



# Soil quality and the nutritional integrity of crops: Impacts on micronutrients, bioactive compounds, and health-promoting foods

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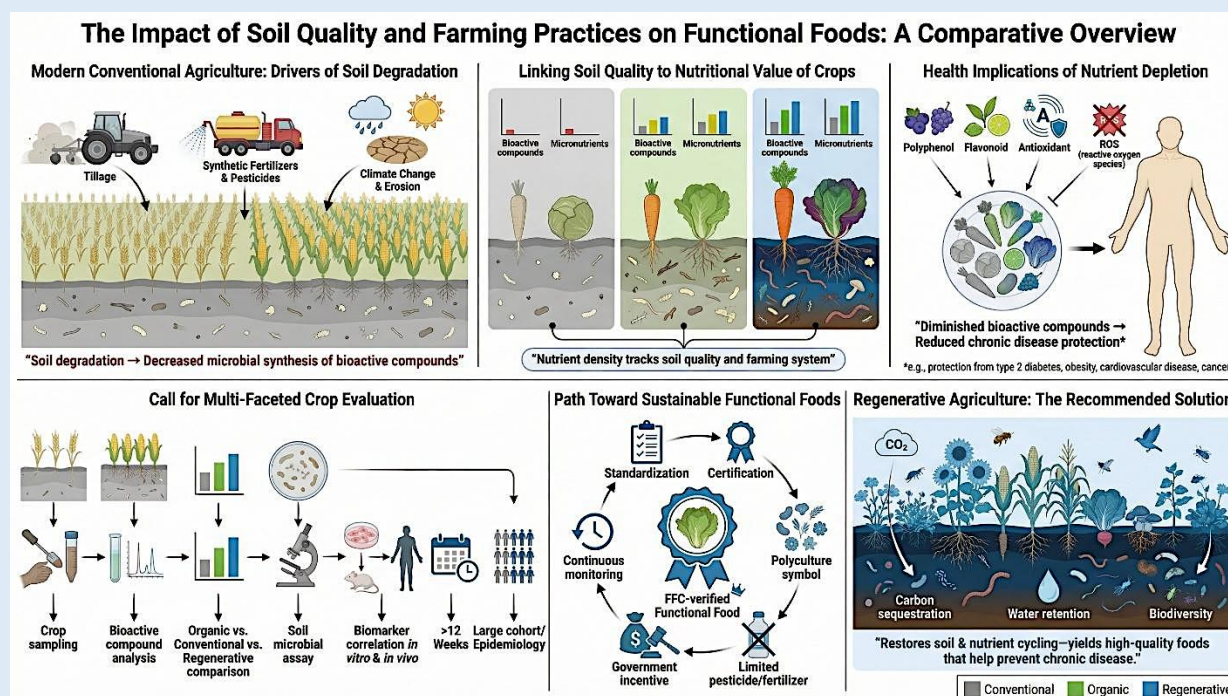
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## ABSTRACT

To meet the escalating food demands of the global population, contemporary agricultural farmers have prioritized increasing crop yield and biomass through aggressive agronomic practices. However, these methods lead to soil degradation, compromising the essential environment for nutrient synthesis. This review examines how the intersection of agricultural practices, such as tillage, synthetic fertilization, and land use, with environmental stressors (climate change and erosion) diminishes soil quality. The deterioration of soil quality directly impacts the nutritional profile of crops, reducing levels of essential micronutrients and bioactive compounds. Analysis indicates that products grown using organic farming techniques contain higher levels of bioactive compounds (e.g., antioxidants), whereas conventionally grown products contain lower levels. Additionally, regenerative farming is entering the mainstream as an alternative to conventional farming, helping restore and maintain soil health while producing nutrient-rich crops. Given the Functional Food Center's (FFC) definition of functional foods, it is vital to re-evaluate current crops through modern clinical trials. Systematic re-evaluation of crops is necessary to verify that these products provide benefits beyond basic nutrition, including the prevention of chronic diseases, and to confirm their status within the FFC's established framework.

**Novelty of the Study:** This review examines how drivers of soil degradation and agricultural practices (i.e., conventional, organic, and regenerative systems) impact soil quality and health. While previous literature has extensively documented the decline in soil quality and its effects on a crop's nutritional profile, this review addresses a conceptual gap by connecting agricultural outcomes directly to the Functional Food Center's (FFC) 17-step framework for functional food verification. Unlike traditional soil-health reviews that focus on agronomic yield or generalized comparisons between agricultural systems, this review introduces the integration of the FFC's framework for re-evaluating crops based on their bioactive potential.

**Keywords:** Soil quality, Nutrient depletion, Bioactive compounds, Organic farming, Conventional farming, Regenerative Farming, Conventional functional foods



**Graphical Abstract:** The importance of soil quality's impact on conventional functional foods

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## INTRODUCTION

Despite the decline in global birth rates, food demand remains high. By the 1900s, governments around the world recognized the urgency of increasing crop production to meet the population's food needs. This led to the Green Revolution, a transformation of agricultural practices that focused on high-yield crop production to meet the demands [1]. The reliance on these agricultural

practices is common in contemporary farms that use conventional farming, where farmers are still driven to meet quantity targets through aggressive agronomic practices, thereby increasing crop productivity and biomass [2]. However, there is an inverse correlation or trade-off: as crop production increases through unsustainable agricultural practices, the crop's nutritional profile decreases [1]. Additionally, these

conventional farming practices degrade soil health and quality, which are essential for continued production and high yields of nutritious crops [3].

To understand this degradation, it is first necessary to examine what soil requires to maintain its structure and function. For a crop to successfully synthesize, it requires 17 essential elements [4]. Crops can retrieve three of the 17 elements, hydrogen, carbon, and oxygen, through water and air, but the other 14 elements are retrieved through the soil [4]. The remaining elements can be divided into two groups: Macronutrients (primary and secondary) and micronutrients. Primary macronutrients include nitrogen (N), phosphorus (P), and potassium (K); secondary macronutrients consist of calcium, magnesium, and sulfur [4]. The primary macronutrients are responsible for ensuring the production of high-quality crops; in crop production, they primarily support structural development, disease prevention, and growth promotion by providing energy for cellular respiration and the synthesis of DNA and RNA [5]. Secondary macronutrients are also essential for structural support, as well as for chemical reactions such as photosynthesis and the synthesis of amino acids, even though they are required in smaller amounts than primary macronutrients [6]. Micronutrients include boron, chlorine, copper, iron, manganese, molybdenum, nickel, and zinc; their functions include maintaining the crop's structural integrity, supporting vitamin production, enhancing the crop's nutritional profile, and increasing yields [7-8]. These 14 elements acquired through the soil are essential for the quality, quantity, and production of crops; regardless of whether the soil has fertilizer that replenishes the primary macronutrients, farmers should ensure their soil quality meets the requirement of all 14 essential elements to produce products that will meet the nutritional needs of the population, but potentially providing benefits beyond basic nutrition, such as preventing chronic diseases [9].

