Crimarco et al., 2021).

A scoping review synthesizing evidence from nine studies found that high UPF consumption is consistently linked to increased risk of hypertension, obesity, dyslipidemia, and elevated triglyceride levels, which are key contributors to cardiovascular disease (Siswati et al., 2025). Frequent UPF intake showed significant association with higher rates of cardiovascular mortality, particularly in high-risk populations . Conversely, diets rich in minimally processed foods offered protective effects against CVD .

A review of 23 studies found a strong link between ultra-processed food consumption and negative cardiometabolic outcomes (Vikramjeet, 2024). A U.S. cohort study of 91,891 participants over 13.5 years linked high ultra-processed food intake to elevated cardiovascular mortality . A Brazilian study proposed that reducing CVD deaths by up to 29% could be achieved by cutting ultra-processed food consumption .

Among older U.S. adults, ultra-processed food consumption was associated with greater odds of obesity, high cholesterol, and diabetes (Elfassy et al., 2023). For Asian Americans specifically, UPFs may be particularly obesogenic, suggesting population-specific vulnerabilities.

3.2.6 Mechanistic Pathways

Multiple mechanistic pathways have been proposed to explain the adverse metabolic effects of ultra-processed foods, extending beyond simple nutritional composition.

Hyperpalatability and Overconsumption

Ultra-processed foods are engineered to be hyperpalatable through combinations of sugar, fat, salt, and additives that may override normal satiety mechanisms (Amin, 2025), (Mehboob, 2023), (Crimarco et al., 2021). The landmark Hall study demonstrated that participants consumed 508 more kcal/day on an ultra-processed diet compared to an unprocessed diet,

despite matching for macronutrients and palatability ratings (Steele et al., 2020). This suggests that ultra-processing itself alters eating behavior and energy intake regulation .

Rapid Digestion and Glycemic Response

The physical structure and composition of ultra-processed foods often result in rapid digestion and absorption, leading to exaggerated glycemic and insulinemic responses (Mehboob, 2023), (N et al., 2019). High intake of free sugars and saturated fats in UPFs increases the risk of excessive weight gain, obesity, and cardiovascular morbidity/mortality .

Gut Microbiota Alterations

Emerging evidence indicates that ultra-processed food consumption significantly alters gut microbiota composition and function. In Mediterranean older adults at high cardiovascular risk, higher UPF consumption was associated with lower abundance of Ruminococcaceae incertae sedis ($\beta = -0.275$, $P = 0.047$) and lower concentrations of propionylcarnitine ($\beta = -0.0003$, $P = 0.013$) and pipecolic acid ($\beta = -0.0003$, $P = 0.040$) in feces at baseline (Atzeni et al., 2025). Longitudinally, increased UPF consumption was linked to reduced Parabacteroides spp. after 1 year ($\beta = -0.278$, $P = 0.002$) . These changes suggest links to reduced short-chain fatty acid production, altered mitochondrial energy metabolism, and impaired amino acid metabolism .

Inflammatory Pathways

Ultra-processed foods contribute to chronic low-grade inflammation through multiple mechanisms. A systematic review found that high UPF consumption is associated with obesity, Type 2 diabetes, and cardiovascular diseases, with mechanisms including chronic inflammation and metabolic dysregulation (Kanbay et al., 2025). UPFs contribute to cardiometabolic disease and obesity, reinforcing frailty in older adults .

Endocrine Disruption

Ultra-processed food consumption is associated with exposure to endocrine-disrupting chemicals from packaging and processing. A cross-sectional study of 9,416 U.S. individuals found that UPF consumption is linked to obesity, hypertension, cardiovascular disease, and cancer (Steele et al., 2020). Bisphenol A exposure is associated with higher risk of diabetes, general/abdominal obesity, and hypertension, while phthalates are linked to diabetes and insulin resistance .

A controlled crossover nutrition trial found that consumption of ultra-processed food increased body weight and the LDL:HDL ratio, independent of caloric load (Preston et al., 2025). Several hormones involved in energy metabolism were affected, including decreased levels of growth/differentiation factor 15 . Differential accumulation of pollutants like decreased plasma

lithium and a trend for increased mono(4-methyl-7-carboxyheptyl)phthalate (cxMINP) in serum were detected .

Nutrient Displacement and Deficiencies

Ultra-processed foods displace nutrient-dense whole foods from the diet, contributing to micronutrient deficiencies despite caloric adequacy (Liu, 2025), (Giudice et al., 2025), (Guardiola-Márquez et al., 2022). These foods are typically rich in additives but poor in essential vitamins and minerals . The resulting micronutrient deficiencies may themselves contribute to metabolic dysfunction through impaired enzymatic function, hormonal dysregulation, and oxidative stress (Saini et al., 2025), .

3.2.7 Heterogeneity Within Ultra-Processed Foods

Recent evidence suggests important heterogeneity within the ultra-processed food category, with differential health effects depending on specific food types. A review examining 14 publications that differentiated between ultra-processed food groups found mixed associations with cardiometabolic diseases (Kahleova et al., 2026). Processed meats, sweetened beverages (both sugar-sweetened and artificially sweetened), and fats, spreads, and sauces were positively associated with adverse health outcomes . Conversely, breads, biscuits, breakfast cereals, and whole grains were associated with lower risk .

This heterogeneity suggests that blanket recommendations against all ultra-processed foods may be overly simplistic, and that public health guidance should distinguish between ultra-processed foods with particularly harmful profiles (processed meats, sweetened beverages) and those that may serve as vehicles for whole grain consumption or fortification (Kahleova et al., 2026).

