MINISTRY OF AGRICULTURE AND ENVIRONMENT

TECHNICAL REPORT

NATIONAL SOIL HEALTH STRATEGY TO 2030, VISION 2050

(Final Draft)

Hanoi, 2025

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1. GENERAL INFORMATION

1.1. Context

Land is a vital resource and plays a fundamental role in sustainable socio-economic development and national food security. However, in Vietnam, more than 11 million hectares of land have been or are being severely degraded. This includes over 100,000 hectares of heavily degraded agricultural land, 1.65 million hectares of moderately degraded land, and 3.3 million hectares of slightly degraded land (General Department of Land Administration, 2020). This alarming situation presents significant challenges, demanding urgent attention and coordinated action from policymakers and society as a whole.

The causes of land degradation in Vietnam stem from multiple complex factors, including excessive intensive farming, overuse of chemical inputs in agriculture, and the negative impacts of climate change, industrialization, and urbanization. Historically, Vietnam's agricultural sector prioritized production expansion to ensure food security and boost exports. This led to unsustainable farming practices, such as excessive cropping without allowing soil recovery. As a result, soil degradation increased, along with heightened risks of pest outbreaks, forcing farmers to rely more heavily on chemical fertilizers and pesticides.

Climate change further exacerbates soil health issues. Rising temperatures and erratic rainfall patterns accelerate soil erosion, deplete moisture levels, and reduce nutrient content. Extreme weather events, such as droughts and floods, disrupt soil structure and degrade beneficial microbial ecosystems. Additionally, sea level rise increases soil salinity, negatively affecting crop productivity and threatening food security.

Industrialization and urbanization have also contributed significantly to soil degradation. Urban expansion reduces arable land while causing soil compaction, which impairs water infiltration and nutrient exchange. Meanwhile, industrial activities release pollutants, including heavy metals and toxic chemicals, contaminating soil and harming microbial biodiversity, ultimately reducing agricultural productivity.

Recognizing these challenges, the Vietnamese government has implemented various measures to protect and restore soil health as part of its sustainable development agenda. Policies such as the Environmental Protection Law, soil pollution reduction programs, and the National Action Plan to Combat Desertification have been put into effect. The government has also promoted organic farming, the use of bio-fertilizers, and the reduction of chemical pesticides to improve soil quality. In addition, afforestation efforts, watershed protection, and soil erosion control in mountainous regions have been strengthened.

On October 11, 2024, the Ministry of Agriculture and Rural Development (MARD) issued Decision 3458/QĐ-BNN-BVTV, approving the "Project on Enhancing Soil Health and Crop Nutrition Management until 2030, with a Vision to 2050." However, this initiative remains focused solely on the agricultural sector, whereas soil health is an interdisciplinary issue requiring collaboration across multiple ministries, sectors, and stakeholders.

Therefore, the development of a National Soil Health Strategy for 2030, with a vision toward 2050, is crucial. Such a strategy would provide a comprehensive scientific, legal, and practical framework for managing, protecting, and improving soil health. It aims not only to halt degradation but also to foster sustainable development, secure long-term livelihoods for farmers, and safeguard the environment. Additionally, it would support Vietnam's economic resilience in the face of climate change and deeper international integration. This strategy would also serve as a foundation for developing a National Soil Health Action Plan, detailing specific solutions and assigning responsibilities to relevant stakeholders.

1.2. Legal basis

- Resolution No. 18-NQ/TW dated June 16, 2022 on "Continuing to innovate, perfect institutions, policies, improve the effectiveness and efficiency of land management and use, creating motivation to bring Vietnam to become a developed country with high income"
- Resolution No. 19/NQ-TW dated June 16, 2022 Resolution of the 5th Conference, the 13th Party Central Committee on agriculture, farmers, and rural areas to 2030, with a vision to 2045;
- Government Resolution No. 34/NQ-CP on Ensuring National Food Security to 2030.
- Law on Cultivation dated November 19, 2018;
- Law on Environmental Protection dated November 17, 2020;
- Land Law dated August 1, 2024;
- Decision 1658/QD-TTg dated 2021 approving the National Strategy on Green Growth for the 2021-2030 period, with a vision to 2050, issued by the Prime Minister
- Decision 150/QD-TTg dated 2022 approving the Strategy for sustainable agricultural and rural development for the 2021-2030 period, with a vision to 2050, issued by the Prime Minister
- Decision 885/QD-TTg of 2020 on approving the Project on organic agriculture development for the period 2020-2030 issued by the Prime Minister
- Decision 3458/QD-BNN-BVTV dated 2024 approving the "Project to improve soil health and plant nutrition management to 2030, vision to 2050" issued by the Minister of Agriculture and Rural Development
- Decision 1748/QD-TTg dated 2023 approving the Crop Development Strategy to 2030, with a vision to 2050, issued by the Prime Minister
- Resolution No. 34/NQ-CP dated March 25, 2021 of the Government on ensuring national food security by 2030;
- Decree No. 35/2015/ND-CP dated April 13, 2015 of the Government on management and use of rice-growing land; Decree No. 62/2019/ND-CP of the Government:

Amending and supplementing a number of articles of Decree No. 35/2015/ND-CP dated April 13, 2015 of the Government on management and use of rice-growing land;

- Decree No. 109/2018/ND-CP dated August 29, 2018 of the Government on organic agriculture;
- Decree No. 08/2019/ND-CP dated January 10, 2022 of the Government detailing a number of articles of the Law on Environmental Protection;
- Decree No. 94/2019/ND-CP dated December 13, 2018 of the Government detailing a number of articles of the Law on Cultivation on plant varieties and cultivation;
- Decree No. 84/2019/ND-CP dated November 14, 2019 of the Government regulating fertilizer management;
- Decree No. 55/2021/ND-CP dated May 24, 2021 of the Government amending and supplementing a number of articles of Decree No. 155/2016/ND-CP dated November 18, 2016 of the Government regulating administrative sanctions for violations in the field of environmental protection;
- Decree No. 105/2022/ND-CP dated December 22, 2022 of the Government stipulating the functions, tasks, powers and organizational structure of the Ministry of Agriculture and Rural Development;
- Decree No. 101/2024/ND-CP dated August 1, 2024 of the Government regulating basic land survey; registration, granting of land use right certificates, ownership of assets attached to land and land information system;
- Decree No. 31/2023/ND-CP dated June 9, 2023 of the Government stipulating administrative sanctions for violations in cultivation;
- Circular No. 32/2014/TT-BNNPTNT dated September 10, 2014 of the Minister of Agriculture and Rural Development regulating environmental monitoring and warning activities in the agriculture and rural development sector;
- Circular No. 05/2017/TT-BTNMT dated April 25, 2017 of the Minister of Natural Resources and Environment regulating the process of building a land database;
- Circular No. 09/2019/TT-BNNPTNT dated August 27, 2019 of the Minister of Agriculture and Rural Development promulgating the National Technical Regulation on Fertilizer Quality (QCVN 01-189:2019/BNNPTNT);
- Circular No. 19/2019/TT-BNNPTNT dated November 15, 2019 of the Minister of Agriculture and Rural Development regulating the collection, treatment and use of crop by-products;
- Circular No. 12/2021/TT-BNNPTNT dated October 26, 2021 of the Minister of Agriculture and Rural Development guiding the collection and treatment of livestock waste and agricultural by-products for reuse for other purposes;
- Circular No. 02/2022/TT-BTNMT dated January 10, 2022 of the Minister of Natural Resources and Environment detailing the implementation of a number of articles of the Law on Environmental Protection;

- Circular No. 28/2022/TT-BNNPTNT dated December 30, 2022 of the Minister of Agriculture and Rural Development promulgating the National Technical Regulation on livestock wastewater used for crops (QCVN 01-195: 2022/BNNPTNT);
- Circular No. 01/2023/TT-BTNMT dated March 13, 2023 of the Minister of Natural Resources and Environment promulgating national technical regulations on ambient environmental quality (QCVN 03:2023/BTNMT - National technical regulations on soil quality; QCVN 05:2023/BTNMT - National technical regulations on air quality; QCVN 08:2023/BTNMT - National technical regulations on surface water quality; QCVN 09:2023/BTNMT - National technical regulations on underground water quality; QCVN 10:2023/BTNMT - National technical regulations on seawater quality);
- Circular No. 11/2024/TT-BTNMT dated July 31, 2024 of the Minister of Natural Resources and Environment regulating techniques for land investigation and evaluation; techniques for land protection, improvement and restoration;
- Circular No. 56/2024/TT-BTC dated July 31, 2024 of the Minister of Finance stipulating the collection rates, collection, payment, management and use of fees for exploiting and using land documents from the national land information system;
- Decision No. 225/QD-TTg dated February 25, 2021 of the Prime Minister on approving the Agricultural Restructuring Plan for the 2021-2025 period;
- Decision No. 882/QD-TTg dated July 22, 2022 of the Prime Minister approving the national action plan on green growth for the 2021-2030 period;
- Decision No. 540/QD-TTg dated June 19, 2024 of the Prime Minister approving the Project on Science Development and Application, Technology Transfer to Promote Circular Economy in Agriculture by 2030;
- Decision No. 2732/QD-BNN-KH dated July 20, 2020 of the Minister of Agriculture and Rural Development on management of basic investigation work in the agriculture and rural development sector;
- Decision No. 555/QD-BNN-TT dated January 26, 2021 of the Minister of Agriculture and Rural Development approving the "Project on restructuring Vietnam's rice industry to 2025 and 2030";
- Decision No. 3444/QD-BNN-KH dated September 12, 2022 of the Minister of Agriculture and Rural Development on approving the action plan of the Ministry of Agriculture and Rural Development to implement the national strategy on green growth for the period 2021-2030;
- Decision No. 4324/QD-BNN-BVTV dated November 9, 2022 of the Minister of Agriculture and Rural Development on approving the Action Plan of the Ministry of Agriculture and Rural Development to promote the production and use of organic fertilizers, use fertilizers economically, balanced and effectively in the period 2022-2025;

- Directive No. 117/CT-BNN-BVTV dated January 7, 2020 of the Ministry of Agriculture and Rural Development on enhancing the development of production and use of organic fertilizers;
- Directive No. 653/CT-BNN-BVTV dated January 25, 2022 of the Minister of Agriculture and Rural Development on economical, balanced and effective use of fertilizers.