When the soil has all the necessary nutrients and its physical, chemical, and microbiological properties are not altered by aggressive agronomic practices, the soil can produce high-quality crops that include essential micronutrients but also bioactive compounds [10]. Bioactive compounds are produced via the phenylpropanoid pathway, which converts the amino acid phenylalanine into various bioactive compounds, including phenolic acids, phytochemicals, flavonoids, and others [11]. The phenylpropanoid pathway is activated when crops face stress (e.g., pests, increased UV light) and produces bioactive compounds, which are also known as secondary metabolites, to protect the crop [12]. Proper or improper soil management affects micronutrient concentrations and, in turn, bioactive compounds [13]. Since bioactive compounds are produced through crops' metabolic pathways, they are directly influenced by soil quality, specifically the levels and diversity of microbes [14]. Different agronomic practices, along with soil management, are crucial tools for maintaining soil biodiversity to support the continued production of micronutrients and bioactive compounds [15]. When researchers examined mineral and phytochemical concentrations in industrially and organically grown managed crops, concentrations in industrially grown crops were significantly lower; industrial practices (e.g., tillage and chemical fertilizers) reduced the number of microbes and the diversity of the microbial community, which aids in 80-90% of the soil's metabolic pathways [16]. Without these crucial metabolic processes, the crop's resilience against diseases and stressors decreases, and the synthesis of bioactive compounds will be diminished. The decrease in bioactive compounds threatens the functionality of conventional functional foods.

Functional foods are generally defined as food products that contain bioactive compounds, either naturally (conventional) or fortified (functional food

product), that promote health benefits and can potentially mitigate the risk of chronic disease [17]. However, this general definition is ambiguous and leads to products labeled as ‘functional’ foods that often lack rigorous research and clinical data to support health benefits. For instance, with increased attention to functional food, companies are using a marketing strategy of labeling products as ‘superfoods’ and positioning them as functional to increase profits. It is crucial to adhere to the rigorous scientific criteria established by the Functional Food Center (FFC) to determine whether a crop is considered a conventional functional food.

The FFC defines a functional food as a product that promotes health and reduces the risk of disease and has established a 17-step framework to verify a functional food’s health benefit [18]. The frame ensures that a product in the marketplace is labeled as ‘functional’ only if it has undergone clinical trials, *in vivo* and *in vitro*, that establish its efficacy and safety; the product’s efficacy and safety are further established through the framework’s epidemiological and market analyses [18]. It is imperative that all functional foods, whether conventional or fortified, undergo rigorous evaluations to validate their health claims. This review examines literature on factors that degrade soil, the resulting decline in crop nutrition, a comparison of organic and conventional farming, and regenerative farming. Based on the evidence gathered, this review aims to suggest reevaluating current crops to assess their nutritional profiles and to develop a certification system that ensures soil quality and the continued production of highly nutritious crops that can be considered conventional functional foods aligned with the FFC’s 17-step framework.

**Retrieval of Published Studies:** A thematic review of the published literature on soil degraders, crop nutritional

decline, organic farming, conventional farming, and regenerative farming was conducted via electronic searches on PubMed, Google Scholar, and Arizona State University’s library database. Articles not available in English were excluded, but no other limitations were imposed. For the comparative analysis of organic and conventional farming systems, inclusion was restricted to primary and secondary studies that provided direct comparison between the two systems; studies that focused on a singular system were excluded. Both review and primary research articles published from 2016-2026 were included. Eligible articles provided relevant evidence on what degrades soil quality (with the aim of at least two studies for each soil degradation), how different agricultural practices affect crop production, and the nutrient trade-off. While a minimum of 2 studies per soil degrader was sought, soil erosion was often considered a component of climate change rather than a standalone topic; therefore, evidence for erosion was integrated into climate change. Articles were included regardless of location or crop type, as this is a global issue; however, the crop type still had to be a food item with the potential to be a conventional functional food (i.e., natural, unfortified foods that contain bioactive compounds) [19-21]. A total of 25 studies were identified and included in this review. Keywords for the search included: soil quality, soil health, bioactive compounds, chemical fertilizer, pesticides, tillage, monoculture, climate change, erosion, nutrition decline, dilution effect, secondary metabolites, nutritional profile, flavonoids, phytochemicals, organic farming, conventional farming, and regenerative farming.

### Drivers of soil degradation

**Overview:** Soil degradation is a decline in soil resilience driven by agronomic practices and climate change. Agricultural productivity in degraded soil slowly diminishes until the degradation becomes severe, and

recovery can take years [22]. Numerous factors can degrade soil, including unsustainable agricultural practices and environmental stressors used to meet the population's food satiety demands at lower cost, such as tillage, chemical fertilizers, pesticides, and monoculture. Tillage is the practice of turning soil for crop preparation, but repeated tillage leads to carbon loss, nutrient runoff, and erosion [23]. Repeated tillage reduces organic carbon storage as carbon is exposed to air and mineralizes faster than it can be replenished [22]. While tillage is for soil preparation, chemical fertilizers, also called synthetic fertilizers, are used to increase crop production [24]. While synthetic fertilizers are often a cost-effective option with immediate results, they lack the organic carbon that organic fertilizers have, which is essential for building Soil Organic Carbon (SOC), a critical factor in strengthening soil resilience against extreme weather and enhancing the soil's fertility [25]. Reliance on these inexpensive synthetic fertilizers results in declines in soil quality (i.e., structure and fertility), increased likelihood of soil acidification, increased pest populations that kill beneficial microbes, and increased overall pollution [26-27].

Pesticides are used to control factors that threaten agriculture, yet their consequences go beyond depleting a crop's nutritional profile, as they can reduce the production of bioactive compounds. Similarly, monoculture, the growth of a singular crop type, depletes specific nutrients, builds up pathogens, and reduces the soil microbes crucial for synthesizing bioactive compounds [29-30]. Without microbial diversity, crop growth is stunted, and nutrient levels are diminished [31].