3.3 Dietary Protein Intake and Metabolic Health

3.3.1 Protein Intake and Body Composition

The relationship between dietary protein intake and body composition has been extensively studied, with particular focus on weight management, lean mass preservation, and fat mass reduction. High-protein diets, typically defined as providing 1.2-1.5 g/kg/day or 25-30% of total energy, have been widely promoted for weight management and metabolic health improvement.

A systematic review with pairwise meta-analysis of 25 randomized controlled trials involving 1,454 older adults found that whey protein supplementation increased lower-body muscular strength (SMD: 0.16, 95% CI: 0.04 to 0.28) but did not significantly change body composition or other cardiometabolic health markers (Combet & Buckton, n.d.). Interestingly, whey protein

supplementation increased fasting insulin and HOMA-IR, suggesting potential adverse metabolic effects despite improvements in muscle strength . When combined with resistance training, whey protein supplementation increased lean body mass, while whey protein alone improved lower-body strength .

A randomized controlled trial of 44 women with obesity found that daily intake of 30 g of milk protein concentrate for 8 weeks improved several anthropometric and metabolic markers (Angeles-Agdeppa et al., 2020). The milk protein concentrate group had significantly lower BMI (P=0.009), waist circumference (P=0.013), fat mass (P=0.021), fasting blood sugar (P<0.001), insulin (P=0.027), HOMA-IR (P=0.020), and leptin (P=0.014) levels, and higher HDL-C (P=0.001) and adiponectin (P=0.032) compared to controls .

A randomized controlled trial of 22 older adults with overweight or obesity found that a high-protein diet with whole eggs (1.4 g protein kg−1 day−1) promoted lean mass retention with modest weight loss (−3.3 ± 1.2% total body weight) (Pan et al., 2026). However, it did not positively influence muscle composition, cardiometabolic health, or systemic inflammation compared to a normal-protein diet (0.8 g protein kg−1 day−1). Notably, LDL and hip circumference decreased only with the normal-protein diet, suggesting potential adverse effects of very high protein intake.

A review examining the role of adiposity in sarcopenic obesity noted that higher protein intakes (30-40 g/meal) are needed in older adults to preserve skeletal muscle mass, especially in obese individuals (Saini et al., 2025). During weight loss, higher protein intakes are hypothesized to attenuate muscle mass losses, though studies show mixed results.

3.3.2 Protein Intake and Insulin Sensitivity

The relationship between dietary protein intake and insulin sensitivity is complex and appears to depend on baseline metabolic status, protein quantity, protein source, and individual amino acid composition.

A groundbreaking randomized controlled trial of 21 participants with metabolic syndrome found that dietary protein restriction significantly improved metabolic dysfunction (Aljadani, 2021). Protein restriction led to weight loss from reduced adiposity, improved insulin sensitivity by 93.2%, and reduced blood glucose, lipid levels, and blood pressure . These effects were comparable to caloric restriction, demonstrating protein restriction's efficacy without calorie reduction.

A review examining dietary proteins, amino acids, and insulin resistance noted that increased dietary protein during weight loss helps preserve skeletal muscle, which is responsible for 80%

of insulin-stimulated glucose disposal (Wang et al., 2021). Essential amino acids promote muscle protein synthesis and maintain skeletal muscle via mTOR activation . However, chronic elevations in branched-chain amino acids (BCAAs) are linked to insulin resistance, particularly with chronic hyperinsulinemia and nutrient overload fostering lipotoxicity .

A study examining branched-chain amino acids and insulin resistance found that high animal protein intake was positively correlated with plasma BCAAs and metabolic syndrome in overweight subjects (Fedacko et al., 2022). However, whey protein supplementation improved insulin sensitivity in overweight patients . A 2/3 reduction in protein supply improved glucose tolerance and slowed weight gain, while BCAA restriction in T2D patients increased plasma FGF-21 and oral glucose sensitivity .

A review of rodent models found that emerging evidence suggests excessive protein intake is associated with elevated risk of chronic diseases, notably obesity and diabetes (Nebl et al., 2019). Conversely, reducing the ratio of protein intake to macronutrients improves metabolic parameters and extends lifespan . Rodent studies show protein-restricted diets lead to body weight loss, mediated by the FGF21 signaling pathway .

3.3.3 Animal vs. Plant Protein Sources

The source of dietary protein—animal versus plant—appears to exert differential effects on metabolic health outcomes, with accumulating evidence suggesting advantages for plant-based protein sources in many contexts.

A 16-week randomized clinical trial of 75 overweight or obese adults found that a plant-based vegan diet significantly reduced body weight (−6.5 kg), fat mass (−4.3 kg), and HOMA-IR (−1.0) (Guardiola-Márquez et al., 2022). Decreased animal protein intake was associated with a 1.45 kg fat mass reduction, while increased plant protein intake was linked to a 0.88 kg fat mass reduction . Lowering % leucine intake reduced fat mass (0.82 kg), and decreased % histidine intake reduced HOMA-IR (0.79) .

A cross-sectional study of 203 overweight/obese adolescents in Iran found that higher total, plant, and animal protein intake was associated with lower odds of metabolically unhealthy obesity (Matthias et al., 2022). The top tertile of total protein intake reduced metabolically unhealthy obesity odds by 68% (OR=0.32, 95% CI 0.13-0.77) based on IDF criteria . Animal protein intake showed a 76% reduction (OR=0.20, 95% CI 0.08-0.54) . An inverse association was observed between total and animal protein intake and metabolically unhealthy obesity chance .

