Perspective

Dietary Diversity Deficiency: The Phytochemical Desert of Ultra-Processed Foods

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ABSTRACT/KEY POINTS

1. Dietary diversity is biologically important for human health.
2. A major benefit of dietary diversity is exposure to diverse phytochemicals.
3. Many food-system practices increase or decrease phytochemical diversity.
4. Ultra-processed foods (UPFs) are unusually poor sources of phytochemical diversity.
5. Chronic consumption of UPFs may create a state of dietary diversity deficiency.
6. Dietary diversity deficiency may contribute to increased risk of chronic diseases.

KEYWORDS

Dietary diversity, phytochemical diversity, ultra-processed foods, dietary diversity deficiency, phytochemical desert

I.INTRODUCTION

A central question regarding ultra-processed foods is whether their adverse health associations arise primarily from harmful constituents or from the beneficial biological diversity these foods fail to provide. Most contemporary discussions of ultra-processed foods (UPFs) focus on what these products contain: excessive amounts of added sugars, refined starches, sodium, unhealthy fats, food additives, and contaminants derived from processing or packaging. These characteristics have been proposed as important contributors to obesity, type 2 diabetes, cardiovascular disease, certain cancers, and other chronic conditions. While these explanations are biologically plausible and supported by a growing body of evidence, they may not fully explain the consistent associations observed between high ultra-processed food consumption and poor health outcomes.

An alternative perspective is that ultra-processed foods may be harmful because they displace dietary diversity. Humans evolved consuming a wide variety of plant and animal foods, each contributing a unique array of nutrients, bioactive compounds, and microbial substrates (*Table* 1). Modern dietary recommendations similarly emphasize diversity among fruits, vegetables, legumes, nuts, seeds, whole grains, and other minimally processed foods because no single food contains the full complement of compounds required to support optimal physiological function.

Diverse diets also provide exposure to thousands of phytochemicals. Their effects on inflammation, oxidative stress, immune regulation, the gut microbiome, vascular function, and metabolism are discussed in detail below. [1-4]

Notably, phytochemical diversity is not restricted to food plants alone. Plant-derived compounds consumed by grazing livestock can be transferred into animal-derived foods, resulting in higher concentrations of carotenoids, phenolic compounds, terpenoids, and other bioactive molecules in products from pasture-based systems. Consequently, the diversity of bioactive compounds available to humans may be influenced not only by the variety of plants consumed directly but also by the biodiversity present within agricultural ecosystems and food production systems. [15]

Viewed from this perspective, ultra-processed foods represent a striking departure from the dietary environments that shaped human biology. Although often energy-dense and highly palatable, they are commonly manufactured from refined ingredients that have been separated from the complex botanical matrices from which they originated. As a result, they may provide calories and selected nutrients while supplying relatively little of the immense phytochemical diversity characteristic of whole and minimally processed foods.

I propose that chronic consumption of phytochemically sparse

diets may create a state of "dietary diversity deficiency," defined here as inadequate exposure to the diversity of phytochemicals, microbial substrates, and other bioactive compounds historically characteristic of human diets. This "phytochemical desert" hypothesis complements established explanations for the health effects of ultra-processed foods and warrants systematic investigation.

***Table* 1. Key Dietary Constituents**

Dietary diversity function	Key rationale
Promotes nutritional adequacy	No single food supplies the full range of nutrients required for human health. Beyond macronutrients, vitamins, minerals, essential amino acids, and essential fatty acids are required for life and health.
Promotes microbiome diversity	A diverse diet provides various fibers, polyphenols, and plant secondary metabolites that support microbial richness, metabolite production, and immune regulation.
Promotes phytochemical diversity	Dietary phytochemicals act as biological regulatory signals that interact with human physiology in ways that influence resilience, adaptation, and regulation across multiple systems.

II. DIETARY DIVERSITY AS A BIOLOGICAL REQUIREMENT

Dietary diversity is a longstanding principle of human nutrition. Across cultures and dietary traditions, healthful eating patterns are characterized not by reliance on a small number of foods, but by the regular consumption of a wide variety of plant and animal food sources. This diversity helps ensure adequate intake of essential nutrients while simultaneously exposing the body to an extensive range of bioactive compounds that influence metabolism, immunity, and physiological resilience.

At its most basic level, dietary diversity promotes nutritional adequacy. No single food contains all essential amino acids, fatty acids, vitamins, minerals, and trace elements required for optimal health. Diets composed of diverse fruits, vegetables, legumes, grains, nuts, seeds, and animal products are therefore more likely to provide the full spectrum of nutrients necessary to support growth, reproduction, tissue maintenance, and healthy aging. For this reason, dietary diversity has long been a cornerstone of nutritional recommendations worldwide.