Environmental stressors, such as climate change, exacerbate these issues by altering precipitation and temperature [32]. Increased rainfall heightens erosion [33], while droughts reduce yields and diminish SOC

storage. Erosion strips the nutrient-rich topsoil, reducing productivity and depositing sediment into water sources. This can trigger harmful algal blooms that produce toxins harmful to human life [34]. Ultimately, contemporary farming practices prioritize quantity and neglect soil maintenance, degrading soil fertility and preventing the production of high-quality crops necessary for food security.

**Review of Findings:** Recent research, including both review and primary research articles, provides evidence that unsustainable agronomic practices and environmental stressors are negatively impacting soil health and quality and decreasing nutrient levels. Beginning with tillage, González-Breijo et al. [35] compared the impact of no-till (NT), minimum conservation tillage (MCT), and conventional tillage (CT) on soil properties in Chapingo, Mexico, after 9, 22, and 25 years. Song et al. compared NT and deep tillage (DT) in northeast Asia [36]. González-Breijo et al. reported that CT soil had lower concentrations of SOC, total nitrogen (TN), available phosphate (AP), and exchangeable potassium (EK) than NT and MCT [35]. NT had the greatest concentration of SOC and exchangeable potassium, but MCT enhanced SOC, TN, AP, and EK, and is recommended over NT and CT [35]. Song et al. compared NT with DT and reported that both practices increased crop yield over conventional tillage, but NT increased yield by only 1% compared to 8% with DT [36]. However, NT improved the soil quality by 8% on the soil quality index (SQI) [36]. While neither study recommended NT, both concluded that CT affects the top layer of soil, which is rich in nutrients, especially SOC, required to maintain microbial communities and reduce the soil's susceptibility to erosion [35-36].

For chemical fertilizers, Wu et al. examined differences in soybean yields and soil quality between the use of solely chemical fertilizer and chemical fertilizers

supplemented with organic amendments [37], and Massah and Azadegan examined how excessive fertilizer use affected wheat production across 12 farms [38]. Wu et al. found that combining organic amendments with chemical fertilizers increased soybean yields by 11.6% and enhanced the SQI by increasing nutrient content and the diversity of bacteria and fungi in the rhizosphere (the thin layer of soil around a plant that is crucial for microbial activity) [37]. The sole use of chemical fertilizer will enhance crop yields in the short term, but long-term usage leads to soil acidification [37]. Massah and Azadegan found that overuse of fertilizers leads to a compaction layer in the soil, formed by the accumulation of mineral salts [38]. The mineral salts convert nutrients into insoluble forms, such as calcium phosphate and potassium carbonate, and sorted into the dense compaction layer, but crops will be unable to utilize them [38]. The bulk density of healthy soil is  $1.34 \text{ Mg.m}^{-3}$ , but the study reported that overuse of chemical fertilizers led to a bulk density of  $1.80 \text{ Mg.m}^{-3}$ , which reduced porosity by 17.4% and water permeability by 81.4% [38]. Additionally, crop roots had to try 14 times harder to reach nutrients compared to roots in healthy soil [38]. Both studies examined different crop types and used different parameters to measure soil quality, but the use of chemical fertilizer alone and its overuse can decrease soil quality, including increases in soil acidification and the formation of a compaction layer [37-38].

In a comprehensive review of the impact of pesticides, Yasir et al. found that pesticides decreased the activities of enzymes such as urease, phosphatase, and  $\beta$ -glucosidase, which are essential for N, P, and carbon cycling, respectively [39]. These cycles, also known as nutrient cycling, are biochemical pathways essential to soil fertility [40]. Additionally, residues of pesticides can bind with micronutrients (e.g., zinc, copper, and iron) and prevent their uptake by crops [39]. Fungicides (pesticides specifically for fungi) also impair

the interaction between roots and fungi, preventing the synthesis of bioactive compounds [39]. Ni et al. investigated how increasing the number of pesticides used simultaneously affected soil bacteria [41]. The results indicate that as pesticide levels increased, soil bacteria had to prioritize detoxifying pesticides at the expense of nutrient cycling, and the Shannon Index (a measure of microbial diversity) decreased [41]. Furthermore, the bacteria's genome size was reduced [41]. Genomes encode bacterial DNA and can be divided into generalists and specialists; bacteria with large genomes are generalists and perform normal functions, such as nutrient cycling, while bacteria with small genomes are specialists and perform a specific task [41]. Since the bacteria's genome size was reduced, there was an increase in specialists that focused solely on detoxifying pesticides, neglecting essential cycles [41].

Long-term monoculture creates a "soil sickness" characterized by severe biological imbalance, even when nutrient levels appear high [42-43]. Research by Li et al. and Shao et al. demonstrates that despite consistent application of chemical fertilizers, which increased soil nutrient concentrations to oversaturation (exceeding over a 100% increase), the yield and quality of crops like tomatoes and peanuts still declined [42, 44]. The decline is due to an imbalance between bacterial and fungal communities, which allowed soil-borne pathogens such as *Aspergillus* and *Fusarium* to accumulate [42]. In Shao et al.'s study, the Shannon-Wiener Diversity Index dropped from 1.23 to 0.53, and the number of beneficial rhizobial genospecies shrank from six to just two after 12 years [44].

Furthermore, the imbalance between bacteria and fungi impairs microbial functions, reduces carbon and nitrogen cycling, and decreases metabolic activity. Li et al. found that short-term monoculture (5-7 years) might increase both the bacterial and fungal networks, but

long-term practice (>10 years) was associated with a reduction in the bacterial network, with decreased node counts and modularity [42]. Furthermore, Wang et al. suggest that declines are exacerbated by autotoxicity, making crop rotation and intercropping a necessary intervention [45]. Application of these interventions can reverse monoculture's damage, increase SOC by 15.5%, and restore microbial diversity, which is essential for the synthesis of bioactive compounds required for conventional functional foods [45].

Climate change and erosion are environmental stressors that contribute to soil degradation, affecting the soil's physical structure and biochemical properties [46]. According to Mbabazize et al. and Yang et al., rising temperatures and intense rainfall (which has increased by 62%) [47], lead to severe soil compaction and a drop in aggregate stability, with bulk density increasing from 1.21g/cm<sup>3</sup> to 1.39g/cm<sup>3</sup> and mean weight diameter dropping from 1.72 mm to 0.88 mm [48], respectively. Additionally, increased rainfall and flooding promote nitrogen leaching, leading to a loss of soil organic matter (SOM) and nitrogen [47, 49]. Conversely, frequent

droughts will inhibit essential enzymes, such as those involved in phosphate uptake, thereby preventing nutrient uptake [47, 50]. Furthermore, warming-induced evaporation increases soil pH above 8, reducing the availability of micronutrients [47]. The biological cost of these stressors is documented in a meta-analysis by Sun et al., which found that a warming magnitude of 2.3°C reduces bacterial and fungal diversity by 16.0% and 19.7%, respectively [51]. Sun et al. also found that warmth increases the metabolic quotient by 83%, a measure of how much CO<sub>2</sub> a microbe releases [51]. The more CO<sub>2</sub> is released, the less carbon will be available for increasing SOM [52].