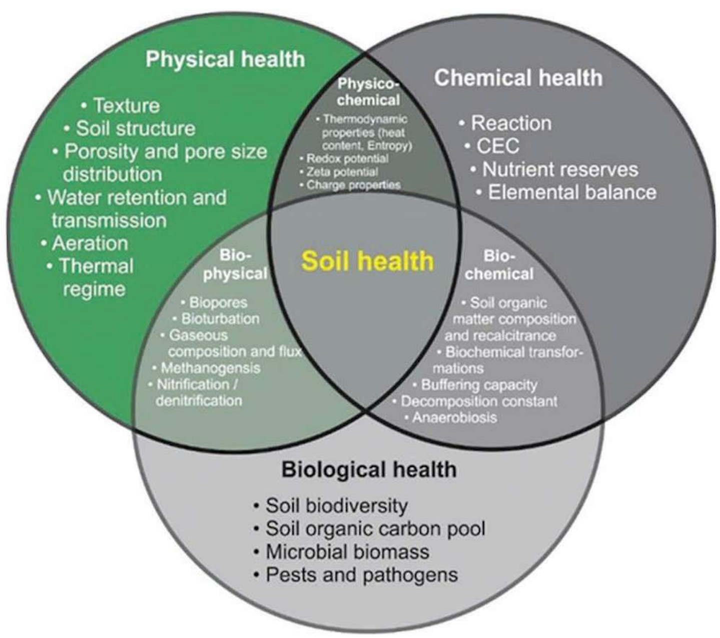
2. SOIL HEALTH AND SOIL HEALTH MANAGEMENT IN VIETNAM

2.1. Definitions and analytical framework

Early definitions of soil health focused on the role of soil in agroecosystems, emphasizing its ability to support adequate biomass production (food and fiber) to meet human needs while maintaining other ecosystem services such as climate regulation or biodiversity conservation (Kibblewhite, Ritz, and Swift, 2008).

Doran, Stamatiadis, and Haberern (2002) defined soil health as synonymous with soil quality, meaning the continuous ability of soil to function as a living system that determines land use systems and their boundaries to support biological productivity, enhance air and water quality, and maintain the health of plants, animals, and humans. It was not until 2016 that Lal distinguished between soil quality and soil health. Specifically, soil quality refers to the functions of soil or what it can do, whereas soil health is seen as a finite and dynamic living resource.

Figure 1. Indicators for soil health assessment



Source: NRCS/USDA (2024).

This report adopts the concept from the Intergovernmental Technical Panel on Soils (ITPS), which defines soil health as "the ability of soil to sustain its productivity, biodiversity, and the ecosystem services of terrestrial ecosystems." In practice, soil health is similar to human health, and there is no single indicator that can fully reflect all aspects of soil health (FAO, 2020). Based on the availability of data in Vietnam, the report uses indicator groups to assess soil health, following the framework of soil health developed by NRCS/USDA (2024). Specifically, the groups of indicators for evaluating soil health include three main categories: chemical, biological, and physical, along with three combined categories: chemical-physical, biological-physical, and chemical-biological.

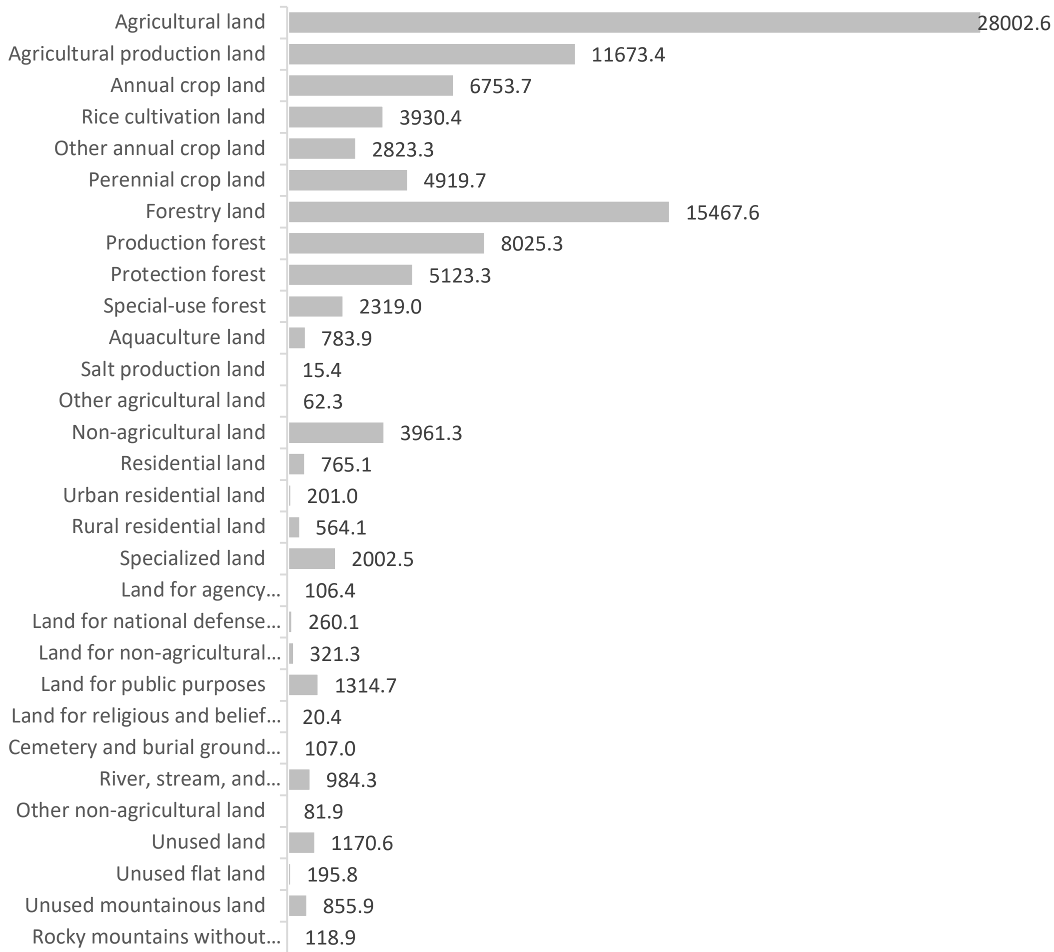
2.2. Vietnam land resources

As of December 31, 2023, Vietnam's total land area reached 33.13 million hectares, ranking 59th globally in terms of size (General Statistics Office, 2025). Vietnam’s land resources are considered abundant in quality and hold significant potential for development. Of the total area, approximately 2 million hectares consist of rivers, streams, rocky mountains, and islands, while three-quarters remain forested or mountainous, with limited exploitation (General Statistics Office, 2025).

Vietnam’s land is predominantly used for agriculture, forestry, and fisheries. About 84% of the total land area is allocated to these sectors, including crop cultivation, forestry, aquaculture, salt production, and other agricultural uses. Non-agricultural land accounts for 12%, with 2.3% designated for residential purposes and 6.1% for specialized uses. The remaining 4% consists of unused land, mostly rocky mountainous terrain (General Statistics Office, 2025).

Between 2018 and 2023, the structure of agricultural land use in Vietnam underwent significant changes as a result of shifts in agricultural development strategies and land resource management. Specifically, the area of forestry land increased by 526.8 thousand hectares, with newly planted forest areas reaching approximately 285 thousand hectares per year (General Statistics Office, 2024). During this period, the cultivated area for major annual crops such as rice, maize, cassava, peanut, sweet potato, and sugarcane showed a declining trend. Notably, the annual rice cultivation area decreased by more than 450 thousand hectares.