Beyond preventing classical nutrient deficiencies, dietary diversity broadens exposure to bioactive compounds that influence cellular signaling, vascular function, energy metabolism, and tissue repair. Major phytochemical classes and their mechanisms are considered in the next section. [1-3] Dietary diversity also supplies varied fibers, resistant starches, and polyphenols that support a broad microbial ecosystem. The bidirectional relationship between phytochemicals and the gut microbiome is discussed below. [3,5] Emerging evidence also suggests that dietary phytochemicals may influence immune tolerance and regulatory T-cell function. [3,4]

It is important to recognize that dietary diversity is not simply the number of foods consumed, but rather the diversity of bioactive chemical signals that are delivered through the food supply. Two diets may contain similar quantities of calories, protein, fat, and carbohydrates while differing profoundly in their diversity of phytochemicals, microbial substrates, and bioactive metabolites. Consequently, conventional measures of nutritional adequacy may underestimate the physiological importance of dietary diversity. From this perspective, dietary diversity can be regarded as a form of biological richness. Just as ecological diversity promotes resilience within natural ecosystems, dietary diversity may promote resilience within human physiological systems by providing a broad array of complementary nutrients, phytochemicals, and microbiome-supporting compounds. The health consequences of reducing that diversity may therefore extend far beyond simple nutrient deficiency and represent an important, but often overlooked, dimension of modern dietary patterns.

III. PHYTOCHEMICALS AS BIOLOGICAL REGULATORS

Unlike vitamins or minerals, many phytochemicals are not required to prevent any well-characterized deficiency disease. Humans can survive without dietary flavonoids, carotenoids, terpenoids, or isothiocyanates. However, accumulating evidence suggests that these compounds help regulate processes that influence long-term health, including inflammation, oxidative stress, metabolism, immune function, and host-micro-biome interactions (*Table* 2).

A useful way to think about phytochemicals is that they are exogenous molecular messengers that provide the body with information about the biological environment represented by the diet and these bioactive compounds mediate some endogenous effects. Greater dietary diversity exposes humans to a broader spectrum of these signaling molecules, potentially enhancing physiological adaptability and resilience.

Effects on Oxidative Stress, Cellular Defense, and Inflammation

Many phytochemicals activate endogenous antioxidant defense systems rather than simply acting as antioxidants themselves. Polyphenols, carotenoids, and related compounds can stimulate cellular pathways such as Nrf2, increasing expression of genes involved in antioxidant protection, detoxification, and cellular repair. As a result, regular exposure to phytochemicals may help reduce cumulative oxidative damage to lipids, proteins, DNA, and cellular membranes, processes implicated in aging, cardio-vascular disease, neurodegenerative disorders, and cancer.

Numerous phytochemicals also influence inflammatory and cellular-defense pathways, including NF-κB, MAPK, Nrf2, and AhR signaling. These effects may alter cytokine production,

oxidative-stress responses, and resolution of inflammation. [3,6]

Effects on the Gut Microbiome

Many phytochemicals reach the colon where they interact directly with gut microorganisms. Some act as microbial substrates, while others selectively inhibit or promote specific microbial populations. This bidirectional relationship is important because gut microbes also transform phytochemicals into biologically active metabolites that may differ substantially from the original compounds consumed. Thus, dietary diversity can generate both greater phytochemical diversity and greater metabolic diversity within the gut eco-system.

Effects on Immune Regulation

Certain phytochemicals and their microbial metabolites may also influence immune homeostasis, including pathways involved in regulatory T-cell differentiation and function. Detailed implications for immune tolerance are considered in Section IV. [3,4]

Effects on Cardiovascular and Metabolic Health

Many phytochemicals affect endothelial function, lipid metabolism, glucose regulation, and insulin sensitivity. Diets rich in fruits, vegetables, legumes, nuts, seeds, and other minimally processed foods consistently correlate with lower risks of cardiovascular disease and metabolic disorders. While these benefits likely arise from multiple dietary factors, phytochemical diversity is increasingly recognized as a potentially important contributor.