Even though the studies used different measurement parameters to assess soil quality, they all report similar findings: aggressive agronomic practices result in decreased soil quality (e.g., reduced microbial community, decreased SOC, and nutrient oversaturation). Researchers can establish similar measurement parameters to improve analysis for future studies.

**Table 1:** Summary of Research on Drivers of Soil Degradation.

Study	Type of Study	Research Design	Agricultural Practice Type	Key Findings
González-Breijo et al., 2025 [35]	Primary Research	Comparison of three tillage systems on soil properties and crop yield	Tillage	CT recorded the lowest concentrations of SOC, TN, AP, and EK in all years; NT exhibited highest SOC and EK; MCT followed NT, but benefits were maintained longer than NT
Song et al., 2026 [36]	Meta-Analysis	Comparison of three tillage systems on SQI and crop yield	Tillage	DT yield increased by 8.0% and soil quality increased by 6.0% over CT; NT yield increased by 1.0% and soil quality increased by 8.0% over CT
Wu et al., 2024 [37]	Primary Research	Controlled field experiment comparing conventional chemical fertilizer and chemical fertilizer with organic manure on soil quality and crop yield	Fertilizer	The treatment group recorded 11.6% more in soybean yield and higher scores in microbial diversity and SQI
Massah et al., 2016 [38]	Primary Research	Comparative field study of different levels of chemical fertilizer application on soil quality and wheat yield in Iran	Fertilizer	Overuse of fertilizers increased bulk density from 1.34 Mg/m <sup>3</sup> to 1.80 Mg/m <sup>3</sup> , decreased in total pore volume and porosity by 17.4%, and reduced permeability by 81.4%; wheat yield was reduced by 40.0%

Study	Type of Study	Research Design	Agricultural Practice Type	Key Findings
Yasir et al., 2025 [39]	Review Article	Comprehensive review of various pesticides on soil enzymatic activity and microbial nutrient cycling	Pesticide	Pesticides decrease the activity of urease, phosphatase, and $\beta$ -Glucosidase, reducing nutrient cycling, as well as reducing crop uptake of micronutrients; fungicides impaired root-to-fungi interaction
Ni et al., 2025 [41]	Primary Research	Controlled experiment on levels of pesticide on average genome size and microbial diversity	Pesticide	As the diversity of pesticides increases, the bacteria's average genome size decreases, leading to loss of nutrient cycling and preventing the synthesis of bioactive compounds
Li et al., 2025 [42]	Primary Research	Longitudinal study (1-3 years, 5-7 years, and >10 years) of monoculture on microbial networks and chemical parameters	Monoculture	Tomato monoculture of 10 years demonstrated an increase in fungal abundance, unbalancing the fungal to bacterial ratio; 10+ had oversaturation of nutrients, including 107.72% increase of TP, 73.16% increase of TN, 61.51% increase SOM, and 43.74% increase in AP; additionally, <i>Aspergillus</i> increased from 0.24% to 1.69%
Shao et al., 2025 [44]	Primary Research	Longitudinal study (3 years and 12 years) of monoculture on symbiotic rhizobia biodiversity	Monoculture	Long-term monoculture of peanuts decreased in rhizobia diversity, dropping to 1.23 at 3 years and 0.53 after 12 years on the Shannon-Wiener Diversity Index; all key nutrients increased over 20.0%
Mbabazize et al., 2025 [47]	Review Article	Comprehensive review of climate change on soil quality	Climate Change	Temperature increases lead to an increase in soil compaction and a decrease in porosity; increased rainfall stripped the soil's fertile topsoil and increased nitrogen leaching; droughts contributed to salinization, increasing the soil's pH levels
Yang et al., 2024 [48]	Primary Research	Gradient analysis of four erosion levels: no erosion (TS), light erosion (US), moderate, and heavy erosion (LS)	Erosion	LS had a decrease in all measurements, including aggregate stability, multifunctionality index, and microaggregates index, SOC, and TN, but an increase in bulk density
Sun et al., 2025 [51]	Meta-Analysis	Meta-analysis of climate change (increase in temperature) on soil quality	Climate Change	An increase of 2.3°C resulted in a 16.0% and 19.7% decrease in bacterial and fungal diversity, respectively; SOC was reduced by 18.1%; an increase in soil pH level

### Dilution Effect and Yield Nutrient Trade Off:

Contemporary agricultural practices have prioritized the production of high-yielding crops and their biomass but have compromised the nutritional profile of global food. This has led to a 'dilution' effect, in which the concentrations of essential minerals and vitamins decrease as the crop's physical mass increases [53]. For instance, longitudinal studies over the past 50-70 years have reported decreases in calcium, magnesium, iron, and phosphorus in fruits and veggies, including a 50% and 10% decrease in iron and magnesium, respectively [53]. According to Bhardwaj et al., even crops that were

traditionally low-yielding but superior in nutrient concentration were altered to become high-yielding, resulting in a decrease in nutrient concentration [53]. Ultimately, this has resulted in crops accumulating carbohydrates at a higher rate than they can absorb minerals from the soil or synthesize vitamins [53].

**Chemical Interference:** The reliance on synthetic N, P, and K fertilizers provide crops with macronutrients but neglects the organic matter and essential trace minerals necessary for healthy soil and soil-to-root interactions necessary for the uptake of essential minerals, therefore

lowering the crop's mineral concentration [54]. Continuous cropping, a form of monoculture, results in soil acidification, with pH levels of 4.19-5.15, reducing the bioavailability of nutrients to crops [55]. For comparison, the standard pH range for soil is 5.5 to 7 [55], which is required for nutrient cycling and microbial development [55-56].