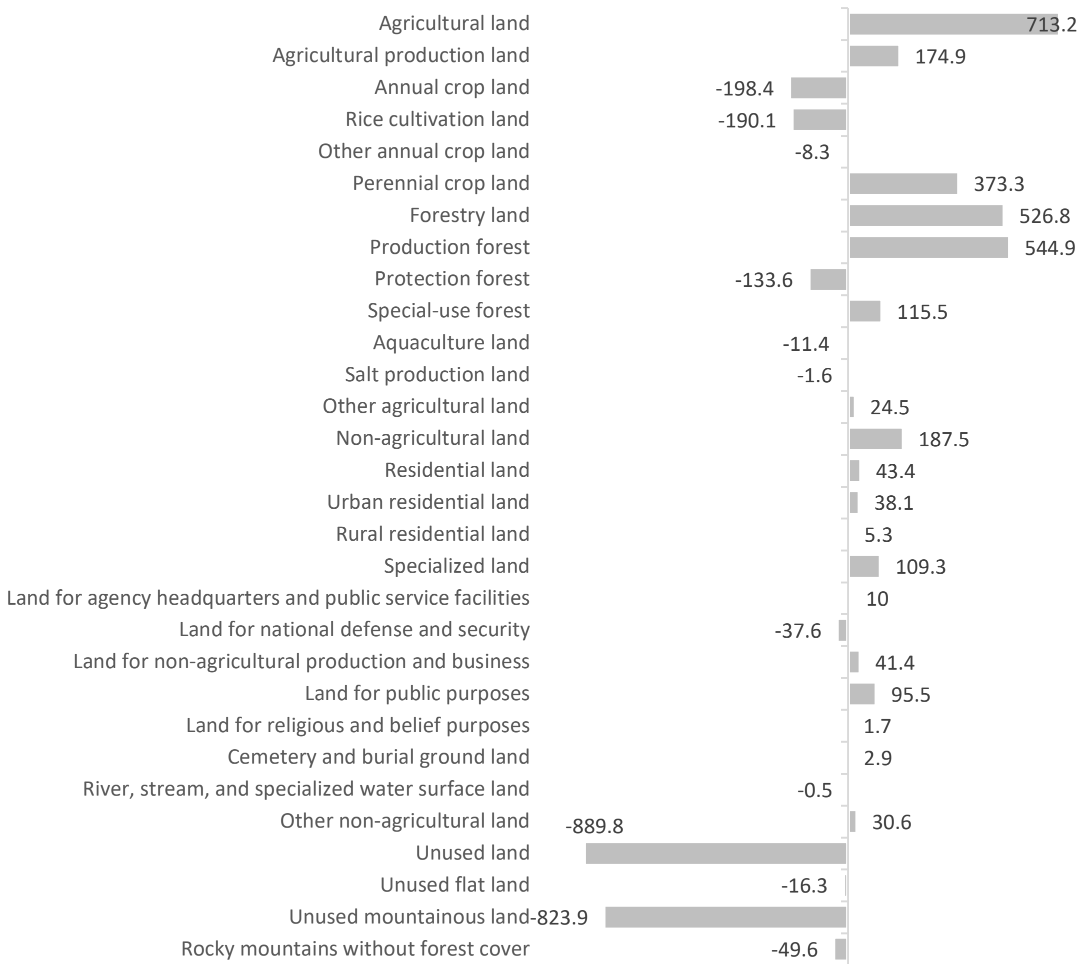
Figure 2. Current land use status in 2023 (km²)



Source: General Statistics Office, 2025.

In contrast, the area allocated to perennial crops continued to expand. In 2023, the area under perennial crops reached 3,766.5 thousand hectares, representing a 7.7% increase compared to 2018 (General Statistics Office, 2025). This increase indicates a strategic orientation toward a more stable and sustainable form of agriculture in the long term, emphasizing the development of large-scale, concentrated fruit production zones. These changes reflect a broader transition in agricultural land use in Vietnam toward a more sustainable, efficient, and climate-resilient agricultural system.

Figure 3. Changes in land use during 2018-2022 period (km^2)



Source: General Statistics Office, 2025.

In terms of soil composition, Vietnam possesses a diverse array of soil types, including alluvial, ferralsol, acid sulfate, and sandy soils, among others. According to the FAO-UNESCO classification system, Vietnam's soils are categorized into 14 major soil groups. Among these, Ferralsols constitute the largest share, covering approximately 54.9% of the country's land area. Ferralsols are characterized by a thick weathered layer, acidic pH, good aeration, and high drainage capacity. However, they are generally low in base nutrients and rich in iron and aluminum oxides, which often accumulate to form hardened layers of laterite or ironstone located 0.5 to 1 meter below the surface. Once exposed due to the loss of topsoil, these layers harden and become impermeable.

The organic accumulation layer (A horizon) in Ferralsols is typically thin, with low organic matter content mainly composed of humus and fulvic acids. The B horizon often contains concentrated aluminum and iron oxides, which give Ferralsols their distinctive red-yellow coloration. The content of primary minerals is generally low, except for very stable minerals such as kaolinite and gypsum. Due to these characteristics, Ferralsols are not suitable for cereal crop production but are more appropriate for cultivating certain industrial crops—particularly perennial industrial crops—as well as some fruit trees, pasture development, and forest plantation.

Alluvial soils represent the second-largest group, accounting for 10.3% of the total land area. These soils are rich in macro- and micronutrients as well as minerals, providing optimal conditions for plant growth. Their inherent fertility, combined with good drainage capacity and the ability to retain nutrients, makes alluvial soils suitable for a wide range of crop cultivation (Ministry of Agriculture and Rural Development, 2006). Red basaltic soils cover 9.1% of the national land area and also represent a highly favorable soil group for agricultural production and industrial crops. Their good structure, fertility, and moisture retention properties make them particularly well-suited to crops such as coffee, rubber, tea, pepper, and various types of fruit.

Table 1. Main soil types in Vietnam classified according to FAO-UNESCO

STT	Main soil types	FAO-UNESCO	Area (ha)	Proportion (%)
1	Sandy land	Arenosols	533,434	1.6
2	Salty soil	Salic fluvisols	971,356	2.9
3	Acid sulfate soil	Thionic Fluvisols	1,863,128	5.6
4	Alluvial soil	Fluvisols	3,400,058	10.3
5	Red basalt soil	Ferralsols	3,010,594	9.1
6	Gray soil	Haplic Acrisol	1,791,021	5.4
7	Ferralitic soil	Other Acrisol	18,179,621	54.9
8	Other lands	Other	3,365,788	10.2
Total			**33,134,480**	**100**

Source: FAO-UNESCO *(1974).*

Vietnam's land resources are generally well-suited to a variety of agricultural and forestry production activities; however, there are pronounced regional differences across agro-ecological zones. The Northern Midlands and Mountainous Region accounts for approximately 31.3% of the country's total land area but holds only 16.4% of the nation's agricultural land. This reflects limitations in terms of terrain, soil quality, and land-use efficiency in upland areas. In contrast, the Mekong River Delta (MRD) possesses highly fertile alluvial soils and, despite covering only 11.95% of the national territory, contributes up to 34.3% of Vietnam's total agricultural land. Similarly, the Red River Delta (RRD), which makes up just 3.78% of the country's land area, accounts for 8.7% of its agricultural land. These disparities underscore the concentration of intensive agricultural production in lowland regions with favorable natural conditions, especially in terms of soil fertility, irrigation infrastructure, and land accessibility. They also highlight the need for regionally differentiated land use strategies and investment in sustainable land management tailored to the specific characteristics of each ecological zone.

Table 2. Distribution characteristics of main soil types in Vietnam and main crops

STT	Main soil type	Main distribution area	Main crops
1	Sandy land	Central Coast	Rice, peanuts and short-term industrial crops.
2	Salty soil	North Central Coast and South Central Coast.	Rice, cassava and short-term industrial crops
3	Acid Sulphate Soil	Red River Delta and Mekong River Delta	Rice, cassava and short-term industrial crops.
4	Alluvial soil	Mekong Delta, Red River Delta and other regions.	Rice, corn and short-term industrial crops.
5	Red basalt soil	Central Highlands.	Corn, coffee, rubber and other industrial crops.
6	Gray soil	Northern mountainous region.	Rice, corn and short-term industrial crops.
7	Ferralitic soil	Northern midlands and mountainous areas and Southeast.	Forestry and short-term industrial crops.

Source: Vietnam Soil Association (Vietsoil), 1996.

The rapid population growth and the ongoing processes of urbanization and industrialization are exerting significant pressure on land resources in Vietnam. While the country ranks 59th in the world in terms of land area, its population ranks 16th globally, resulting in an increasingly high population density. As of 2024, Vietnam's population density reached 322 people per square kilometer, ranking 44th in the world. The average land area per capita has declined to only 0.46 hectares of total natural land and less than 0.12 hectares of agricultural land (World Bank, 2025). This places Vietnam among the countries with the lowest per capita land availability globally.

The rising demand for housing, transportation infrastructure, industrial space, and various economic development projects has accelerated the conversion of agricultural land to non-agricultural uses. Rapid urban infrastructure development, particularly in central areas and emerging urban zones, is causing an annual reduction in agricultural land. Urbanization is increasingly generating a conflict of interest between economic development and the conservation of land resources. Within the structure of agricultural land, there has been a noticeable decline in rice cultivation areas. This trend is mainly attributed to the conversion of low-efficiency rice fields—particularly those affected by salinization due to climate change—into alternative agricultural uses such as vegetable cultivation, industrial crops, fruit orchards, and aquaculture. In addition, some areas have undergone permanent conversion into non-agricultural land types (including urban areas, rural residential zones, and industrial zones) to support socio-economic development (Ministry of Natural Resources and Environment, 2022). The agricultural soil environment in areas near zones of concentrated industrial activity or in intensive monoculture regions has shown signs of degradation. This deterioration is driven by the impact of industrial waste, urban domestic waste, and waste from craft villages, as well as from intensive crop cultivation practices. Increased use of chemical fertilizers and plant protection agents has further contributed to the decline in soil quality, posing challenges to the sustainability of agricultural production systems.