***Table* 2. Major Classes of Dietary Phytochemicals**

Phytochemical class	Examples or subclasses	Functional domains influenced
Polyphenols	Flavonoids, phenolic acids, lignans	Antioxidant signaling, inflammation regulation, microbial interactions, immune modulation
Carotenoids	Lutein, zeaxanthin, beta-carotene	Antioxidant signaling and endothelial health
Organosulfur compounds	Glucosinolate derivatives and related compounds	Inflammation regulation and cellular defense
Terpenoids, alkaloids, and phytosterols	Diverse plant-derived secondary metabolites	Endothelial health, microbial interactions, and immune modulation

IV. DIETARY DIVERSITY IN PLANT AND ANIMAL FOODS

Beyond individual food choices, dietary diversity also reflects ecological diversity within food-production systems. Humans obtain phytochemicals directly from plants and indirectly from some animal foods produced in biologically diverse environments.

A. Dietary Diversity of Plants Yields Phytochemical Diversity

A diverse diet of plant foods appears to benefit human health by improving overall diet quality, broadening intake of fiber and micronutrients, lowering inflammatory burden, and associating with lower risks of mortality, stroke, gout, and biological aging. Additionally, diverse non-nutritive phytochemicals matter because different plant foods supply distinct bioactive compounds that act through antioxidant, anti-inflammatory, microbiome, hormonal, and epigenetic pathways. [1-3,5] The evidence spans observational cohorts, a meta-analysis of longitudinal studies, and mechanistic reviews, so the broad direction is consistent, but causality is not equally strong for every outcome, [1,2,4,5]

Plant Diversity and Human Health

Dietary diversity is generally interpreted as a food-based marker of healthier eating because people who consume a wider range of food groups tend to achieve better nutrient adequacy and higher overall diet quality. [5,7] In the I. Family Cohort, higher dietary diversity scores were positively associated with diet quality across children, adolescents, and adults. [7] Higher-diversity participants in that cohort also consumed more fiber, fruit, and vegetables and less ultra-processed food, placing plant-food diversity within an overall healthier dietary pattern. [7]

The same meta-analysis concluded that the protective signal was strongest for survival and some cardiovascular out-comes, while evidence for cancer was limited or null in several analyses. [5] That nuance matters because "dietary diversity" is not automatically beneficial if it simply adds more foods without regard to quality (*Table* 3). [5,7]

Specific Human Outcomes

In the strongest outcome-level evidence, adults consuming more diverse diets had lower all-cause mortality, and diets with diversity across healthy foods showed an additional survival advantage (*Table* 4). [5] The meta-analysis also found an inverse association between total dietary diversity and incident cardiovascular disease in non-European populations consuming diverse food groups. [5]

A Mediterranean dietary pattern, which is explicitly characterized by high consumption of plant foods, was associated with lower total, ischemic, and hemorrhagic stroke risk in women over long follow-up. [8] Higher adherence to this plant-rich pattern has also been associated in that cohort background with longer survival and lower cardiovascular and neurodegenerative risk. [8]

Dietary diversity was also associated with lower gout risk in a large prospective cohort of 161,213 participants, with intermediate and high diversity scores linked to hazard ratios of 0.798 and 0.807. [9] In that same study, grains, dairy, vegetables,

and fruits each showed inverse associations with gout risk, supporting the idea that diverse healthy foods rather than single "superfoods" drive benefit. [9]

***Table* 3. Strength of Evidence for Plant-Rich Diet Diversity Benefits**

Evidence strength	Evidence source	Claim
Strong (8/10)	Meta-analysis of 20 longitudinal studies [5]	Greater total dietary diversity was associated with 22% lower all-cause mortality.
Moderate (7/10)	Meta-analysis of dietary diversity and mortality [5]	Diversity across healthy foods was associated with 16% lower all-cause mortality.
Moderate (6/10)	I. Family Cohort [7]	Higher dietary diversity was associated with better diet quality and higher fiber, fruit, and vegetable intake.

***Table* 4. Major Human Outcomes Linked to Diverse Plant-Rich Diets**

Outcome	Main finding	Evidence source	Evidence type
All-cause mortality	22% lower risk with higher total diversity	Mozaffari et al [5]	Meta-analysis
Stroke	HR 0.82 for high Mediterranean adherence	Sherzai et al [8]	Prospective cohort
Gout	HR 0.798 to 0.807 for intermediate to high diversity	Liu et al [9]	Prospective cohort
Biological aging	Better diet quality linked to slower aging measures	Reynolds et al; Ferreri et al [1,2]	Cross-sectional human studies