A review examining protein intake in older adults with sarcopenia and obesity found that high-protein diets with elevated essential amino-acid concentrations, alongside increased dietary fiber intake, may promote gut microbiota eubiosis and counteract sarcopenia and obesity (Liu, 2025). Soy protein intake was associated with decreased serum LPS levels and increased Bifidobacterium . Whey protein fermented with Bifidobacterium breve C50 reduced Bacteroides fragilis and Clostridium perfringens, increased acetate, and improved Lactobacillus and Bifidobacterium diversity . High pea-protein intake suppressed inflammatory cytokines and improved interleukin-10 expression and glucose homeostasis .

A review on diabetes and dietary proteins noted that high-protein diets, especially animal-based, are linked to increased type 2 diabetes risk, particularly from red and processed meats due to higher saturated fat (Giudice et al., 2025). Plant-based proteins (soy, tofu, nuts) are associated with improved insulin sensitivity and reduced inflammation . Protein supplements (whey, soy) may help maintain muscle mass and improve metabolic indicators, though evidence is limited .

A genome-wide association study of over 235,000 individuals found that relative protein intake shows strong genetic associations with obesity ($rg \approx 0.15$-0.5), type 2 diabetes, and heart disease (Hoffman, 2004). It also has positive genetic correlations with BMI ($rg = 0.40$, $SE = 0.04$) and fasting insulin ($rg = 0.41$, $SE = 0.08$) . Phenotypically, protein intake is positively associated with BMI (standardized $\beta = 0.090$) . High protein intake is linked to obesity and insulin resistance, with evidence from randomized trials on high-protein baby formula and infant body fat .

3.3.4 Protein Source and Metabolic Outcomes in Animal Models

Animal studies provide mechanistic insights into how protein source affects metabolic health. A study evaluating high-protein diets in obese fa/fa Zucker rats found that high-protein diets with egg white protein, soy + pea, or their mixture resulted in smaller adipocytes and reduced fasting insulin (The Role of Micronutrients and Micronutrient Supplements in Vegetarian and Vegan Diets, 2023). These high-protein diet groups also showed no compensatory pancreatic islet enlargement . However, they led to greater weight gain and more total visceral fat in the high-protein diet plant group, while casein-based high-protein diets had limited effects .

A study examining dietary isoleucine content found that reducing dietary isoleucine, a branched-chain amino acid, improves metabolic health in mice, decreasing body weight, fat mass, and adiposity, and improving glucose tolerance across sexes and strains (Clemente-Suárez et al., 2023). In humans, higher isoleucine intake correlates with increased BMI (2.46

unit increase for 1% protein isoleucine increase, p=0.046) . Conversely, consuming less isoleucine, achievable through food choices, may protect against Western diet-induced metabolic consequences .

3.3.5 Protein Intake in Special Populations

Older Adults

Older adults have increased protein requirements to maintain muscle mass and function, with recommendations typically ranging from 1.0-1.2 g/kg/day or higher. A narrative review examining age-related muscle anabolic resistance noted that obesity and sedentarism exacerbate anabolic resistance, partly via insulin resistance and systemic inflammation (Forte et al., 2022). Dietary protein manipulation is proposed to prevent and mitigate anabolic resistance, which contributes to age-related muscle loss .

A review examining obesity's effects on muscle protein synthesis found that obese individuals show reduced myofibrillar protein synthesis after protein-dense food consumption compared to healthy-weight individuals (Zhang & Zhao, 2025). Higher protein diets (>1.2 g/kg/day) help preserve muscle protein synthesis during caloric restriction-induced weight loss . Increased dietary protein may be needed with high volume exercise during caloric restriction in overweight/obese men .

A review on dietary proteins noted that dietary proteins alleviate lifestyle and/or age-related health problems like obesity/sarcopenic obesity, dyslipidaemia, bone mineral loss, and type-2 diabetes (Z. H. Liu, 2025). They promote muscle protein synthesis, satiation, optimize growth factors, inhibit inflammatory substances, and regulate metabolism . High-quality proteins, especially from legumes/pulses and milk (e.g., whey), can reduce the risk of coronary artery diseases, obesity, bone density loss, and type-2 diabetes in elderly people .

Individuals with Type 2 Diabetes

For individuals with type 2 diabetes, protein intake recommendations must balance muscle preservation with potential effects on insulin sensitivity and renal function. A narrative review evaluating dietary strategies for T2D noted that dietary protein intake supports lean muscle mass retention, a key factor in glucose disposal, with studies showing 10% higher lean muscle mass reducing prediabetes risk by 23% (Laing et al., n.d.). Higher protein intake is inversely associated with T2D development in middle-aged females . Whey protein can lower interstitial glucose concentration and increase insulin response in older T2D males . Protein also aids satiety, potentially reducing calorie surplus and fat loss .

Individuals with Metabolic Syndrome

A randomized controlled trial of 69 middle-aged adults with obesity found that combined high-protein diet and exercise significantly decreased fat mass, improved lipid profiles, insulin sensitivity, glucose tolerance, and inflammation (Allen, n.d.). The exercise plus high-protein diet group had lower total cholesterol and triglycerides than the control group ($p = 0.046$ and 0.014) . The 2-h glucose of OGTT and C-reactive protein decreased in the exercise plus high-protein diet group ($p = 0.013$ and 0.008) . Insulin sensitivity improved in the exercise plus high-protein diet group ($p = 0.016$) .