Despite these pressures, Vietnam still possesses a substantial amount of unused land, distributed across its diverse agro-ecological regions. The Northern Midland and Mountainous Region and the Central Highlands hold the largest shares of unutilized land; however, these areas are characterized by low population densities and challenging development conditions. Unused land typically consists of forested areas and barren hills, where natural conditions are often unsuitable for conventional agriculture. Nonetheless, with adequate investment, the exploitation of these lands could yield considerable socio-economic benefits.

In addition to mountainous regions, the Central Coastal Region also has reserves of unused land, primarily in the form of coastal sandy areas. These zones possess strong potential for the development of aquaculture, tourism, and renewable energy projects, including wind and solar power. To efficiently harness the remaining land reserves, it is essential to formulate appropriate policies that combine infrastructure investment with the application of science and technology to enhance production conditions. However, the utilization of unused land must be accompanied by strict environmental safeguards and a commitment to sustainability to prevent negative impacts such as soil erosion, desertification, or land degradation. This represents a critical challenge that requires close coordination among local authorities, scientific communities, and private investors.

In recent years, although forest area in Vietnam has increased, forest quality has shown a declining trend. Primary forests currently account for only about 7% of the total forest area, with intact primary forests comprising a mere 0.25%. In contrast, degraded secondary forests make up nearly 70% of the total forested area nationwide. Primary forests play a critical role in maintaining soil health. Their well-developed root systems and rich biodiversity help protect soil from erosion. Tree roots in primary forests anchor the soil effectively, preventing runoff and maintaining soil moisture. Moreover, these forests contribute substantial amounts of organic matter through the decomposition of fallen leaves and plant debris, which enriches the soil and improves its fertility (Trinh Nhat, 2023).

Conversely, degraded secondary forests—with their simplified vegetation structure and low biodiversity—fail to provide comparable ecological benefits. They are more prone to wildfires and lack the capacity to stabilize soil effectively, leading to increased soil erosion and declining soil quality. This situation underscores the importance of protecting and restoring primary forests as a vital strategy for maintaining soil health and sustaining broader ecosystem integrity.

2.3. Situation of soil health in Vietnam

2.3.1. Changes in biological indicators

Soil is the second-largest carbon reservoir on Earth, storing approximately 2000 Pg C (equivalent to 2 billion tons of carbon) in the form of soil organic carbon (SOC). Due to its vast capacity and long retention time, SOC plays a crucial role in the global carbon cycle. The production and decomposition of SOC significantly influence carbon sequestration and CO2 emissions, while also being essential for maintaining soil health and ecosystem functions. SOC provides vital nutrients and energy for plant growth and microbial activity (Jansson, 2020).

Although plant-derived humus is traditionally considered the primary source of soil organic carbon, research indicates that bacteria contribute significantly to SOC, with microbial biomass accounting for up to 50–80% of total SOC (Liang, 2019). The soil microbiome is the most diverse community in the biosphere, containing at least one-quarter of Earth's total biodiversity. It consists of tens of millions of species, including bacteria, archaea, fungi, viruses, and protists (Soko, 2022). Soil microorganisms obtain energy through catabolic processes involving electron transfer reactions such as respiration and fermentation, which release carbon and synthesize organic compounds for assimilation and fixation. The carbon cycle in soil is regulated by a balance between biotic and abiotic factors, as well as microbial communities.

Microbial carbon release occurs through different catabolic pathways, including fermentation and respiration. During fermentation, microbes release carbon as CO2 or produce compounds such as pyruvate, ethanol, glycerol, and lactic acid. Major fermentation pathways include Embden-Meyerhof-Parnas (EMP), hexose monophosphate (HMP), Entner-Doudoroff (ED), Warburg-Dickens (WD), and Stickland reactions. In respiration, anaerobic or facultative anaerobic microbes can respire without oxygen, using oxygen-containing compounds such as NO3−, NO2−, and SO42− as final electron acceptors (Pelczar, 2017).

Human activities, particularly intensive agriculture, have led to a decline in earthworm diversity in Vietnam compared to the global average (Bảo Thắng, 2024). Vietnam has recorded 186 species of earthworms out of the more than 3,000 identified species worldwide (with an estimated total of 7,000 species). The distribution of earthworms in Vietnam follows a pattern: mountainous regions have higher species diversity but lower density and biomass than lowland areas; in most regions, species numbers, density, and biomass are lower during the rainy season compared to the dry season; and diversity, density, and biomass decrease with increasing human disturbance. According to biodiversity theory, higher diversity corresponds to longer food chains and increased symbiotic and parasitic interactions. Soil cover and coverage rates significantly influence earthworm density and species diversity. Studies indicate that in natural farming conditions, balanced organic and inorganic fertilization, along with appropriate irrigation and soil management, can mitigate pesticide toxicity, enhance soil fertility, and maintain habitats for soil invertebrates. However, pesticides, particularly organophosphates and carbamates, have had negative impacts on soil environments and arthropod populations.

2.3.2. Changes in chemical indicators

a. pH

Soil pH levels in Vietnam exhibit significant variation across different ecological zones. In the Mekong River Delta (MRD), rice-growing soils have pH values ranging from 3.5 to 5.06, with the lowest levels found in acid sulfate soils (pH 3.5), indicating a high degree of acidity. In contrast, paddy soils in the Red River Delta (RRD) show slightly higher pH values, ranging from 3.8 to 5.85, yet still fall within the acidic category (Tran Minh Tien et al., 2021). In the northern mountainous regions, soil pH ranges from 4.0 to 5.0, with an increasing trend of acidity, particularly in the yellow-red soils on high mountains (Tran Minh Tien, 2015). The Central Highlands (Tay Nguyen) have very low soil pH levels, ranging from 3.4 to 4.9, while the optimal pH for coffee growth and development is between 5.0 and 5.5 (Dinh Thi Ngoc Hanh et al., 2023).

Soil pH in Vietnam exhibits dynamic variations depending on soil type and geographical location, reflecting changes in environmental conditions and agricultural practices. In the Mekong River Delta (MRD), fluctuations in soil pH over time are closely linked to salinity levels and land use transformations. Comparative data between 1975 and 2005 show that strongly saline soils experienced a significant decrease in water-measured pH (pH H_2O), from 7.20 to 6.53—a drop of 1.17 units—indicating a trend toward increasing soil acidity over three decades. In contrast, moderately and slightly saline soils showed a slight increase in pH, from 6.09 to 6.32 (an increase of 0.23 units), possibly due to salt leaching, hydrological changes, or the implementation of soil improvement measures. These pH shifts have direct implications for plant nutrient uptake and highlight the importance of regular monitoring to support sustainable land management (Ho Quang Duc & Nguyen Van Dao, 2011).

Research by the Institute of Agricultural Environment and Soil Science further indicates that acid sulfate soils in the MRD showed a slight pH increase from 3.59 in 1975 to 3.62 in 2011, suggesting a marginal reduction in acidity. In contrast, saline soils in this region became more acidic, with pH levels dropping from 5.06 to 4.46 over the same period. Alluvial soils in the MRD demonstrated a moderate pH improvement, increasing from 4.15 in 1990 to 4.42 in 2011.

In the Red River Delta (RRD), grey soils maintained relatively stable pH levels, ranging from 4.92 in 1990 to 4.93 in 2011. Acid sulfate soils showed a notable increase in pH from 3.90 (1975) to 4.36 (2011), suggesting the effectiveness of cultivation and soil improvement practices. Similarly, saline soils in the RRD became more neutral, with pH levels increasing from 4.19 to 5.08. Conversely, the alluvial soils in this region exhibited a decline in pH, from 5.07 (1990) to 4.64 (2011), raising concerns about declining soil fertility and crop productivity (Tran Minh Tien et al., 2014). The MRD comprises three ecological zones, all of which are characterized by acidic soils with pH levels ranging from below 5.0 to 5.5 (Bui Luong, 2024). In the RRD's rice-growing areas, pH values (measured in KCl solution) range from 3.85 to 5.85, reflecting soil conditions from mildly acidic to moderately acidic (Tran Minh Tien et al., 2021).

b. CEC

Cation exchange capacity (CEC) of soil represents its ability to retain and provide nutrients for plants. In the Mekong Delta (ĐBSCL), the CEC of rice paddy soils ranges from 5.6 to 14.6 meq/100g, with the lowest CEC observed in degraded grey soils (5.6). In the Red River Delta (ĐBSH), the CEC is generally higher than in the Mekong Delta, reflecting better soil fertility, with CEC values ranging from 14.1 to 16.7 meq/100g in alluvial, saline, and acid sulfate soils. In particular, the CEC of grey soils in the Red River Delta is similar to that of the Mekong Delta, around 5.5 meq/100g. In the northern mountainous regions, CEC ranges from 9 to 26 meq/100g, but there is a trend of decreasing base saturation due to nutrient loss (Trần Minh Tiến, 2015). In the Central Highlands, CEC ranges from 7 to 20 meq/100g, with soils used for coffee and pepper cultivation showing lower CEC compared to natural forests, indicating nutrient depletion (Trần Minh Tiến & cs., 2014).