Why Phytochemical Diversity Matters

Plant diversity in the human diet matters not only for vitamins, minerals, and fiber, but also because different plant subtypes provide different secondary plant metabolites, including phytochemicals. [5] Vegetable subtype diversity is specifically emphasized because eating many items from one subtype can miss unique compounds found in others. [5]A diet rich in raw fruits and vegetables supplies phytoestrogen and other bioactive compounds with antioxidant and anti-inflammatory actions, and these compounds are presented as capable of activating protective biological mechanisms. [3] Dietary patterns likely work through synergistic or cumulative effects of many compounds rather than through one isolated nutrient. [3,5]

Specific plant foods provide distinct phytochemical profiles. Cruciferous vegetables, onions and garlic, berries, flax and chia seeds, and mushrooms contain compounds with demonstrated anticancer or anti-inflammatory activity in experimental or intervention literature. [2] Mushrooms are also the primary dietary source of ergothioneine, a specialized antioxidant proposed as a longevity mediator. [2] Peanuts provide resveratrol, phenolic acids, flavonoids, phytosterols, fiber, vitamin E, and other antioxidant compounds, and reviews describe these bioactive phytochemicals as disease-preventive and potentially longevity-promoting (*Table* 5). [10]

***Table* 5. Examples of Bioactive Phytochemicals from Diverse Plants**

Plant food group	Examples of non-nutritive phytochemicals	Reported relevance	Evidence source
Crucifers, alliums, berries	Multiple experimental anticancer and anti-inflammatory compounds	Protective mechanisms	Ferreri et al [2]
Mushrooms	Ergothioneine	Specialized antioxidant, proposed longevity role	Ferreri et al [2]
Peanuts	Resveratrol, flavonoids, phenolic acids, phytosterols	Antioxidant and cholesterol-related effects	Arya et al [10]
Fruits and vegetables broadly	Phytoestrogens and multiple others	Antioxidant and anti-inflammatory actions	Ionescu et al [3]

Aging, Inflammation and Mechanisms

Better diet quality scores that emphasize fruits, vegetables, greens, beans, whole grains, nuts, legumes, and plant-based proteins were inversely associated with several DNA methylation measures of biological aging in postmenopausal women, with the largest effects seen for DunedinPACE. [1] Because that analysis was cross-sectional and based on self-reported food-frequency data, it supports association rather than causation. [1]

A nutrient-dense, plant-rich diet emphasizing legumes,

crucifers, alliums, berries, mushrooms, nuts, and seeds was associated with slower epigenetic aging, lower dietary inflammatory potential, lower CRP-related signals, and more favorable immune-cell proxies than a standard American diet in women who had followed these patterns for at least five years. [2] That pattern also aligns with prior work cited by Ferreri et al linking the diet to improved cardiovascular risk markers, glycemic control in diabetes, and weight loss. [2]

Work by various investigators seems to converge on several mechanisms (*Table* 6). Diverse diets can increase gut microbiota variety and adaptability. [5] Diet constituents can modulate inflammation, immune function, oxidative stress, metabolite profiles, hormonal responses, and epigenetic regulation. [3] Plant-based eating can rapidly alter gut microbial structure and microbial gene expression, which is relevant because microbial metabolism helps transform plant precursor compounds into active metabolites. [3]

Limits and Open Questions

The evidence is not uniformly definitive. Reviews of dietary diversity note inconsistent findings for some non-communicable disease outcomes, adiposity, and cancer, partly because studies use different diversity definitions and due to population and disease heterogeneity, cannot always separate healthy from unhealthy outcomes. [5,7] Several authors therefore call for standardized diversity measures and better control for quantity and quality of intake (*Table* 7). [5]

Taking the class of phytoestrogens as one well-studied example, the evidence therein is mixed. Reviews describe many proposed benefits, including lower risks of menopausal symptoms, osteoporosis, cardiovascular disease, metabolic syndrome, diabetes, and some cancers. [4] However, the same reviews stress that phytoestrogens can also act as endocrine disruptors, note that current evidence does not clearly show that benefits outweigh risks, and comment that no definitive conclusion on overall benefit can yet be made. [4] Inter-individual differences in gut microbial metabolism of this class of bioactive molecules further complicates interpretation because different people produce different downstream metabolites from the same dietary compounds. [3,4]

Bottom Line

Taken together, the evidence supports a clear overall message; namely, that eating a diverse range of plant foods is associated with healthier diet patterns and with favorable outcomes for survival, vascular health, inflammation, gout risk, biological aging, and others. [2,5,7-9] The most important shift in this evidence is from thinking about single nutrients to thinking about diverse whole-food patterns that deliver complementary phytochemicals and shape the microbiome, inflammation, and epigenetic regulation. [3,5,7] The principal open questions concern which forms and amounts of plant-food diversity provide the greatest net benefit, for whom, and with what balance of benefit and risk for specific phytochemical classes such as phytoestrogens. [3-5]