**Physical and Biological Breakdown:** According to Bhardwaj et al., crops are unable to access nutrient reservoirs due to physical degradation, such as soil compaction and erosion, caused by tillage, which shrinks pore space and water-holding capacity [53]. Additionally, soil compaction and erosion are exacerbated when soil organic matter is depleted, leading to decreased soil aggregate stability; without stable soil organic carbon levels, the soil structure will be unstable [55, 57]. This degradation results in a low cation exchange capacity, meaning the soil will be unable to retain essential minerals such as calcium, magnesium, and potassium [55]. From a biological standpoint, intensive agricultural practices have reduced microbial diversity, notably the

loss of mycorrhizal fungi, the primary organisms responsible for transporting minerals into plant roots [53, 58]. Furthermore, the use of pesticides and herbicides interferes with secondary metabolic pathways (e.g., the phenylpropanoid pathway) responsible for the synthesis of bioactive compounds, such as phytochemicals and antioxidants [53].

**The Path Toward Resilience:** Due to the direct relationship between soil health and a crop's nutritional profile, it is necessary to transition from aggressive and unsustainable agronomic practices to not only maintain the nutritional quality of crops but also restore the nutritional quality in crops that have shown a reduction of nutrient concentration over the years [53]. Yilmaz et al. suggested diverse cropping rather than monoculture to reduce pest accumulation and pesticide use, thereby preserving and increasing soil microbial diversity and the soil's stability against environmental stressors [54]. Additionally, organic and regenerative farming practices offer a pathway to maintain soil quality while producing nutritionally superior, bioactive-dense crops.

**Table 2:** Summary of Research on Nutritional Decline in Crops

Study	Type of Study	Research Design	Agricultural Practice Type	Evidence of Nutritional Declining
Bhardwaj et al., 2024 [53]	Review Article	Critical review of longitudinal data (50-70 years) examining nutritional quality decline	Intensive Farming, Erosion, and Tillage	Crops have less minerals and vitamins, including calcium, magnesium, iron, phosphorus, vitamin A, vitamin C, and riboflavin; pesticides and herbicides interfere with the crop's pathway for creating bioactive compounds
Yilmaz and Yilmaz, 2024 [54]	Review Article	Reviewed studies on the Green Revolution across diverse geographic regions	Chemical Fertilizers and Monoculture	The Green Revolution has resulted in a dilution effect and yield-nutrient trade off; chemical fertilizer uses and monocultural systems have reduced crop's nutritional content and decreased the soil's resilience against environmental stressors
Kartini et al., 2024 [55]	Primary Research	Analysis of soil samples from farms in the Bali Province	Monoculture (continuous cropping)	Continuous cropping resulted in soil acidification with pH levels falling between 2.19-5.15; SOC levels were critically low; loss of organic matter led to degradation of soil aggregates

**Organic Farming vs Conventional Farming:** Organic and conventional farming differ in the farming techniques

utilized. Conventional farming relies on chemical fertilizers, pesticides, tillage, and monoculture to

maximize productivity and meet global food demands [59]. These conventional farming practices are linked to soil degradation because they prioritize high crop yields over sustainability and crop as well as soil health. Additionally, the chemical fertilizers and pesticides used are highly likely to pollute water sources and harm human, pet, and livestock life [60-61]. Pesticides that are inhaled or digested accidentally are linked to lung-related issues (e.g., chronic bronchitis, asthma, lung cancer) [53]. An example is organophosphate insecticides, which are insect-specific pesticides used to control insects but can easily enter the body and increase the risk of cancer [53]. They can be deposited in the body through the digestion of improperly cleaned vegetables. Furthermore, since conventional farming requires fertilizer to constantly replenish soil that degrades, it consumes excessive resources just to maintain productivity.

Organic farming takes a stricter approach that ensures the nutritional quality of crops while retaining and maintaining soil quality and preventing further environmental damage. Unlike conventional farming, organic farming prohibits the use of chemical fertilizers and pesticides [59]. As it focuses on producing high-quality crops, it benefits the cultivable land by promoting biodiversity and soil nutrient retention. It also reduces agricultural production costs [59], as there is no need for continuous fertilizer application to replenish soil nutrients.

**Review of Findings:** Kashyap and Jain, and Pereira and Angelis-Pereira, two review articles, both share similar findings on the benefits of organic farming. Organically grown crops exhibit a superior nutritional profile compared to conventionally grown counterparts, characterized by higher concentrations of vitamins and bioactive compounds and lower levels of heavy metal residues [59, 62]. Specifically, Pereira and Angelis-Pereira report a 5.7% higher concentration of vitamins and

minerals in organic crops across studies spanning 1980 to 2007 [62]. The accumulation of bioactive compounds results from the absence of pesticides, which allows the crop to synthesize secondary metabolites as a natural defense [59, 63]. On average, organic crops demonstrated 60.57% higher carotenoid levels, 123.28% higher phenolic acid levels, and 21.29% greater antioxidant activity [62]. Additionally, organic practices increase soil microbial activity, facilitating enhanced nutrient cycling and carbon sequestration; the use of organic amendments can help reduce erosion risk by stabilizing the soil [59].

The benefits of organic agricultural practices for soil quality are shown in different studies examining the impact of organic farming in their respective regions and specific crop production. Wen et al. report an increase in soil quality for both the topsoil and subsoil of 53-103% and 25-142% respectively [63]; note that soil quality was measured by the SQI, which combines the total SOC, TN, total phosphorus, etc. [63]. Carneiro et al. also report an increase in total soil carbon, with organic practices reaching 38.1 g kg<sup>-1</sup> and conventional practices only reaching 28.1 g kg<sup>-1</sup> [64], and Nghia et al. report 18% higher SOC in organic systems, 4% higher in soil porosity, and 11% lower in soil bulk density for organic practices [65]. Additionally, elevated levels of dehydrogenase (a critical marker of metabolic life), arylsulfatase, and c- and n-acquiring enzymes were higher in organic practices, indicating enzymatic activity, which is correlated with the bioactivity of nutrients [63-65]. While Wen et al. and Carneiro et al. do not explicitly mention the reasoning behind the increase in enzymatic activity [63-64], Nghia et al. attribute it to organic amendment [65].

However, the three studies measured soil quality using different parameters (i.e., SQI, SOC, or total soil carbon), underscoring the need for standardized soil quality metrics to properly evaluate the relationship between soil quality and agricultural practices.

Additionally, the three studies did not examine the impact on crop nutritional profiles. Future studies should measure the nutrient content of crops grown in both

organic and conventional practices alongside soil quality measurements.