In general, the CEC of many soils across various regions of Vietnam tends to decrease, indicating a decline in the soils' ability to retain nutrients. In the Mekong Delta, saline soils showed a significant reduction in CEC from 16.32 meq/100g (1990) to 11.45 meq/100g (2011), reflecting the impacts of salinization and nutrient imbalance. In the Red River Delta, all types of soils showed a reduction in CEC. The CEC of degraded grey soils decreased sharply from 6.45 meq/100g (1990) to 5.54 meq/100g (2011), illustrating the negative impact of long-term cultivation without proper soil restoration measures. Additionally, acid sulfate, saline, and alluvial soils in the Red River Delta also experienced a decrease in CEC, from 20.4 (1990) to 17.2 (2011), 17.7 (1990) to 14.38 (2011), and 16.6 (1990) to 15.97 (2011), respectively, reflecting a general trend of soil fertility decline in this region (Trần Minh Tiến & cs., 2014).

Some soils have shown an increase in CEC, possibly due to positive effects from appropriate soil restoration and management practices. In the Mekong Delta, acid sulfate soils exhibited an improvement, with CEC rising from 14.8 meq/100g (1975) to 15.35 meq/100g (2011), demonstrating the effectiveness of leaching and soil amendment measures. Alluvial soils in the region also saw a slight increase in CEC, from 14.08 meq/100g (1990) to 14.63 meq/100g (2011), helping maintain soil fertility and nutrient supply to crops. Although the increase was modest, this indicates the potential for improving CEC in certain soils through proper management practices such as organic fertilization, crop rotation, and effective water management (Trần Minh Tiến & cs., 2014).

c. OC

Organic carbon (OC) content is an important indicator of soil quality. In the Mekong Delta (ĐBSCL), rice paddy soils have OC levels ranging from 1.2% to 4.4%, with acid sulfate soils having the highest OC content (Bùi Hải An et al., 2016). Rice paddy soils in the Red River Delta (ĐBSH) have OC levels ranging from 1.4% to 2.6%, lower than those in the Mekong Delta, reflecting long-term cultivation and a lack of organic amendments (Trần Minh Tiến et al., 2021). Soils in the northern mountainous regions have OC content ranging from 1.0% to 6.0%, with red-yellow soils on the mountains having the highest OC levels (Trần Minh Tiến, 2015). In the Central Highlands, soils used for coffee and pepper cultivation show a significant reduction in OC compared to natural forest soils (5.14%), indicating the negative impacts of long-term farming practices (Nguyễn Đức Dũng et al., 2019).

OC) content in soils across many regions shows an increasing trend, particularly in saline soils, alluvial soils, and degraded gray soils, reflecting improvements in soil management and organic fertilization practices in recent years. In the Mekong Delta (ĐBSCL), saline soils have seen a significant increase in OC, from 2.09% (1975) dropping to 0.95% (1990) but then rising sharply to 4.7% (2011). Alluvial soils in the Mekong Delta have also shown a slight increase, from 2.54% (1990) to 2.57% (2011), indicating the positive impact of soil improvement measures. However, acid sulfate soils in the Mekong Delta have shown a decreasing trend, from 5% (1975) to 4.7% (2011), possibly due to leaching and the depletion of natural organic matter.

In the Red River Delta, the trend of increasing OC content has also been observed in several soil types. Degraded gray soils increased from 0.71% (1990) to 1.41% (2011), acid sulfate soils increased from 1.67% (1975) to 2.52% (2011), saline soils increased from 1.27% (1975) to 2.32% (2011), and alluvial soils increased from 1.03% (1990) to 2% (2011). These results show the accumulation of organic matter in the soil, likely due to improvements in cultivation techniques and the reasonable application of organic fertilizers (Trần Minh Tiến et al., 2014).

However, in highland areas, OC in sloped soils tends to decrease. In the Central Highlands, OC in soils used for perennial industrial crops has decreased significantly compared to natural forest soils. This reflects the degradation of organic matter due to prolonged cultivation, lack of organic matter replenishment, and the effects of soil erosion. The decreasing trend of OC in the Central Highlands highlights the need for sustainable farming practices, such as organic fertilization, ground cover, and crop rotation, to maintain soil fertility. A comparison of the analysis results in the framework of the study "Research on Improving the Efficiency of Agricultural Land Use in the Northwestern Mountain Region of Vietnam" with previous research on soils in the Northern Mountain region of Vietnam (Nguyễn Tử Siêm & Thái Phiên, 1999) indicates that soils in the Northwestern Mountain region have experienced a decline in total organic carbon content, particularly in red-yellow soils on high mountains (Alisols), red soils on limestone (Ferralsols), and yellow-red soils on shale (Acrisols) (Trần Minh Tiến, 2015).

The depletion of organic matter in the soil not only affects crop yield and quality but also contributes to climate change through the emission of greenhouse gases. Research results worldwide have shown that the sequestration (fixation) of organic carbon in the soil essentially means transferring CO2 from the atmosphere into the soil. Achieving this can bring numerous benefits, including: promoting green growth, increasing crop yield and quality, ensuring food and nutritional security, enhancing water regeneration and quality, improving biodiversity, and controlling climate change. Typically, the threshold of organic carbon content for optimal crop growth in the root zone is between 1.5% and 2.0%. However, soils in agricultural ecosystems are depleting their organic carbon reserves and degrading. Restoring soil quality requires increasing organic carbon content through the implementation of integrated management practices and technical measures. At the COP 21 conference, soil scientists from France and Europe proposed the "4 per 1000" program, which aims to neutralize carbon emissions from the use of fossil fuel sources by increasing the organic carbon content in the entire surface layer of agricultural soils by 4/1000 (Chenu et al., 2018). Vietnam is also one of the first countries in Asia to support and sign up for this program.

In Vietnam, the organic carbon content in the surface soil layer currently ranges from 1-2%, with the highest levels found in acid sulfate soils (3-4%) and the lowest in sandy soils and degraded gray soils (0.6-1.5%). Recent studies have shown that the organic carbon content in the surface layer of most soil types in various ecological regions has decreased by 20-30% compared to data analyzed in the 1980s and 1990s. Organic matter in the soil is lost at a slow rate, but other soil properties that influence crop growth, such as soil structure and physical, chemical, and biological characteristics, degrade much faster than the loss of organic matter. When the organic matter content falls below a critical threshold, the soil will no longer be capable of sustaining production; many of the cultivated soils in Vietnam today have organic matter levels approaching this threshold. Additionally, the degradation of organic matter in agricultural systems is one of the significant pressures on global warming. The increase or decrease of carbon in the soil will determine whether the soil acts as a carbon sink or a source of CO_2 emissions into the atmosphere (IPCC, 2010). The process of carbon loss in the soil requires replenishment through plant biomass, animal remains, and microorganisms to maintain organic matter content in the soil. Changes in water management practices, fertilizer use, and straw management can reduce CO_2 emissions by about 10.2 tons CO_2 eq/ha/year. Managing straw left in the field results in 9.38 tons CO_2 eq/ha/year emissions, while composting it reduces CO_2 emissions to only 0.38 tons CO_2 eq/ha/year (Nguyễn Thị Ngọc Anh, 2019).

d. Other chemical indicators

Most soil types in Vietnam have higher K_2O content compared to nitrogen (N) and phosphorus (P_2O_5). This reflects a general characteristic of Vietnamese soils, where total potassium is often present at higher levels than nitrogen and phosphorus, especially in alluvial soils, basalt soils, and ferralsols. Potassium plays a crucial role in plant growth, enhancing plants' resistance to adverse conditions. However, potassium is prone to leaching, particularly in sloping and sandy soils, which results in lower available potassium levels in soils compared to available phosphorus (Lưu Thế Anh, 2017).

The levels of major nutrients such as nitrogen, phosphorus, and potassium vary across different soil types and regions. Nitrogen in the Mekong Delta (ĐBSCL) across major cultivated soils such as alluvial, acid sulfate, and saline soils ranges from 0.17-0.26%, while the range in the Red River Delta (ĐBSH) is from 0.16-0.19%, and in the Northwest region, it varies from 0.09-0.41%. Total phosphorus in the Mekong Delta ranges from 0.08-0.1%, in the Red River Delta from 0.08-0.17%, and in the Northwest region from 0.07-0.15%. Total potassium in the major cultivated soils of the Mekong Delta ranges from 1.11-1.68%, in the Red River Delta around 1.25-1.27%, in the Northwest from 0.05-1.03%, and in the Central Highlands (Tây Nguyên) from 0.04-0.5%. The degraded gray soils generally have much lower levels of nitrogen, phosphorus, and potassium compared to other soils in the region (Trần Minh Tiến, 2014; Trần Minh Tiến, 2015; Nguyễn Đức Dũng & cs., 2019; Trần Minh Tiến, 2021).

Over time, the proportion of major nutrient elements has changed, but generally, these changes are not significant, indicating that the regular addition of macronutrients in agricultural practices has helped maintain soil fertility. Data from different periods show a slight decrease in total nitrogen in some areas due to continuous agricultural land exploitation, while total phosphorus has increased due to the widespread use of phosphorus fertilizers in agricultural production. Total potassium has decreased in some soil types, such as alluvial soils and degraded gray soils. However, these fluctuations are generally small when viewed over the long term. Meanwhile, soils used for growing coffee and pepper in the Central Highlands have much higher available P2O5, K2O, and SO42- compared to natural forest soils, due to the high intensity of chemical fertilizer use (Nguyễn Đức Dũng & cs., 2019).