***Table* 6. Mechanisms Linking Plant Diversity to Human Health**

Mechanistic domain	Evidence	Evidence source
Microbiome	Greater diversity can increase intestinal microbiota variety and adaptability	Mozaffari et al [5]
Inflammation	Plant-rich diets showed lower inflammatory potential and CRP-related signals	Ferreri et al [2]
Epigenetics	Diet quality and phytoestrogens can modulate DNA methylation-related pathways	Reynolds et al; Ionescu et al [1,3]
Oxidative stress	Plant bioactive molecules are described as antioxidant and protective	Ionescu et al [3]

***Table* 7. Main Uncertainties in Diet Diversity and Phytochemical Research**

Uncertainty	Source/cause	Evidence source
Measuring diversity	No standardized definition or method exists	Mozaffari et al; Di Russo et al [5,7]
Causality	Several key studies are observational or cross-sectional	Reynolds et al [1]
Phytoestrogen balance	Benefits and risks remain unresolved	Rietjens et al [4]
Heterogeneity	Gut microbiota changes metabolite production across individuals	Ionescu et al; Rietjens et al [3,4]

B. Dietary Diversity Beyond Plants: Transfer Through Some Animal Foods

Phytochemicals Consumed by Animals

When grazing animals consume mixed pastures, they ingest thousands of plant secondary metabolites, including:

- carotenoids
- flavonoids
- phenolic acids
- terpenoids
- tannins
- glucosinolate derivatives
- phytoestrogens
- other polyphenols

The quantity and diversity of these compounds depend on forage biodiversity. In pasture-based systems, plant-derived compounds or their metabolites enter animal tissues and products, with lipophilic compounds preferentially accumulating in adipose tissue, milk fat, egg yolk, and intramuscular fat. [15]

Transfer Into Human Foods

The transfer pathways differ by food type.

Eggs

In laying hens, carotenoids are transported directly into the developing yolk. The deep orange color of egg yolks from pastured poultry reflects accumulation of lutein, zeaxanthin and β-carotene derived from forage plants and insects. Compared with eggs from conventionally managed poultry, eggs from pastured poultry contain higher levels of lutein, zeaxanthin, beta-carotene, vitamin E, and various terpenoids. [15]

Dairy Products

In dairy cattle, absorbed phytochemicals and metabolites are secreted into milk. Examples include carotenoids, phenolic metabolites, terpenoids, and phytoestrogen metabolites such as equol. These compounds partition preferentially into the milk fat fraction. Compared with dairy products from more conventionally managed ruminant livestock, dairy from pastured livestock contains higher levels of carotenoids, phenols, terpenoids, and omega-3 fatty acids. [15]

Meats

Animals grazing diverse pastures accumulate phytochemicals within fat and muscle tissues. Grass-fed beef and lamb contain higher concentrations of carotenoids, vitamin E, phenolic metabolites, and certain terpenoid compounds compared with animals raised principally on grain-based diets. [15]

Rumen and Intestinal Metabolism

Not only do phytochemicals transfer through animals but those compounds often undergo biological transformations rather than simple accumulation. Many phytochemicals are altered by microbial and enzymatic metabolism before entering the animal's circulation. [15]

For example:

- Isoflavones from clover are converted by rumen microbes into metabolites such as equol.
- Polyphenols may be broken down into smaller phenolic compounds.
- Carotenoids may be partially absorbed intact or converted into retinoids.
- Terpenoids often survive digestion and enter circulation with relatively little modification.

The compounds found in dairy, eggs, and meat may therefore differ from those in the original plants. Grazing livestock can act as biological concentrators and trans-formers of plant-derived compounds, translating pasture diversity into the molecular profile of foods consumed by humans. [15]

V. ULTRA-PROCESSED FOODS AS PHYTOCHEMICAL DESERTS

Ultra-processed foods represent the extreme endpoint of a

continuum of declining dietary phytochemical diversity. In addition to established concerns involving sugars, sodium, unhealthy fats, hyper-palatability, additives, and processing-related contaminants, UPFs may chronically reduce expo-sure to the phytochemical diversity characteristic of whole-food diets. [11-14]

The Phytochemical Desert Hypothesis

The term “phytochemical desert” describes the foods or dietary patterns that provide energy and essential macronutrients while offering limited exposure to the bioactive compounds that are characteristic of diverse whole -food diets. UPFs are manufactured from isolated ingredients, largely stripped of plant diversity and are depleted of phytochemicals. Consequently, they provide calories and macronutrients but mini-mal exposure to polyphenols, carotenoids, organosulfur compounds, terpenes, and numerous other plant metabolites. [11-14] The term is intended to serve as a conceptual analogy, not as evidence of a recognized deficiency disorder.