**Table 3:** Summary of Research on Organic vs Conventional Farming

Study	Type of Study	Research Design	Key Findings
Kashyap et al., 2025 [59]	Review Article	Comparison of global organic and conventional farming systems	Organic-grown crops have superior nutritional profiles, including higher levels of antioxidants and polyphenols, vitamin C, iron, magnesium, and phosphorus; organic farming promotes diverse microbiomes, promoting natural nutrient cycling and allowing for the synthesis of bioactive compounds
Pereira et al., 2022 [62]	Review Article	Integrative review (1980-2008) of organic and conventional farming systems on bioactive compounds	Organically grown crops had higher concentrations of carotenoids (60.57%) and phenolic acids (123.28%) and higher antioxidant activity (21.29%); also, 5.7% higher content of minerals and vitamins
Wen et al., 2025 [63]	Primary Research	Long-term field investigation (5, 15, and 20 years) between organic and conventional farming regarding SQI and enzymatic activities in subtropical soils	Organic farming soil increased soil quality by 53-103% in topsoil and 25-142% in subsoil; enzymatic activities of C- and N-acquiring enzymes were 3 and 2 times more active in organic farming
Carneiro et al., 2025 [64]	Primary Research	Comparative field study examining organic and conventional soil samples for carbon accumulation and enzyme activities in the Brazilian Cerrado	Organic systems reached 38.1 g kg <sup>-1</sup> for total carbon, compared to 28.1 g kg <sup>-1</sup> in conventional systems; 1.3 times higher levels of particulate organic carbon; 2 times higher arylsulfatase activity
Nghia et al., 2025 [65]	Primary Research	Comparative field study examining organic and conventional soil samples in different Vietnamese cities	Organic systems had 11% lower soil bulk density and 4% higher soil porosity; 18% higher in SOC; AP and NH <sup>4+</sup> (ammonium) were higher, 39.9 mg kg <sup>-1</sup> and 69.0 mg kg <sup>-1</sup> , respectively; dehydrogenase enzyme activity was 0.14 µg TPF g <sup>-1</sup> soil hour <sup>-1</sup> higher

**Regenerative Farming:** Regenerative farming is entering the mainstream as an alternative to conventional farming and is considered a holistic approach. Regenerative farming seeks to grow nutrient-dense crops while also maintaining and restoring soil health by restoring SOC [10]. While organic farming sounds similar to regenerative farming, the difference is that organic farming strictly prohibits chemical fertilizers and pesticides to increase microbial diversity, resulting in

higher-quality crops and improved soil quality, but soil restoration and improvement are not the main goals [59]. Regenerative farming does not prohibit the use of synthetic products or avoid tillage, but it limits their use to maintain soil quality. Additionally, there is no universally accepted definition for regenerative farming, nor are there specific practices that are considered regenerative farming [66]. For this review, studies that incorporated agricultural practices that had goals of

improving both the nutrient content of crops and maintaining or restoring the soil's health, even if not explicitly stating that the practice is considered regenerative.

**Review of Findings:** Crops grown through regenerative farming are nutritionally denser than their conventional counterparts across a variety of crops, including leafy greens, cruciferous vegetables, tomatoes, berries, etc. [10]. These crops have increased concentrations of glucosinolates and flavonoids, both bioactive compounds that have antioxidant and potential cancer-preventing properties [10]; additionally, organic tomatoes and berries exhibit higher concentrations of the following bioactive compounds: lycopene, anthocyanins, and polyphenols [10]. The increase in bioactive compounds results from reduced pesticide use, which allows crops to allocate energy to the synthesis of secondary metabolites (bioactive compounds) for natural defense rather than detoxifying pesticides [10]. As bioactive compounds are beneficial for crop protection, they also provide benefits when consumed (e.g., immune support, metabolic regulation, chronic disease prevention) [67]. Additionally, these crops have higher levels of zinc, magnesium [68], potassium, and vitamin C [69].

As previously stated, regenerative farming lacks a universal definition that allows for quantifiable measures [66]. The studies examined in this review employ different agricultural practices that can be considered regenerative. In Feliziana et al., the researchers utilized regenerative organic agriculture (ROA) [10]. ROA adheres to organic farming's prohibition on chemical fertilizers

and pesticides, but integrates regenerative practices such as reduced tillage, multi-species overcropping, and rotational grazing to maintain and restore soil quality [10]. Montgomery et al. defined their regenerative practice as NT and cover and rotation cropping, also known as conservation agriculture [68]. In contrast, Rosier et al. included reduced tillage, cover cropping, and biomass retention for their definition of regenerative farming.

While these studies explicitly stated that their farming/agricultural practices are regenerative, two studies that incorporated regenerative farming methods were included. In Martirosyan et al.'s study, the researchers mention "re-engineering" the soil's physical and chemical properties by incorporating different green manure variants, including soybean, clover, and a mixture of both, back into the soil to not only maintain the soil's health, but also produce higher-quality crops [69]. Yeritsyan et al. also incorporate a similar practice in their study, including a fertilizer known as complexon, which contains macro- and micronutrients, amino acids, and complex-forming agents [70]. Both Martirosyan et al. and Yeritsyan et al. are similar in how they organically package their components to allow nutrient release, with Martirosyan et al. focusing on slow nutrient release [69], while Yeritsyan et al. allows for faster nutrient release, resulting in a boost in crop yield and promotion of soil health [70].

Beyond the definitions of these practices, research indicates that regenerative systems enhance SOC, with average of 3.38% in regenerative farming and 2.43% in conventional farming, thereby increasing SOM [69, 71].

The increase in SOM contributes to nutrient retention through nutrient cycling, enabling the cultivation of nutrient-dense crops with higher concentrations of phytochemicals and micronutrients [66]. Furthermore, Hawes et al. reported higher aggregate stability (63.4%) and faster microbial activity with regenerative farming [71]. These systems also mitigate environmental impact as regenerative-grown crops have a reduced carbon footprint, while conventionally grown crops have a positive carbon footprint [71]; this is also supported by Rosier et al., who reported that in Great Britain, regenerative farming alleviated 16-27% of greenhouse gas emissions [66].

In a study conducted by Montgomery et al., which compared regenerative and conventional farming of paired farms across the United States, regenerative farms had a 7% to 21% increase in SOM, the soil had higher levels of SOC, and the crops were richer in vitamins, minerals, and phytochemicals [68]. Additionally, in the two studies that utilize agricultural practices that were not explicitly labeled as regenerative practices, their method of the green manure incorporation back into the soil [69] and the application of organo-mineral fertilizer [70] have promoted the health of the soil while also increasing crop yield [69-70]. Martirosyan et al. reported a 9.2% to 14.4% reduction in bulk density, an 8.1% to 30.0% increase in lettuce yield, and increases in vitamin C, phenolic acids, and carotenoids [69]. Yeritsyan et al. compared farms that used organo-mineral fertilizer, which combined mineral fertilizer with organic components to the usage of mineral fertilizer alone and found that the organo-mineral fertilizer increased wheat

yields by 28.3% to 64.5%, while mineral fertilizer alone only increased yield from 17.66% to 37.5% [70]. Martirosyan et al. also reported an increase in vitamin C, phenolic acids, and lutein (another bioactive compound) [69], and Yeritsyan et al. reported a 2.0% to 2.2% increase in dry matter [70].