For agricultural soils in mountainous regions, sloping land subject to strong erosion and leaching, the topsoil is often heavily eroded, leading to significant reductions in organic matter in the soil. This is due to the extensive farming system without organic fertilization or insufficient fertilizer use, especially on sloped lands used for growing short-term crops in provinces such as Hòa Bình, Sơn La, Điện Biên, Lai Châu, Lào Cai, and Yên Bái. Soil samples from areas growing maize and cassava show that organic matter levels in cultivated soils have dropped below 1.0%, and the levels of essential nutrients such as available nitrogen, phosphorus, and potassium are at depleted levels. Secondary nutrients such as calcium and magnesium have also decreased significantly, ranging from 1.0-1.2 cmol/kg. The texture of the topsoil has changed, with an increase in the proportion of stones and gravel due to the leaching of finer particles during the rainy season. Soil acidity has increased, as shown by the soil pH values ranging from 4.2 to 5.0, and in some cases even lower, such as in tea-growing soils in Mộc Châu, Sơn La, where the pH has dropped to 3.8-4.0. Acidic soils increase the mobility of aluminum and iron, which can become toxic to crops. These changes, which have occurred over decades, have clearly affected crop yields, yet the quality of soil and crop yields in these regions have not been given much attention. This is despite scientific community warnings about the risk of land degradation and the sustainability of agricultural production on sloped lands since the 1990s (Minh An, 2024).

In contrast to extensive farming areas on sloping land, in intensively farmed regions, soil quality changes in a way that leads to nutrient imbalances due to the impact of chemical fertilizers. After 20 years of growing oranges, the available zinc in the soil decreases significantly, the soil becomes acidic to very acidic, and the levels of exchangeable calcium (Ca), magnesium (Mg), and cation exchange capacity (CEC) are all at low levels (Ngô Thị Dung, 2020). The soil degradation in orange orchards in Cao Phong, Hòa Bình is quite evident, with acidic to very acidic soils and signs of sulfate salinity, imbalance in nutrients, and high to very high levels of available P2O5 and K2O, exceeding the optimal levels for citrus crops. There is also contamination of copper (Cu) and zinc (Zn), with the spread and accumulation of Cu affecting deeper soil layers, reflecting increased Cu contamination over the years of farming. The main reason for this is the widespread use of copper-based fungicides and manure from industrial livestock farming. The total Cu content at a depth of 0-40 cm in orchards aged 4, 9, and 17 years was 133.6 ± 5.4, 133.0 ± 3.3, and 194.9 ± 66.2 ppm, respectively, which is 1.3 to 2 times higher than the allowable limits set by QCVN 03-MT:2015/BTNMT. The orange orchards in Cao Phong also showed a significant decline in the Arbuscular Mycorrhizal Fungi (AMF) population, which is essential for symbiotic relationships with citrus roots, and more worryingly, there was an increase in Fusarium fungi and plant-parasitic nematodes (Trần Thị Tuyết Thu, 2018). The soil degradation in the orange orchards of Phủ Quỳ, Nghệ An is marked by acidic pH (pH < 5.5), with over 60% of sites having total nitrogen levels at medium to poor levels (N < 0.2%) (Phạm Văn Linh, 2017).

Soil chemical degradation varies by orchard age in the Mekong Delta region, with orchards ranging from 7 to 33 years old. In older orchards (26-33 years), chemical degradation is more pronounced compared to younger orchards (7-9 years). The most noticeable change is the decrease in soil pH, which is inversely related to the age of the orchards (specifically, pH in KCl in 7-9-year-old orchards is around 5.3; in 16-26-year-old orchards, it ranges from 4.6 to 4.7; and in 33-year-old orchards, it is as low as 3.5). Organic matter and total nitrogen levels are poor, and exchangeable cations like K+, Ca2+, Mg2+, and trace elements such as Zn are very low in orchards older than 16 years (Võ Thị Gương, 2021).

Soil analysis in lychee orchards in Bắc Giang reveals a significant accumulation of phosphorus in the soil, with the average available phosphorus content ranging from 12 to 15 mg/100g. In some regions, the phosphorus levels have risen to 30-35 mg/100g. This high phosphorus accumulation is due to excessive phosphorus fertilization over the years, particularly with high-phosphorus NPK fertilizers such as NPK 5:10:3. Meanwhile, the available potassium in the soil is at a low to medium level, averaging only 8-10 mg/100g (Bắc Giang Department of Science and Technology, 2024).

In the Central Highlands (Tây Nguyên), where industrial crops such as coffee and pepper are grown, soil quality has also undergone unfavorable changes. The average organic carbon content in the soil ranges from 1.2% to 2.5%, which is much lower compared to natural forest soils, which contain 5.14%. The pH of soils in coffee and pepper orchards ranges from 3.14 to 4.6, while in natural forest soils, it is 5.6. The levels of available phosphorus and potassium in the red soils of coffee and pepper plantations have accumulated to relatively high levels, 7 to 10 times higher than those in natural forest soils. Similarly, the sulfur content in these soils has accumulated to significantly higher levels compared to the natural forest soils. Conversely, the cation exchange capacity (CEC) of coffee and pepper soils ranges from 7 to 14 cmol/kg, while in natural forest soils, it is 20 cmol/kg (Nguyễn Đức Dũng et al., 2019). The high accumulation of phosphorus and potassium in the soil is attributed to the extensive and continuous use of chemical fertilizers over the years.

2.3.3. Changes in physical indicators

In addition to the biological and chemical properties, the physical properties of the soil are also changing in ways that undermine soil health. In Hàm Yên, Tuyên Quang, where the orchards have been exclusively growing oranges for 2 to 20 years, the soil has deteriorated in multiple aspects. Soil compaction increases with tree age (with a decrease in the proportion of large aggregates (d > 10 mm) and a significant increase in the proportion of smaller aggregates (d < 10 mm)), leading to increased clay leaching to deeper soil layers, reduced soil porosity, and lower soil moisture retention across the field (Ngô Thị Dung, 2020). The physical degradation of soil in the Mekong Delta region (ĐBSCL), which has been planted with crops for 7 to 33 years, is evident through a decline in soil permeability. In older orchards, soil compaction increases, significantly reducing permeability. At a depth of 30-40 cm, the lowest water infiltration rate is found in orchards that are 33, 26, and 16 years old (Võ Thị Gương, 2005).

Analysis of the physical properties of soils in the Central Highlands (Tây Nguyên) reveals that natural forest and production forest soils, which are less affected by cultivation, have bulk densities ranging from 0.95 to 1.10 g/cm³. In contrast, soils used for long-term rubber cultivation have a bulk density ranging from 1.23 to 1.27 g/cm³. For soils used for coffee and pepper cultivation, bulk density increases significantly, leading to a reduction in soil porosity. The corresponding porosity values are 51.64% for rubber plantations, 47.87% for coffee, and 44.18% for pepper. On basalt red-brown soils, the bulk density for pepper plantations is 15.79% higher than that of natural forest soils, coffee soils are 8.42% higher, and rubber soils are 12.63% higher. Porosity also decreases accordingly, with pepper plantations reducing by 13.67%, coffee by 9.32%, and rubber by 9.08%. The stable aggregate composition also undergoes significant changes, particularly in pepper soils, which have a 15.77% decrease, coffee soils show a 22.36% decrease, and rubber soils (over 30 years) decrease by 4.92% compared to natural forest soils. This indicates that continuous farming activities such as plowing, tilling, and fertilizing have altered the natural soil structure, impacting water infiltration, aeration, and the activity of both plant roots and soil microorganisms. The trend of soil structural degradation in feralit soils derived from basalt is consistent with previous research (Nguyễn Đức Dũng et al., 2019). In summary, when red-brown basalt soils and gray soils are converted from natural forest to production forest or cultivated with coffee and pepper, significant changes occur, adversely affecting the crops in terms of bulk density, porosity, and aggregate composition.

The land in Vietnam is currently facing desertification and degradation due to erosion, laterization, shifting sand, sand flows, as well as salinization and acidification. Currently, around 7.6 million hectares of land in Vietnam are affected by these processes, leading to desertification, with the rate of degradation increasingly alarming. The areas most severely affected include the Northwest, Central Highlands, and the South Central Coast, especially the coastal region from Quảng Bình to Bình Thuận – the area with the largest desertified land in the country (Phương Anh, 2020).

2.3.4. Changes in compound indicators

Soil degradation is one of the key indicators for assessing soil health. Specifically, soil degradation refers to the decline in the biological productivity of the soil, reduced plant cover, reduced quality and water storage capacity, land degradation, and air pollution. Soil degradation is a dual aspect of the development and evolution process, which leads to a reduction in the potential of land resources. The causes of soil degradation are diverse and complex, associated with the conditions of soil formation. While soil degradation can occur due to natural disasters (natural degradation), it is primarily caused by human activities.

In 2021, the national land survey and assessment results (Decision No. 1432/QĐ-BTNMT) showed that the entire country has 11,838,000 hectares of land affected by degradation, including 1,207,000 hectares of severely degraded land, 3,787,000 hectares of moderately degraded land, and 6,844,000 hectares of lightly degraded land. Agricultural land has 114,000 hectares of severely degraded land, 1,655,000 hectares of moderately degraded land, and 3,308,000 hectares of lightly degraded land. Soil degradation due to a significant loss in fertility accounts for 1,526,000 hectares (in the midland and mountainous areas of the North with 450,000 hectares, and in the Southeastern region with 382,000 hectares); areas with moderate fertility decline cover 4,409,000 hectares, and areas with slight fertility decline cover 7,482,000 hectares (Ministry of Natural Resources and Environment, 2021b).