Unlike whole or minimally processed foods, UPFs are typically manufactured from refined fractions of plants and animals, including purified starches, sugars, oils, protein isolates, and other ingredients. During processing, much of the structural, chemical, and biological complexity present in the original food is removed. Although some vitamins and minerals may be added back through fortification, the thousands of bioactive compounds naturally present in diverse food matrices are rarely restored.

As a result, UPFs often provide calories and macronutrients while supplying relatively little phytochemical diversity. Polyphenols, flavonoids, carotenoids, terpenoids, organo-sulfur compounds, and numerous other plant-derived metabolites are markedly reduced or absent following extensive processing. Even when ingredients derived from plants remain present, their phytochemical profiles are frequently diminished through refining, fractionation, extraction, heating, storage, and formulation processes.

The consequences may extend beyond conventional nutrient loss because phytochemicals participate in oxidative-stress responses, inflammation, immune function, microbial ecology, vascular health, and cellular signaling. [2,3,6]

Moreover, diets high in UPFs do not merely reduce phytochemical intake directly; they often displace foods that are naturally rich in phytochemicals. Each serving of a highly processed snack, sugar-sweetened beverage, or industrially formulated meal may represent a missed opportunity to consume fruits, vegetables, legumes, nuts, seeds, whole grains, or animal products derived from biologically diverse production systems. Consequently, the biological impact of UPFs may arise both from their intrinsic characteristics and from the loss of dietary diversity that accompanies their consumption.

This perspective suggests that the adverse health associations of UPFs may partly reflect dietary diversity deficiency. Such diets may meet caloric requirements while providing limited exposure to phytochemicals, microbial substrates, and other bioactive compounds. UPFs therefore occupy one extreme of a

continuum from biologically rich food systems to biologically simplified products.

From a phytochemical perspective, UPFs may be regarded as dietary diversity deserts. They are convenient, shelf-stable products that often provide only a fraction of the chemical diversity present in whole-food dietary patterns. The following examples illustrate a continuum of phytochemical exposure rather than a binary classification of healthy and unhealthy foods:

A. Extreme Phytochemical Deserts

These foods contain few if any naturally occurring phytochemicals because they are manufactured largely from refined ingredients.

- Sugar-sweetened soft drinks
- Energy drinks
- Candy
- Hard candies and gummies
- Frosting
- Refined sugar products
- Flavored gelatin desserts

Such products may provide calories, sweetness, and palatability but essentially no meaningful phytochemical diversity.

B. Ultra-Processed Starch-Based Foods

These foods are often derived from plants but retain little of the original plant's chemical complexity.

- Potato chips
- Corn chips
- Cheese puffs
- Crackers made from refined flour
- Instant noodles
- Many breakfast cereals
- Packaged snack foods

Although originating from plant sources, processing removes much of the fiber, polyphenols, carotenoids, and other secondary metabolites present in the original ingredients.

C. Reconstituted Industrial Foods

These may contain long ingredient lists and substantial fortification yet remain phytochemically sparse.

- Many frozen entrées
- Fast-food products
- Mass-produced pastries
- Shelf-stable meal replacements
- Processed meat sandwiches
- Packaged desserts

Nutritionally, they may contain added vitamins and minerals while remaining biologically simplified.

D. Animal Food Phytochemical Deserts

The same compositional limitations are relevant for animal food products in the human diet.

Examples are summarized in *Table* 8. The point is not that these foods are uniquely unhealthy. Rather, they tend to contain substantially less phytochemical diversity because the animals themselves consumed less diverse diets.

***Table* 8. Animal-Food Examples Along a Continuum of Phytochemical Exposure**

Food type	Higher phytochemical exposure	Lower phytochemical exposure	Evidence source
Eggs	Pasture-raised eggs	Eggs from hens fed monotonous grain diets	Provenza et al [15]
Dairy	Grass-fed dairy	Dairy from confined corn-soy feeding systems	Provenza et al [15]
Meat	Pasture-raised beef	Feedlot beef	Provenza et al [15]
Fish	Fish consuming wild diets	Fish raised on highly standardized aquaculture diets	Conceptual extension from animal-food transfer framework [15]

E. Dietary Patterns as Phytochemical Deserts

Moving beyond individual foods, entire dietary patterns can become phytochemical deserts.