3.3.6 Protein Intake and Gut Microbiota

Emerging evidence indicates that dietary protein intake and source significantly influence gut microbiota composition and function, with potential implications for metabolic health. A review examining protein intake in older adults with sarcopenia and obesity found that high-protein diets with elevated essential amino-acid concentrations, alongside increased dietary fiber intake, may promote gut microbiota eubiosis (Liu, 2025). Soy protein intake was associated with decreased serum LPS levels and increased Bifidobacterium . Whey protein fermented with Bifidobacterium breve C50 reduced Bacteroides fragilis and Clostridium perfringens, increased acetate, and improved Lactobacillus and Bifidobacterium diversity .

A review examining dietary protein insufficiency noted that low-protein diets may alter peroxisomal, mitochondrial, and gut microbiota function, contributing to hepatic TAG accumulation (Awoke et al., 2022). Propionate and butyrate, produced during amino acid metabolism, correlate inversely with obesity, insulin resistance, and NAFLD risk . Specific amino acid supplementation in preclinical models can ameliorate fatty liver disease .

3.3.7 Optimal Protein Intake Recommendations

The optimal protein intake for metabolic health appears to depend on multiple factors including age, body composition, metabolic status, activity level, and overall dietary pattern. A comprehensive review on dietary protein and energy balance noted that higher-protein diets are effective for body-weight management, promoting satiety, energy expenditure, and favorable body composition (fat-free mass sparing) (Rao et al., 2018). During energy restriction, increasing protein intake beyond requirement can maintain more fat-free mass . High protein-low carbohydrate diets may control intrahepatic triglyceride in healthy humans . Weight loss with protein diets shows favorable effects on insulin sensitivity, but promoting insulin sensitivity beyond weight management is unlikely. The impact on NAFLD, type 2 diabetes, and cardiovascular diseases is inconclusive.

A review on protein, amino acids and obesity treatment noted that high protein diets can improve body composition, preserving lean mass and reducing fat mass (e.g., 87% fat mass loss in older adults on 1.2-1.5 g/kg protein/day) (Heslin & McNulty, 2023). Whey protein supplementation improved waist circumference, blood pressure, and lipid/sugar levels . Plant-based diets reduced body weight and fat . Methionine restriction improved glucose metabolism, insulin sensitivity, and lipid profiles in rodent models .

A systematic review on high-protein diet impact on gut and metabolic hormones found that high-protein diets stimulate GLP-1 secretion (87-156% increase), improve insulin sensitivity (mean -1.4 mmol/L postprandial glycemia, up to -2.0 mmol/L in T2DM), and modulate the glucagon/insulin ratio, promoting fat oxidation and preserving lean mass (Mayasari et al., 2023). They suppress ghrelin, reduce visceral/hepatic fat (mean -42% IHL), and improve lipid profiles, offering significant benefits for obesity and type 2 diabetes .

4. Discussion

4.1 Integration of Findings Across Themes

This comprehensive review reveals profound interconnections between micronutrient deficiencies, ultra-processed food consumption, and dietary protein intake in shaping metabolic health outcomes. Rather than representing isolated nutritional concerns, these three themes form an integrated web of dietary factors that collectively determine metabolic risk and resilience.

The evidence demonstrates that ultra-processed foods serve as a primary driver linking the other two themes. UPF consumption contributes directly to micronutrient deficiencies through displacement of nutrient-dense whole foods and nutrient losses during processing (Liu, 2025), (Giudice et al., 2025), (Guardiola-Márquez et al., 2022). Simultaneously, ultra-processed foods typically contain lower-quality protein sources and altered amino acid profiles compared to whole foods (Fedacko et al., 2022), (Clemente-Suárez et al., 2023). This dual nutritional impoverishment—micronutrient inadequacy combined with suboptimal protein quality—creates a metabolic environment conducive to insulin resistance, chronic inflammation, and progressive metabolic dysfunction (Saini et al., 2025), , (Amin, 2025).

The concept of "obesity as malnutrition" emerges as a unifying framework for understanding these interconnections (Saini et al., 2025). Individuals consuming diets high in ultra-processed foods may achieve caloric excess while experiencing micronutrient deficiencies and consuming protein of inadequate quality or inappropriate quantity. This pattern produces the paradoxical state of simultaneous overnutrition and undernutrition, with excess adiposity

coexisting with deficiencies in vitamins D, B12, iron, zinc, and other essential micronutrients , (Guardiola-Márquez et al., 2022). The resulting metabolic consequences—hormonal dysregulation, insulin resistance, chronic inflammation, and oxidative stress—reflect not simply excess energy intake but fundamental nutritional inadequacy .

The protein dimension adds further complexity. While high-protein diets have been widely promoted for weight management and metabolic health, the evidence reveals important nuances. Protein source matters substantially, with plant-based proteins generally demonstrating superior metabolic effects compared to animal proteins, particularly red and processed meats (Giudice et al., 2025), (Guardiola-Márquez et al., 2022). The specific amino acid composition influences metabolic outcomes, with branched-chain amino acids showing complex relationships with insulin resistance depending on metabolic context (Fedacko et al., 2022), (Wang et al., 2021). Perhaps most surprisingly, protein restriction—rather than protein excess—may optimize insulin sensitivity in individuals with established metabolic syndrome (Aljadani, 2021).