In summary, regenerative farming offers a solution to increase crop yields, produce nutrient-dense crops, maintain soil quality, and mitigate climate change. However, because the field of regenerative farming lacks a universal definition for quantifiable measurements and a standardized certification framework, categorizing specific practices as regenerative can be difficult. Additionally, studies that use regenerative agricultural practices may be overlooked if they do not explicitly state that they are regenerative, yet they can be crucial for the comparative analysis of conventional and regenerative farming. For example, Feliziana et al. mention that regenerative agriculture can improve the slow-release of nitrogen through the decomposition of organic amendments [10]. Martirosyan et al.'s study mirrors this exactly because, before the green manure, an organic amendment, is incorporated back into the soil, it collects atmospheric nitrogen [69]. Once green manure is added to the soil, the nitrogen previously fixed by the legumes is slowly released by soil microbes through mineralization. As in the previous section on organic and conventional farming, there should be established parameters for measuring both soil quality and a crop's nutritional profile, in addition to a definitive definition of regenerative farming.

**Table 4:** Summary of Research on Regenerative Farming

Study	Study Type	Benefits	Limitations
Feliziana et al., 2025 [10]	Review article comparing regenerative organic and conventional systems on crop density	Regenerative organically grown crops had higher concentrations of phytochemicals, vitamins (Vitamin C), and minerals (zinc, iron, magnesium, and phosphorus); organic cruciferous vegetables have increased glucosinolates and flavonoids; organic tomatoes and berries have higher concentrations of lycopene, anthocyanins, and polyphenols	The study reported a need to quantify soil composition, climatic conditions, and cropping systems for future studies examining the impact of regenerative practices on crop nutrient density
Rosier et al., 2025 [66]	Literature review examining how a balanced soil ecosystem can achieve long-term nutrient security  Note: regenerative practices in this study included reduced tillage, cover cropping, and biomass retention	Regenerative practices increased SOM; the balanced soil ecosystem supported nutrient cycling, producing crops rich in nutrients and higher concentrations of phytochemicals; cover cropping in Great Britain could mitigate 16-27% of greenhouse emissions	Regenerative agriculture lacks a universally accepted quantifiable definition and a certification system; current policies also favor large-scale monoculture
Montgomery et al., 2021 [68]	Primary research comparing 8 paired farms (regenerative farms with neighboring conventional farms) across the U.S.  Note: regenerative practices in this study included no-till cover, and rotation cropping (considered as conservation agriculture)	Regenerative farms showed a 7% to 21% increase in SOM; higher scores on the Haney Test (soil health measurement) by 11% to 24%; regenerative crops contained higher levels of vitamins, minerals, phytochemicals, total phenolics, and phytosterols	There were only 8 pairs of farms, and the observations were on-farm rather than a controlled experiment
Martirosyan et al., 2024 [69]	Primary research comparing two lettuce varieties (Manushak and Veradarz) in plots treated with green manure vs non-treated control plots	Green manure applications reduced soil bulk density by 9.2-14.4% (maximized in soybean variants); increased lettuce yield by 8.1%-20.0%; nitrogen, potassium, and phosphorus accumulation exceeded the control by 1.69-2.39 mg/100g, 1.2-3.1 mg, and 0.1-0.5 mg respectively; vitamin C, phenolic acids, and b-carotenoids were higher in the treatment than control	The research was conducted in Armenia, which may have a specific climate, limiting its generalizability
Yeritsyan et al., 2025 [70]	Primary research comparing mineral-only synthetic fertilizer and complexon, an organo-mineral fertilizer	Complexon fertilizer increased winter wheat yields by 28.3% to 64.5%; mineral-only fertilizer increased yields by 17.66% to 37.5%; a 2.0-2.2% rise in dry matter for the complexon fertilizer	The experiment was done in Armenia, which can limit generalizability. Furthermore, longitudinal studies are needed to examine whether a boost in yields and quality will be sustained in the long term
Hawes et al., 2025 [71]	Primary research examining long-term effects of regenerative practices on a variety of crops	Regenerative soil average 3.38% carbon content; aggregate stability had a 37.7 percentage point increase in regenerative systems; total soil nitrogen was higher by 0.08%; the regenerative system yields were lower and maximized at 64% for all crops compared to the conventional system, yielding 75%	The experiment was done in Scotland, which can limit generalizability

**Soil-Nutrient-Bioactive Relationships in Armenian**

**Agriculture:** As a critical case study to validate the previously mentioned global trends, regional research from the Republic of Armenia has demonstrated that targeted soil interventions meet the clinical requirements of the FFC's 17-step framework by optimizing bioactive accumulation. Licorice (*Glycyrrhiza glabra* L.) roots collected across five Armenian regions showed significant variation in flavonoid, tannin, and anthocyanin content linked to local soil properties, while heavy metal concentrations remained below regulatory limits and antioxidant activity was preserved across all sites [72].

In Armenian potato trials, organic Biohumus fertilization produced 41.9 t·ha<sup>-1</sup> with residual nitrogen of 57.4 mg·kg<sup>-1</sup> (below permissible limits), whereas ammonium nitrate yielded 42.6 t·ha<sup>-1</sup> but accumulated 72.7 mg·kg<sup>-1</sup> residual nitrogen—exceeding safety thresholds by 12.7 mg·kg<sup>-1</sup> [73]. Similarly, pumpkin cultivation under crop rotation on forest brown soils increased soluble solids by 1.46%, dry matter by 1.63%, reducing sugars by 1.63%, and total sugars by 1.63% compared to monoculture, while boosting yield by approximately 5 t·ha<sup>-1</sup> [75].

The most dramatic increases in bioactive compounds emerge from targeted organo-mineral interventions; combined root and foliar application of fulvic-humic fertilizers in cluster tomatoes elevated lycopene by 15.9% and total phenols by 22.8% [76]. In the Ararat Plain, organo-mineral fertilization influenced vitamin C and anthocyanin dynamics in sweet peppers, while water-absorbing polymers increased the protein and carbohydrate content of grains, though they were associated with increased *Fusarium* crown rot incidence [77]. Beyond mineral amendments, the use of a two-component microbial inoculant (*Azotobacter chroococcum* MDC 6111 and *Pseudomonas tritici* MDC 9168) in the Armenian field trials has demonstrated yield

increases in barley and sunflowers, underscoring the role of rhizospheric microorganisms in enhancing nutrient uptake and crop yield [78]. These findings confirm that soil type and amendment choice exert quantifiable effects on functional compounds required for certified functional foods.