For example:

Breakfast

- Sweetened cereal
- White toast
- Fruit-flavored beverage

Lunch

- Fast-food burger
- Fries
- Soda

Dinner

- Frozen pizza
- Dessert snack cake

This diet may supply adequate calories, protein, fat, and carbohydrates while exposing the individual to only a narrow spectrum of phytochemicals.

Contrast that with:

Breakfast

- Berries
- Nuts
- Oats

Lunch

- Mixed vegetables
- Legumes
- Whole grains

Dinner

- Diverse vegetables
- Herbs and spices

- Pasture-derived animal foods

The latter delivers hundreds of distinct phytochemicals daily.

The phytochemical desert hypothesis does not replace established explanations for UPF-associated health risks. It adds a complementary focus on the biological signals that are absent when whole foods are refined, fractionated, or displaced.

VI. BIOLOGICAL CONSEQUENCES OF DIETARY DIVERSITY DEFICIENCY

Diseases Potentially Affected

If the hypothesis is correct, phytochemically sparse diets could contribute to chronic disease through interacting effects on the gut microbiome, immune regulation, oxidative-stress responses, and metabolism. These mechanisms remain plausible hypotheses rather than established causal pathways.

Reduced microbial diversity/gut microbiome effects

↓ phytochemical diversity → ↓ microbial diversity → ↓ beneficial metabolites

Gut microbes both respond to phytochemicals and transform them into bioactive metabolites. A low-diversity diet could therefore reduce or alter microbial diversity and the production of metabolites involved in barrier integrity, mucosal immunity, inflammatory regulation, and Treg development.

Immune dysregulation and Immune tolerance

↓ phytochemical exposure → ↓ Treg support → ↑ chronic inflammation

Chronic exposure to a chemically simplified diet may reduce the diversity of signals that support immune homeostasis. The concern is not the absence of any single phytochemical, but the cumulative loss of multiple direct and microbiome-mediated regulatory inputs. For example, regulatory T cells (Tregs) help limit excessive inflammation and inappropriate immune responses. Flavonoids, polyphenols, indole derivatives, and microbial metabolites of plant compounds have been reported to influence pathways involving FoxP3 expression, IL-10 production, Treg differentiation, and Treg stability. [3,4] Through direct effects on immune cells and indirect effects mediated by the gut microbiome, diverse phytochemical exposure may support immune tolerance. Conversely, prolonged exposure to phytochemically impoverished diets could contribute to immune dysregulation and persistent low-grade inflammation; this proposed pathway requires direct testing.

Reduced antioxidant signaling

↓ antioxidant signaling → ↑ oxidative stress → ↑ vascular and cellular injury

Reduced activation of endogenous antioxidant-defense pathways could increase susceptibility to cumulative oxidative damage. This mechanism is biologically plausible but has not been established as a consequence of dietary diversity deficiency. [3,6]

Metabolic dysfunction

↑ adiposity → ↑ insulin resistance → ↑ type 2 diabetes risk

Reduced phytochemical and fiber exposure may adversely affect glucose regulation, insulin sensitivity, lipid metabolism, and energy balance. Whether these effects are independently attributable to phytochemical diversity remains to be determined. [5,8,9]

VII. TESTING THE HYPOTHESIS

The hypothesis requires additional studies that distinguish the effects of UPF exposure, phytochemical exposure, and dietary diversity while accounting for dietary quality, quantity, and other confounding factors. Complementary biomarker, index-based, and prospective approaches could test whether phytochemical diversity adds predictive or mechanistic information beyond conventional nutrient measures. Potential approaches are likely to integrate biomarker studies and diet diversity scores in prospective cohort studies.