2.4. Causes of soil health decline in Vietnam

2.4.1. Causes of deciline in biological indicators

a. Impact of using chemical fertilizers

The application of chemical fertilizers can have significant negative impacts on soil organisms and biodiversity. When used excessively, nutrients such as nitrates and phosphates can be supplied in quantities exceeding plant requirements. These excess nutrients may accumulate in the soil, leading to environmental pollution. This, in turn, adversely affects soil organisms, including bacteria, fungi, and small invertebrates, ultimately reducing soil biodiversity (Pahalvi, et al., 2021; Chandini, et al., 2019). In particular, certain beneficial bacteria that support plant growth may be suppressed or eliminated due to excessive nutrient concentrations and the presence of toxic chemical compounds. Furthermore, chemical fertilizers can alter the structure and physicochemical properties of the soil, contributing to erosion, reducing aeration, and decreasing water retention capacity. These changes negatively impact soil organisms and disrupt the overall soil ecosystem (Dincă, 2022).

b. Impact of using chemical plant protection

Similar to the use of chemical fertilizers, the application of pesticides and herbicides also has negative impacts on soil biology. Due to overuse, lack of regulation, and improper application techniques, several adverse effects of pesticides have become evident, including soil and water pollution, residual contamination on agricultural products, toxicity to humans and warm-blooded animals, and disruption of natural ecological balance. These chemicals contribute to the decline of biological diversity within ecosystems, the emergence of new pest species, and the development of pesticide-resistant organisms. Furthermore, they disrupt the complex interactions among species within ecosystems, leading to pest outbreaks and re-infestations, ultimately diminishing or eliminating the effectiveness of pest control measures.

Pesticides and herbicides not only eliminate pests and weeds but also harm beneficial soil organisms such as bacteria, fungi, and small invertebrates. Excessive use of these chemicals can reduce soil biodiversity, disrupt ecosystem balance, and degrade soil quality. In particular, these substances can persist in the environment for long periods, leading to soil and groundwater contamination. Residual pesticides and herbicides accumulate in the soil, affecting the health of soil organisms and impairing plant growth. Moreover, the improper use of pesticides and herbicides contributes to the development of resistance in pests and weeds, increasing the cost and complexity of pest management efforts (Dincă, 2022; Vietnam Communism Party, 2023).

c. Impacts of over-intensification

Intensive farming and monoculture are common agricultural practices in modern farming systems aimed at increasing crop yields. However, the simultaneous application of these methods often results in negative consequences for agricultural ecosystems. Specifically, monoculture reduces biodiversity, creating favorable conditions for the spread of pests and diseases (Altieri, M. A., 1999). Additionally, intensive farming relies heavily on chemical inputs such as synthetic fertilizers and pesticides, leading to soil degradation and nutrient imbalances. The loss of biodiversity and disruption of ecological communities in monoculture systems are associated with higher rates of pest and disease outbreaks. In response, pesticides are widely applied in agricultural fields, further harming insect diversity, pollinator populations, and human health (Tilman, 2002). This not only weakens soil health but also increases the risk of environmental pollution. Research suggests that implementing crop rotation and using organic fertilizers can improve soil structure and restore the health of soil ecosystems (Gattinger, 2012).

d. Burning agricultural by-products

The practice of burning straw and rice husks has a multi-dimensional negative impact on soil biological properties. The most pronounced effect of burning straw is the reduction in soil microorganisms. The heat generated from the burning process diminishes the activity of enzymes in the surface soil layers (0–2 cm and 2–5 cm). The most significant negative impact of straw burning occurs in the 0–2.5 cm soil layer, where more than 50% of microorganisms are killed immediately after burning (Kumar et al., 2019; Guo, L., 2021; Mohammadi et al., 2022).

This reduction in microbial activity disrupts soil fertility and the nutrient cycling process, further exacerbating soil degradation and reducing the overall health of the soil ecosystem.

In the long term, such practices can lead to a depletion of beneficial microorganisms, which are crucial for maintaining soil structure and fertility.

2.4.2. Causes of deciline in chemical indicators

a. Impact of using chemical fertilizers

The use of physiologically acidic fertilizers such as ammonium sulfate ((NH4)2SO4), potassium sulfate (K2SO4), and potassium chloride (KCl) without neutralization measures can alter soil composition and properties. If misused, these fertilizers can acidify the soil, disrupt nutrient balance, deplete essential base ions, and lead to the accumulation of toxic elements like Al^{3+}, Fe^{3+}, and Mn^{2+}, reducing soil biological activity. According to Lê Văn Khoa (2004), soil acidity (pH_KCl) in the Red River Delta decreased by an average of 4.5% over ten years (1990–2000) due to continuous farming. Additionally, fertilizers contribute to heavy metal accumulation in the soil, as many fertilizer products contain significant amounts of heavy metals.

b. Impact of pesticide use

The use of pesticides can lead to changes in soil pH over time, primarily through indirect mechanisms such as the reduction of soil microorganism activity and the disruption of organic matter decomposition. This decline disturbs biochemical cycles in the soil, which in turn promotes reactions that lead to either soil acidification or alkalization, depending on the characteristics of the active ingredients and their breakdown products (Manuchehri & Arnall, 2018; Boe, 2023).

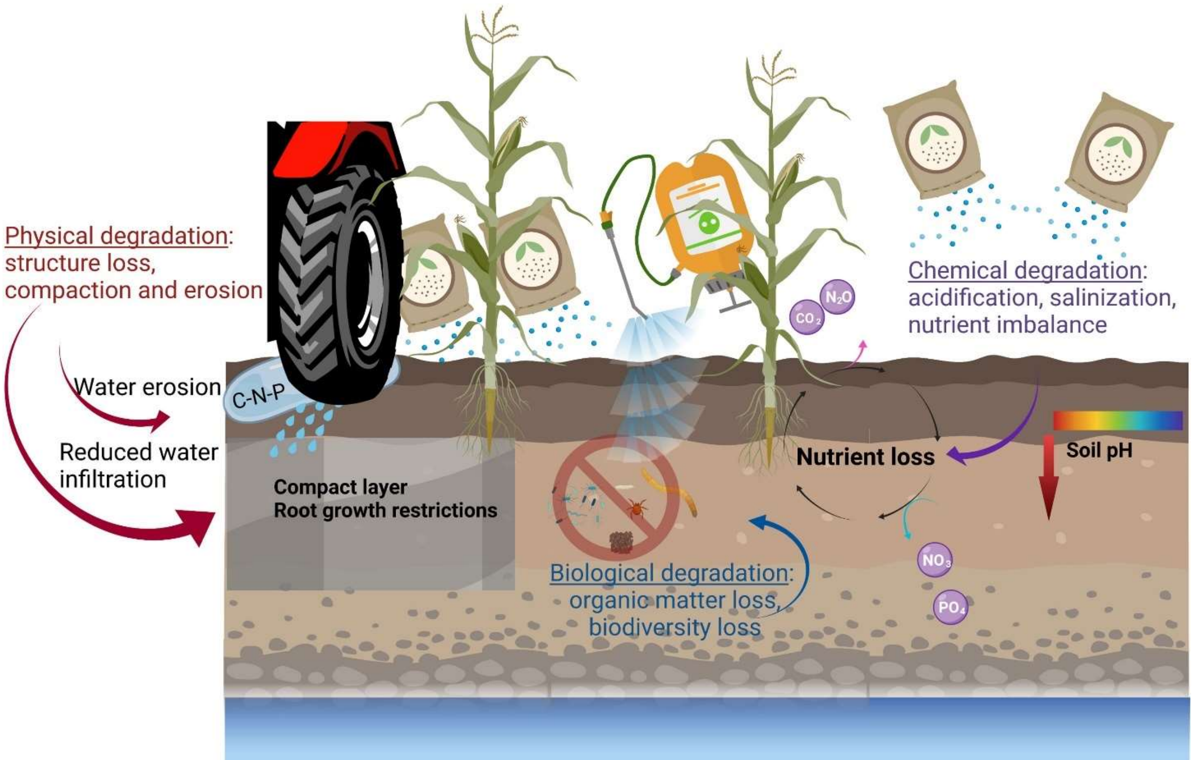
Some pesticides, especially when used in conjunction with chemical fertilizers like nitrogen fertilizers, can increase the risk of soil acidification—a phenomenon commonly observed in long-term intensive farming systems. This characteristic can affect not only soil fertility but also the chemical behavior of the pesticide's active ingredients in the soil environment (Seymour, 2005). Specifically, pH changes alter the adsorption capacity, mobility, and degradation rates of pesticides. Herbicides such as triazine and sulfonylurea groups tend to persist longer in alkaline soils ($pH > 7.0$), while active ingredients in the imidazoline group exhibit higher stability in acidic soils ($pH < 6.0$). These changes not only affect the efficacy of the pesticides but also increase the risk of residue accumulation and soil contamination (Manuchehri & Arnall, 2018; Boe, 2023).

In conclusion, the use of pesticides negatively impacts the chemical properties of the soil by altering pH, disrupting nutrient balance, and increasing salinity. These effects can be long-lasting and accumulate over time, highlighting the urgent need for the rational use of pesticides and monitoring of their residues in the soil environment.

c. Over-intensive farming

Soil degradation in Vietnam results from prolonged negative impacts of monoculture and excessive intensification. Many agricultural areas focus on a single crop, preventing the natural replenishment of nutrients, such as nitrogen fixation. As a result, farmers increasingly rely on chemical fertilizers to maintain productivity. However, excessive fertilizer use not only depletes soil fertility and disrupts microbial balance but also contaminates water sources and the surrounding environment. As crop yields decline, farmers apply even more fertilizers, creating a difficult-to-break negative cycle.