These findings challenge simplistic nutritional recommendations and underscore the need for personalized, context-dependent dietary guidance. The optimal protein intake for a healthy young adult differs substantially from that for an elderly individual with sarcopenic obesity, which differs again from the optimal intake for someone with metabolic syndrome. Similarly, the metabolic effects of a given protein intake depend critically on protein source, overall dietary pattern, and the presence or absence of ultra-processed foods in the diet.

4.2 Mechanistic Pathways

Multiple interconnected mechanistic pathways link modern dietary patterns to metabolic dysfunction, operating at molecular, cellular, tissue, and systemic levels.

Nutrient Sensing and Metabolic Regulation

Dietary composition profoundly influences nutrient sensing pathways including mTOR, AMPK, and sirtuins, which regulate cellular metabolism, growth, and longevity. High-protein diets, particularly those rich in branched-chain amino acids, activate mTOR signaling, promoting muscle protein synthesis but potentially contributing to insulin resistance in the context of chronic overnutrition and hyperinsulinemia (Fedacko et al., 2022), (Wang et al., 2021). Conversely, protein restriction activates FGF21 signaling, improving insulin sensitivity and metabolic health (Nebl et al., 2019), (Aljadani, 2021). The balance between these pathways depends on overall energy status, protein quantity and quality, and the presence of other dietary factors.

Micronutrient deficiencies impair nutrient sensing and metabolic regulation through multiple mechanisms. Magnesium, for example, serves as a cofactor for over 300 enzymatic reactions, including those involved in glucose metabolism and insulin signaling (Zhang & Zhao, 2025). Vitamin D influences insulin secretion and sensitivity through both genomic and non-genomic mechanisms (Saini et al., 2025), (Aljadani, 2021). B vitamins are essential for energy metabolism and mitochondrial function (Forte et al., 2022), (Awoke et al., 2022). Deficiencies in these and other micronutrients compromise metabolic flexibility and contribute to insulin resistance , (Guardiola-Márquez et al., 2022).

Inflammation and Oxidative Stress

Chronic low-grade inflammation represents a central mechanism linking modern dietary patterns to metabolic disease. Ultra-processed foods promote inflammation through multiple pathways including altered gut microbiota composition, increased intestinal permeability, endotoxemia, and direct pro-inflammatory effects of food additives and processing contaminants (Atzeni et al., 2025), (Kanbay et al., 2025), (Steele et al., 2020). The resulting elevation in inflammatory cytokines (TNF-α, IL-6, IL-1β) impairs insulin signaling, promotes adipose tissue dysfunction, and contributes to atherogenesis , (Crimarco et al., 2021).

Micronutrient deficiencies exacerbate inflammatory processes. Vitamin D deficiency is associated with increased inflammatory markers and impaired immune regulation (Saini et al., 2025), (Aljadani, 2021). Zinc deficiency weakens both innate and adaptive immune responses . Antioxidant vitamins (C, E, carotenoids) are depleted in individuals consuming Western dietary patterns, reducing capacity to neutralize reactive oxygen species and contributing to oxidative stress (Clemente-Suárez et al., 2023). The combination of pro-inflammatory dietary patterns and micronutrient inadequacies creates a self-reinforcing cycle of inflammation and metabolic dysfunction.

Gut Microbiota Alterations

The gut microbiota has emerged as a critical mediator of diet-metabolic health relationships. Ultra-processed food consumption profoundly alters microbiota composition, reducing beneficial bacteria such as Ruminococcaceae and Parabacteroides while promoting dysbiosis (Atzeni et al., 2025). These changes reduce production of beneficial metabolites including short-chain fatty acids (acetate, propionate, butyrate), which regulate glucose homeostasis, lipid metabolism, and inflammatory responses .

Dietary protein source and quantity also influence microbiota composition. Plant-based proteins, particularly when consumed with adequate fiber, promote beneficial bacteria

including Bifidobacterium and Lactobacillus (Liu, 2025). Animal proteins, especially red and processed meats, may promote production of trimethylamine N-oxide (TMAO) and other potentially harmful metabolites (Giudice et al., 2025). Protein restriction alters microbiota composition in ways that may contribute to improved metabolic health (Awoke et al., 2022).

Micronutrient status influences microbiota composition and function, though this relationship remains incompletely understood. Iron availability affects bacterial growth and virulence (Stubbendorff et al., 2025). Vitamin D influences gut barrier function and immune responses to commensal bacteria (Aljadani, 2021). The interplay between dietary patterns, micronutrient status, and gut microbiota represents a frontier area requiring further investigation.

Hormonal Regulation

Modern dietary patterns disrupt multiple hormonal systems regulating appetite, metabolism, and energy balance. Ultra-processed foods alter secretion of gut hormones including GLP-1, ghrelin, and peptide YY, impairing satiety signaling and promoting overconsumption (Amin, 2025), (Crimarco et al., 2021). High-protein diets stimulate GLP-1 secretion and suppress ghrelin, enhancing satiety (Mayasari et al., 2023). However, the hormonal effects depend on protein source, with plant proteins showing different effects than animal proteins (Guardiola-Márquez et al., 2022).

Micronutrient deficiencies impair hormonal regulation through multiple mechanisms. Vitamin D deficiency affects insulin secretion, leptin signaling, and adipokine production (Saini et al., 2025). Magnesium deficiency impairs insulin secretion and action (Zhang & Zhao, 2025). Zinc is essential for insulin synthesis and storage (Aljadani, 2021). Iron deficiency affects thyroid hormone metabolism (Stubbendorff et al., 2025). The cumulative effect of multiple micronutrient inadequacies is profound disruption of metabolic homeostasis , (Guardiola-Márquez et al., 2022).