**Implications for Functional Food Status:** With the increase in chronic diseases, consumers are seeking additional resources beyond medication to prevent a chronic disease diagnosis or to mitigate its symptoms. One resource gaining traction is the consumption of functional foods, often labeled 'superfoods.' However, with conventional functional foods, current soil quality and unsustainable agricultural practices are threatening crops' nutritional profile and their conventional functional food claim. The degradation in soil health significantly reduces the microbial population responsible for synthesizing bioactive compounds.

Current epidemiological studies report that consuming conventional functional foods rich in phytochemicals (i.e., fruits, vegetables, and whole grains) can be associated with a decreased risk of various chronic diseases (e.g., cancer, type 2 diabetes, obesity, cardiovascular diseases) [79]. Flavonoids, like other phytochemicals, have been linked to a reduced risk of chronic diseases, as well as anti-aging properties and immune health benefits [80]. However, as current crops are grown with the focus on satisfying satiety rather than nutritional health, reports of health benefits from conventional functional foods may be compromised and need to be reevaluated. Additionally, a portion of these reports are studies from the 1950s and may overestimate the health benefits of modern, nutrient-diluted crops.

**Soil-Plant-Human Health Nexus:** The translational relevance of this review lies in the strong link between soil quality and human health. Nutrition is one of the

primary determinants of the prevention and management of chronic diseases and of overall health; however, the efficacy of conventional functional foods depends on the quality of the soil in which they are grown. Degraded soil lacks the nutrients and microbial drivers necessary to produce crops that contain bioactive compounds with metabolic health benefits, such as cardiovascular protection and glycemic control [81]. For example, research on a multi-strain microbial consortium in Armenia demonstrated that targeted biological inoculants increased the organic layer content from 2.73% to 5.79%, plant biomass, and decreased the ripening time for plants; this ensures that the nutritional profile of plants are consistently met and demonstrates how maintaining and improving soil quality is relevant in providing the nutrients the public health desires and needs [82].

**Integration of the FFC's 17-step framework based on review:** To protect public health, current conventional functional food claims should be re-evaluated for their nutritional profiles to prevent the public from overestimating the health benefits of consuming these products. Based on this review, we recommend a multi-faceted re-evaluation in alignment with the FFC's 17-step framework [18]. Step 2 (Bioactive Confirmation): Contemporary crops of all types (e.g., fruits and vegetables) must be reexamined to account for nutrient dilution and to confirm bioactive compound concentrations. Step 7 (Choosing an Appropriate Food Vehicle): Crops should be compared across conventional, organic, and regenerative farming methods to justify a transition towards organic systems, but preferably regenerative systems for proper bioactive compound accumulation. Additionally, researchers should examine the soil quality, including its microbial activity, to determine how it affects the crop's nutrient profile. Steps 5, 6, and 8 (Preclinical Efficacy): Compare the crop with

its corresponding biomarker in in vitro and in vivo studies to properly reestablish the functional food claim. Step 9 (Clinical Efficacy): A minimum of 12 weeks is required to assess metabolic outcomes and ensure the observed changes in biomarkers are due to the functional foods and not to other factors. Step 16: Additionally, epidemiological studies should be conducted to evaluate the long-term effects of conventional functional foods. However, in accordance with the FFC's step 13, researchers should work together to establish standardized parameters for measuring crop nutritional profiles and soil quality; these parameters can then be submitted to government agencies for approval and universally applied in future studies. While standardization of research protocols is essential, these parameters must remain adaptable to the diversity of cultivable land; given that global soil types vary, different agricultural approaches are necessary.

However, as researchers continue to reassess whether contemporary crops meet their functional food claims, agronomic practices should be transitioned toward sustainable approaches that maintain the soil's structure, functionality, and biodiversity. A way to mandate this is to integrate soil quality metrics into farms' certifications. Agricultural departments in each country can develop a list of standardized soil metrics before granting certification for farms in their country. This can include limited use of pesticides and chemical fertilizers, along with promoting the growth of diverse crops (polyculture) rather than monoculture. While organic farming is considered better for the environment because it prohibits synthetic products, it does not always actively protect the environment. Regenerative practices should be strongly considered as a new farming method and incentivized by the government to promote the nutritional health of their people and reduce overall agricultural costs (i.e., a reduced need for fertilizers to

replenish the soil). However, regenerative practices should also be universally defined to allow easier transition and help agricultural departments implement them.

When farms are certified for regenerative practices, the crops grown on the farm should be examined for related functional food claims using the same multifaceted re-evaluation previously mentioned. The farm's soil and crops should be re-evaluated regularly (possibly on a quarterly or yearly basis) to assess crop quality and, if needed, re-evaluate the farm's certification.

## CONCLUSION

Aggressive agronomic practices common in conventional farming have been used by farmers since the 1900s to meet global food demands, but this has resulted in a nutritional trade-off, soil degradation, and exacerbation of factors that contribute to climate change. As a result, this threatens the possible conventional functional food status of many crops. Organic farming produces nutrient-dense crops with higher concentrations of vitamins and bioactive compounds but does not explicitly attempt to restore and maintain soil quality. As a result, regenerative farming is recommended not only to produce high-quality conventional functional foods that can satisfy nutritional needs and help prevent chronic diseases, but also to uphold soil quality. However, for effective evaluation of contemporary crops and soil quality, standardized parameters should be established for both. Additionally, agricultural departments should support and incentivize farms in their country to adopt sustainable agricultural practices. Given the direct link between soil quality and a crop's nutritional profile, restoring soil quality while continuously evaluating crop nutrient density is essential to enable crops to be

considered conventional functional foods and aid in chronic disease prevention.

**List of abbreviations:** Available Phosphorus, AP; Conventional Tillage, CT; Deep Tillage, DT; Exchangeable Potassium, EK; Functional Food Center, FFC; Heavy Erosion, LS; Potassium, K; Minimum Conservation Tillage, MCT; Nitrogen, N; No Erosion; TS; No Tillage, NT; Phosphorus, P; Regenerative Organic Agriculture, ROA; Soil Organic Carbon, SOC; Soil Quality Index, SQI; Total Nitrogen, TN

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