A. Biomarker studies

Use urinary biomarkers and complementary plasma measures to quantify exposure to food-derived phytochemicals and their metabolites. Urine is often a preferred matrix for dietary biomarker studies because many food-derived metabolites are excreted in urine, and metabolomics can detect panels of non-nutrient biomarkers that reflect intake of specific foods, food groups, or broader dietary patterns. [16]

- proline betaine
- alkylresorcinol metabolites
- isothiocyanate metabolites
- flavonoid metabolites
- targeted or untargeted urinary metabolomic panels that quantify multiple dietary polyphenol metabolites and other non-nutrient biomarkers
- polyphenol metabolites

Examples include proline betaine as a biomarker of citrus intake, alkylresorcinol metabolites as biomarkers of whole-grain intake, and urinary polyphenol metabolite panels associated with plant-derived food groups such as citrus fruit, coffee, tea, and wine. A biomarker strategy for dietary diversity deficiency should therefore emphasize panels rather than single markers, because the hypothesis concerns breadth of phytochemical exposure rather than exposure to one food or compound. [16]

Biomarker validation should include plausibility, dose-response behavior, temporal response, robustness across populations, analytic reproducibility, and cross-validation across laboratories. Because different specimens capture different exposure windows, urinary biomarkers should be interpreted alongside plasma or other matrices when feasible, particularly in prospective studies designed to relate phytochemical diversity to disease risk. [16]

B. Diet diversity scores

The dietary diversity index, phytochemical diversity index and UPF consumption fraction are complementary but distinct exposure metrics. The dietary diversity index captures the breadth of food groups consumed [5,7], the phytochemical diversity index estimates the range of non-nutrient bioactive compounds delivered by the diet [1-5,16], and the UPF

consumption fraction quantifies the share of total energy or food intake derived from ultra-processed foods [11-14]. These measures should not be treated as interchangeable. A high dietary diversity score may reflect a broad diet but not necessarily a phytochemically rich one if diversity is driven by refined or ultra-processed products; conversely, a phytochemical diversity index may better capture the biological richness of minimally processed plant foods and pasture-derived animal foods. [1-5,15,16] The UPF fraction provides a complementary negative exposure metric because it may identify displacement of phytochemical-rich foods as well as exposure to industrial formulations. [11-14]

Analyses should examine correlations among the three metrics and assess whether each retains independent associations with biomarkers or outcomes after mutual adjustment. This approach can distinguish whether UPF exposure is primarily acting as a marker of low dietary diversity [5,7], whether phytochemical diversity captures additional biological information [1-5,16], or whether combined indices best represent the hypothesized dietary diversity deficiency state. [5,7,11-16]

C. Prospective cohort studies

Prospective cohort studies should model incident disease risk using parallel exposure variables for UPF fraction, dietary diversity score, phytochemical diversity score, measured phytochemical biomarkers where available, and combinations thereof. Predictive strength can be compared by estimating mutually adjusted hazard ratios, dose-response gradients, model fit, discrimination, calibration, and reclassification when each exposure is added to a base model containing demographic, lifestyle, total energy intake, and overall diet-quality covariates. [5,7,11-16] A useful analytic sequence would test: first, each exposure separately [5,7,11-16]; *second*, UPF fraction and dietary diversity in the same model [5,7,11-14]; *third*, phytochemical diversity or urinary biomarker panels added to those models [1-5,16]; and fourth, interaction or mediation models to evaluate whether low phytochemical exposure explains part of the UPF-associated risk. [11-16] If UPF fraction remains strongly predictive after adjustment for phytochemical exposure, harmful constituents or processing-related factors may be important. [11-14] If phytochemical exposure weakens or mediates the UPF association, dietary diversity deficiency may be a plausible mechanism. [1-5,16]

VIII. ECOLOGICAL PERSPECTIVE

The phytochemical desert may be a property not only of a food item but also of the agricultural and food processing system that produced it.

a Healthful dietary exposure to biologically active dietary phytochemicals is fostered by ecosystem diversity, leading to food-system diversity, leading to dietary diversity.

b Monoculture production, confined feeding systems, industrial fractionation and further refinement progressively reduces the compositional complexity and phytochemical content before food reaches the consumer.

IX. SUMMARY

Dietary diversity may promote health not only by improving nutrient adequacy but also by broadening expo-sure to phytochemicals that influence oxidative-stress responses, inflamemation, immune function, microbial ecology, and cellular signaling. The central hypothesis is that UPFs may contribute to chronic disease both through potentially harmful constituents and through chronic underexposure to the phytochemical richness of diverse, minimally processed diets. This complementary framework is plausible but requires direct measurement and prospective testing.

CONFLICTS OF INTEREST

The author declares no conflicts of interest regarding the publication of this paper.

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During the preparation of this work, the author used Google Gemini AI to identify some of the relevant references for the subject. The author used Consensus AI and MS CoPilot AI to enhance readability and language of the manuscript. After using these AI tools, the author reviewed and edited the contents as needed and takes full responsibility for the content of the published article.

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