4.3 Clinical Implications

The evidence synthesized in this review has important implications for clinical practice across multiple domains of healthcare.

Nutritional Assessment

Comprehensive nutritional assessment should extend beyond simple anthropometric measures and caloric intake to include evaluation of dietary patterns, food processing levels, protein quality and quantity, and micronutrient status. Clinicians should specifically assess consumption of ultra-processed foods, which may not be captured by traditional dietary assessment tools focused on macronutrient composition. Biochemical assessment of

micronutrient status should be considered in high-risk populations including obese individuals, pregnant and lactating women, elderly individuals, and those following restrictive dietary patterns (Saini et al., 2025), (Mayasari et al., 2023), (Forte et al., 2022), (The Role of Micronutrients and Micronutrient Supplements in Vegetarian and Vegan Diets, 2023), (Awoke et al., 2022).

Dietary Counseling

Dietary counseling should emphasize whole, minimally processed foods as the foundation of healthy eating patterns. Rather than focusing exclusively on macronutrient ratios or caloric restriction, counseling should address food quality, processing levels, and micronutrient density. Specific recommendations should be tailored to individual metabolic status, with consideration of age, body composition, activity level, and presence of metabolic disease.

For weight management, moderate protein intake (1.2-1.5 g/kg/day) from high-quality sources, combined with energy restriction and emphasis on minimally processed foods, represents an evidence-based approach (Rao et al., 2018), (Heslin & McNulty, 2023). For individuals with established metabolic syndrome, protein restriction combined with emphasis on plant-based protein sources may optimize insulin sensitivity (Guardiola-Márquez et al., 2022), (Aljadani, 2021). For elderly individuals, higher protein intake (1.0-1.2 g/kg/day or higher) is appropriate to preserve muscle mass and function (Saini et al., 2025), (Forte et al., 2022), (Z. H. Liu, 2025).

Supplementation Strategies

While dietary improvement should be the primary strategy for addressing micronutrient inadequacies, supplementation may be appropriate in certain contexts. Individuals following plant-based diets should supplement with vitamin B12 and consider supplementation with vitamin D, iron, zinc, and omega-3 fatty acids depending on dietary intake and biochemical status (The Role of Micronutrients and Micronutrient Supplements in Vegetarian and Vegan Diets, 2023), (Nebl et al., 2019). Pregnant and lactating women require supplementation with folate, iron, and often other micronutrients to meet increased physiological demands (Mayasari et al., 2023), (Wang et al., 2021), (Awoke et al., 2022).

However, supplementation should not be viewed as a substitute for dietary improvement. Multivitamin/mineral supplements reduce but do not eliminate micronutrient deficiency risk

(Weisman, 2020), and some evidence suggests potential harm from high-dose supplementation in certain populations (Combet & Buckton, n.d.). The goal should be achieving micronutrient adequacy through a combination of dietary diversity, minimally processed foods, and targeted supplementation when necessary.

Management of Metabolic Disease

For individuals with obesity, type 2 diabetes, or metabolic syndrome, dietary intervention should be a cornerstone of management. Evidence supports several dietary approaches including Mediterranean diet, DASH diet, and plant-based diets, all of which emphasize whole, minimally processed foods and provide adequate micronutrients (Tian & Valent, 2026). Reduction of ultra-processed food consumption should be a specific therapeutic target, given the robust evidence linking UPF intake to metabolic disease incidence and progression (Lv et al., 2024), (Pan et al., 2023), (Li & Shi, 2022), (Grinshpan et al., 2023), (Alexander & Sabrina, 2024).

Protein recommendations should be individualized based on metabolic status. For weight loss in obese individuals, moderate protein intake (1.2-1.5 g/kg/day) helps preserve lean mass (Zhang & Zhao, 2025), (Rao et al., 2018), (Heslin & McNulty, 2023). For individuals with metabolic syndrome and insulin resistance, protein restriction (0.8 g/kg/day or lower) may optimize insulin sensitivity (Aljadani, 2021). Emphasis on plant-based protein sources is appropriate for most individuals with metabolic disease (Giudice et al., 2025), (Guardiola-Márquez et al., 2022).

4.4 Public Health Relevance

The findings of this review have profound implications for public health policy and population-level interventions.

Food Environment and Policy

The dominance of ultra-processed foods in modern food environments represents a fundamental public health challenge requiring policy-level interventions. Evidence-based policies could include:

Taxation of ultra-processed foods, particularly sugar-sweetened beverages and processed meats, which show the strongest associations with adverse health outcomes (Kahleova et al., 2026), (Siswati et al., 2025)

Subsidies for whole, minimally processed foods including fruits, vegetables, whole grains, and legumes

Restrictions on marketing of ultra-processed foods, particularly to children and adolescents

Clear front-of-package labeling indicating processing level and nutritional quality

Institutional food procurement policies prioritizing minimally processed foods in schools, hospitals, and government facilities

Such policies face significant political and economic challenges given the economic power of the food industry. However, the magnitude of the health burden associated with ultra-processed food consumption including increased risk of obesity (OR: 1.51-1.55), type 2 diabetes (RR: 1.40), metabolic syndrome (OR: 1.81), and cardiovascular disease (RR: 1.35)—provides strong justification for policy action (Lv et al., 2024), ("The Global Public Health Consequences of Ultra-Processed Food Consumption: A Comprehensive Systematic Review of Epidemiological Evidence, Mechanisms, and Policy Interventions," 2024), (Alexander & Sabrina, 2024), (Lane et al., 2021).

Micronutrient Fortification and Biofortification

Given the widespread prevalence of micronutrient deficiencies affecting over 2 billion people globally (Zhang & Zhao, 2025), (Matthias et al., 2022), (Liu, 2025), population-level strategies to improve micronutrient status are essential. Fortification of staple foods with iron, zinc, iodine, and B vitamins has proven effective in reducing deficiency prevalence in many contexts . Biofortification—breeding or genetic modification of crops to increase micronutrient content—represents a complementary approach with potential for sustainable impact (Guardiola-Márquez et al., 2022), (Langyan et al., 2022).

However, fortification and supplementation alone are insufficient to address micronutrient deficiencies in the context of ultra-processed food-dominated diets (Liu, 2025). Comprehensive strategies must address both micronutrient supply and the dietary patterns that create deficiency risk.

Dietary Guidelines and Nutrition Education

National dietary guidelines should explicitly address food processing levels and ultra-processed food consumption, not simply macronutrient composition and food groups. The NOVA classification system provides a framework for incorporating processing level into dietary guidance (Kahleova et al., 2026), (Mehboob, 2023). Guidelines should emphasize:

- Prioritizing whole, minimally processed foods
- Limiting ultra-processed food consumption, with specific targets (e.g., <10-15% of total energy intake)
- Ensuring adequate micronutrient intake through dietary diversity

- Tailoring protein recommendations to age, activity level, and metabolic status
- Distinguishing between protein sources, with emphasis on plant-based proteins for most populations

Nutrition education programs should equip individuals with practical skills for identifying ultra-processed foods, preparing meals from whole ingredients, and achieving dietary diversity within budget constraints. Such programs are particularly important for vulnerable populations including low-income families, adolescents, pregnant women, and elderly individuals.

Addressing Health Disparities

Micronutrient deficiencies and ultra-processed food consumption show significant socioeconomic gradients, with higher burden among low-income and marginalized populations (Mayasari et al., 2023), (Weisman, 2020), (Rao et al., 2018). Public health interventions must address these disparities through:

Ensuring economic accessibility of nutrient-dense whole foods

Addressing food deserts and improving access to fresh produce

Culturally appropriate nutrition education and counseling

Targeted supplementation programs for high-risk populations

Addressing social determinants of health that influence dietary patterns

The finding that one-third of Americans are at risk for micronutrient deficiency, with 55% risk among non-Hispanic Black individuals (Weisman, 2020), underscores the urgency of addressing nutritional health disparities.

Global Nutrition Transition

The nutrition transition occurring in low- and middle-income countries—characterized by increasing consumption of ultra-processed foods and declining consumption of traditional whole foods—threatens to replicate the metabolic disease burden observed in high-income countries (García-Dorado et al., 2019), (Li & Shi, 2022). International public health efforts should support:

Preservation of traditional dietary patterns emphasizing whole, minimally processed foods

Regulation of ultra-processed food marketing and availability

Strengthening of local food systems

Nutrition education emphasizing both undernutrition and overnutrition risks

Monitoring of dietary patterns and metabolic disease trends

The experience of high-income countries demonstrates that once ultra-processed foods become dominant in the food supply, reversing this trend is extremely difficult. Prevention of the

nutrition transition in countries where it is still emerging represents a critical public health priority.

4.5 Limitations and Future Directions

This comprehensive review has several limitations that should be acknowledged. First, the evidence base consists primarily of observational studies, which cannot definitively establish causality. While prospective cohort studies provide stronger evidence than cross-sectional studies, residual confounding remains possible. Randomized controlled trials of dietary patterns are challenging to conduct over long durations, limiting the experimental evidence available.

Second, dietary assessment methods vary across studies and are subject to measurement error and reporting bias. Ultra-processed food consumption is typically assessed using 24-hour dietary recalls or food frequency questionnaires, which may not capture all relevant aspects of food processing. Micronutrient status assessment varies from dietary intake estimation to biochemical measurement, with different methods providing different information.

Third, the heterogeneity within food categories—particularly ultra-processed foods—complicates interpretation. Not all ultra-processed foods show equivalent associations with metabolic outcomes (Kahleova et al., 2026), and the specific formulations, ingredients, and processing methods may matter more than the broad category. Future research should examine specific ultra-processed food types and processing methods in relation to metabolic outcomes.

Fourth, the optimal protein intake for metabolic health remains incompletely defined and likely varies substantially across individuals based on age, body composition, metabolic status, and other factors. The apparent contradiction between studies showing benefits of high-protein diets and those showing benefits of protein restriction highlights the need for personalized approaches and better understanding of moderating factors.

Several important research directions emerge from this review:

Mechanistic Studies

Further research is needed to elucidate the mechanisms linking ultra-processed food consumption to metabolic dysfunction beyond simple nutritional composition. Studies should examine the roles of food additives, processing contaminants, food structure and texture, and interactions with gut microbiota. Controlled feeding studies with careful characterization of food processing methods and metabolic outcomes would be particularly valuable.

Micronutrient-Metabolic Health Relationships

While associations between micronutrient deficiencies and metabolic disease are well-documented, the causal relationships and potential for intervention remain unclear. Randomized controlled trials of micronutrient supplementation or dietary interventions to improve micronutrient status, with metabolic outcomes as endpoints, would help clarify whether addressing micronutrient deficiencies can improve metabolic health independent of other dietary changes.

Protein Quality and Metabolic Health

The differential effects of animal versus plant protein sources on metabolic health require further investigation. Studies should examine not only protein source but also specific amino acid composition, protein digestibility, and interactions with other dietary components. The role of individual amino acids, particularly branched-chain amino acids, in insulin resistance and metabolic disease warrants continued investigation.

Personalized Nutrition

Given the substantial inter-individual variability in responses to dietary interventions, research should identify factors that predict optimal dietary patterns for individuals. Potential moderating factors include genetics, gut microbiota composition, metabolic status, age, sex, and lifestyle factors. Integration of multi-omics approaches (genomics, metabolomics, proteomics, microbiomics) may enable more precise dietary recommendations.

Long-term Intervention Studies

Most dietary intervention studies are relatively short-term (weeks to months). Long-term randomized controlled trials (years) examining the effects of reducing ultra-processed food consumption, improving micronutrient status, and optimizing protein intake on metabolic disease incidence and progression would provide stronger evidence for causality and inform clinical and public health recommendations.

Implementation Science

Even with strong evidence for dietary interventions, translating this evidence into practice remains challenging. Research is needed on effective strategies for reducing ultra-processed food consumption, improving dietary quality, and ensuring micronutrient adequacy at individual and population levels. Implementation science approaches examining barriers, facilitators, and effective intervention strategies would help bridge the gap between evidence and practice.

5. Conclusion

This comprehensive review of evidence from 2018-2026 reveals that modern dietary patterns characterized by high ultra-processed food consumption, micronutrient deficiencies, and suboptimal protein quality and quantity collectively contribute to the global burden of metabolic disease. These three nutritional themes are not independent but rather interconnected aspects of contemporary dietary patterns that synergistically influence metabolic health.

Ultra-processed foods, now comprising 50-60% of caloric intake in many populations, are associated with substantially increased risk of obesity (OR: 1.51-1.55), type 2 diabetes (RR: 1.40), metabolic syndrome (OR: 1.81), and cardiovascular disease (RR: 1.35). These associations persist after adjustment for nutritional composition, suggesting that ultra-processing itself—through effects on eating behavior, gut microbiota, inflammation, and exposure to processing contaminants—drives metabolic dysfunction.

Micronutrient deficiencies affect over 2 billion people globally, with particularly high prevalence of vitamin D (57-94% in obese populations), iron (89% in India), magnesium (64.4% of Chinese adults), and B vitamins (86.5% B12 deficiency in vegetarians). These deficiencies occur even in affluent populations consuming calorically excessive diets, reflecting the poor nutritional quality of ultra-processed food-dominated dietary patterns. The resulting metabolic consequences—hormonal dysregulation, insulin resistance, chronic inflammation, and oxidative stress—contribute substantially to metabolic disease burden.

Dietary protein intake shows complex relationships with metabolic health depending on quantity, quality, source, and individual metabolic status. While moderate protein intake (1.2-1.5 g/kg/day) supports weight management and lean mass preservation, protein restriction may optimize insulin sensitivity in individuals with metabolic syndrome. Plant-based protein sources generally demonstrate superior metabolic effects compared to animal proteins, particularly red and processed meats.

The evidence supports a paradigm shift in nutritional approaches to metabolic health, moving beyond simple calorie counting or macronutrient ratios to emphasize food quality, processing levels, micronutrient density, and protein source. Effective interventions must address the food environment and policy context that shapes dietary patterns, not simply individual behavior change.

Clinical practice should incorporate comprehensive nutritional assessment including evaluation of ultra-processed food consumption, micronutrient status, and protein quality. Dietary counseling should emphasize whole, minimally processed foods as the foundation of healthy eating, with personalized recommendations for protein intake based on age, body

composition, and metabolic status. Targeted supplementation may be appropriate for high-risk populations but should not substitute for dietary improvement.

Public health policy should prioritize reduction of ultra-processed food consumption through taxation, marketing restrictions, clear labeling, and institutional procurement policies. Population-level strategies to improve micronutrient status through fortification, biofortification, and improved dietary diversity are essential. Dietary guidelines should explicitly address food processing levels and distinguish between protein sources.

The global nutrition transition, characterized by increasing ultra-processed food consumption in low- and middle-income countries, threatens to replicate the metabolic disease burden observed in high-income countries. International efforts to preserve traditional dietary patterns, regulate ultra-processed food marketing, and strengthen local food systems represent critical public health priorities.

Future research should elucidate mechanisms linking ultra-processed foods to metabolic dysfunction, clarify causal relationships between micronutrient status and metabolic health, examine differential effects of protein sources, develop personalized nutrition approaches, and identify effective implementation strategies for translating evidence into practice.

The convergence of evidence across micronutrient deficiencies, ultra-processed food consumption, and dietary protein intake reveals that addressing the global burden of metabolic disease requires comprehensive transformation of food systems and dietary patterns. The challenge is substantial, but the evidence base for action is compelling. The health and economic costs of inaction—measured in billions of people affected by micronutrient deficiencies, hundreds of millions with metabolic diseases, and trillions of dollars in healthcare costs and lost productivity—demand urgent and sustained response from clinicians, researchers, policymakers, and society as a whole.

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