Figure 4. Impact of monoculture and over-intensive corn farming on soil health



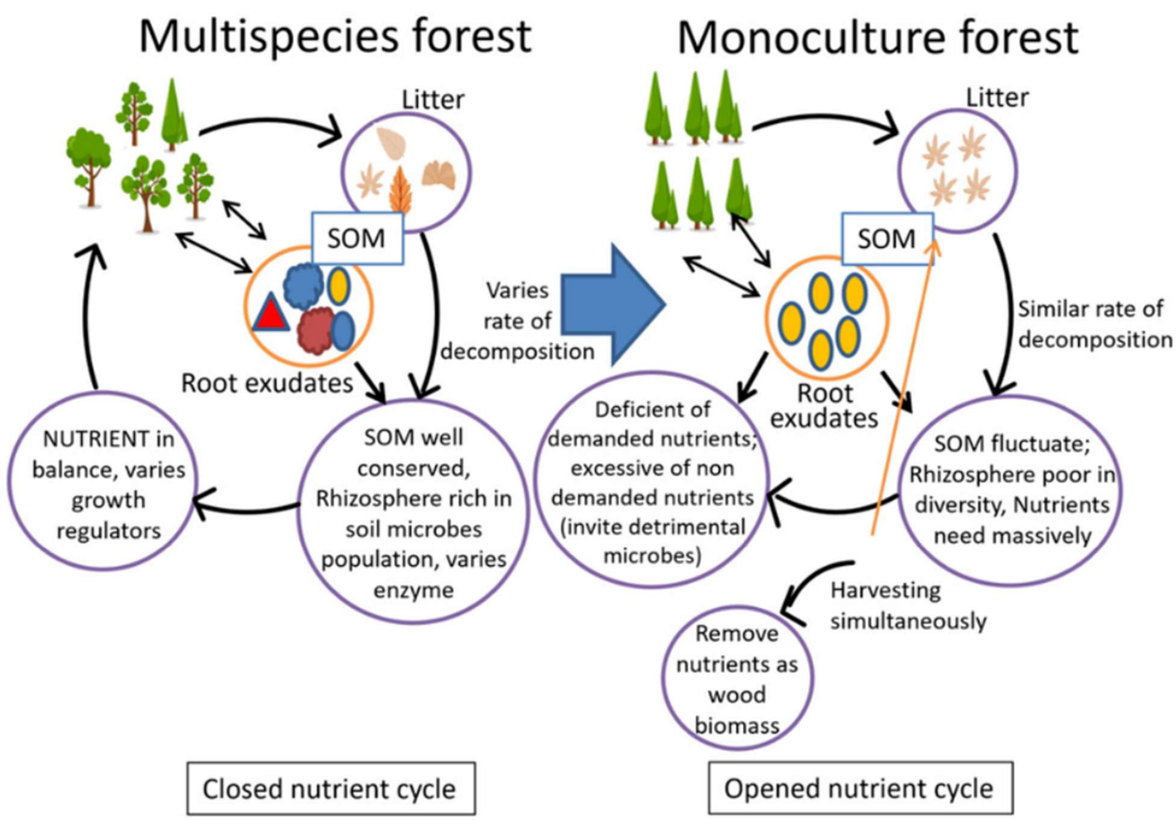
Source: Dessureault-Rompré, J., 2022.

Continuous intensive farming aimed at maximizing yield has led to soil depletion and degradation in the Mekong Delta. This situation negatively affects agricultural production and wastes resources. In the fertile alluvial soils of the Mekong Delta, where rice fields are highly productive and highly responsive to nitrogen fertilizers, the recommended nitrogen application rate is 100–120 kg N/ha for the Winter-Spring crop and 80–100 kg N/ha for the Summer-Autumn crop. However, in practice, farmers often exceed these recommendations, especially in the Summer-Autumn crop, where nitrogen application sometimes surpasses even Winter-Spring levels.

For acid sulfate soils in the Long Xuyen Quadrangle, Western Hau River, and Dong Thap Muoi regions, the recommended nitrogen application is lower: 80–100 kg N/ha for the Winter-Spring crop and 60–80 kg N/ha for the Summer-Autumn crop. Meanwhile, in coastal rice-growing areas from Long An to Ca Mau, where seasonal rice is the main crop, nitrogen recommendations are around 30–50 kg N/ha (Pham Sy Tan, 2005).

In triple-crop rice-growing areas such as Dong Thap and An Giang, the pressure of multiple cropping has led to improper fertilizer use, deteriorating soil quality. Over time, farmers must increase fertilizer inputs to maintain yields, resulting in resource waste and environmental pollution. Previously, fertilizer use in rice farming ranged from 40–50 kg per 1,000 m², but this has now risen to 60–70 kg per 1000 m2. The intensification of cropping cycles and improper fertilizer application have accelerated soil degradation in the Mekong Delta, contributing to increased pest and disease pressure on rice crops (Kim Anh, 2024).

Figure 5. Comparison of nutrient cycles in multi-species forests and monoculture forests



Source: Widyati et al., 2022.

Intensive farming and monoculture also have negative effects on the chemical properties of agricultural soils. Intensive farming that uses high input levels such as chemical fertilizers and pesticides leads to soil degradation and nutrient imbalances. A study in Colombia found that planting perennial crops in monoculture systems, such as oil palm, sugarcane, tea, and pine, can alter the chemical composition of the soil, resulting in acidification, degradation, and the emergence of soil-borne diseases, ultimately reducing yields and threatening the sustainability of agriculture (Tayyab, 2021). Uncontrolled irrigation in monoculture fields, such as soybean, also contributes to soil erosion and water depletion. As soil health deteriorates, the increased use of chemical fertilizers leads to negative consequences for human health through the contamination of water sources by chemical-laden runoff (Lopes, 2021).

The intensive three-crop farming system in the Mekong Delta and human activities during rice cultivation, such as wet plowing, increased mechanization in soil preparation, and the application of inorganic fertilizers, have an impact on soil health. At a depth of less than 10 cm, the presence of a plow pan with unfavorable physical properties, such as high bulk density, lack of structure, low porosity, and low saturated hydraulic conductivity (Ksat), is observed. The cause of this is the wet plowing process in rice cultivation, which has disrupted soil structure and caused clay particles to move downward, filling some soil pores (Nguyễn Minh Phượng, 2009).

Worldwide, studies on soil organic matter have observed a decline in organic carbon content in soils. In India, a study by Choudhury et al. (2016) revealed significant changes in organic carbon content in the surface soil layer across different elevations and cropping systems (Choudhury, 2016). The application of appropriate farming practices can increase organic carbon content in the surface layer of soil, particularly in dryland and rice-growing soils. In China, research findings showed that organic carbon content in non-intensive farming soils concentrated mainly in the surface soil layer (0-20 cm) ranged from 8.6 to 31.3 g/kg, compared to 5.3 to 26.8 g/kg in intensively tilled soils. Organic carbon content in the soil has been declining not only in tropical regions like India and China, but also in temperate regions (Hai-Lin Zhang, 2014). A study on the changes in organic carbon content in the 0-15 cm surface soil layer in the United Kingdom showed that from 1978 to 2003, the rate of organic carbon loss was 0.6% per year (Pat H. Bellamy, 2003).

d. Polluted irrigation water

Irrigating crops with polluted water causes significant changes in the chemical properties of soil, often leading to a decline in soil quality and posing risks to plant health and ecosystems. The main effects observed include changes in soil pH, salinity, and the accumulation of toxic substances such as heavy metals.

Many studies have shown that soil irrigated with polluted or wastewater tends to have a higher pH compared to soil irrigated with clean water. This increase is often associated with the alkaline nature of polluted water and the accumulation of sodium and other base ions in the soil solution. For example, in Egypt, soil irrigated with wastewater from drainage systems showed significantly higher pH levels compared to soil irrigated with clean water, with the cause identified as the high sodium content and pH in the irrigation water (Mahmoud & Ghoneim, 2016).

Polluted irrigation water often contains heavy metals such as cadmium (Cd), lead (Pb), chromium (Cr), nickel (Ni), manganese (Mn), and iron (Fe). Due to their low mobility and slow degradation rates, these metals tend to accumulate in the soil over time. When concentrations exceed permissible limits, they can be toxic to plants, soil microorganisms, and eventually to humans and animals through bioaccumulation in crops. In fact, studies in Egypt and Pakistan have shown that heavy metal concentrations in soil irrigated with wastewater are higher than baseline levels and exceed safe thresholds (Mahmoud & Ghoneim, 2016; Kalsom et al., 2020).

The environmental quality monitoring results from the Institute of Agricultural Environment for the period 2010 - 2014 show that soil environments in highly urbanized areas such as Hanoi, Phu Tho, Da Nang, and Ho Chi Minh City are tending towards acidification due to the impact of waste, industrial activities, and urbanization. The accumulation of heavy metals (HMs) in the soil is also increasing and fluctuating significantly due to industrial and urban waste impacts. Out of 25 monitoring points for heavy metal content in the soil, only 10 points have HM levels within the safe limits according to QCVN 03:2008. These are areas less affected by waste sources, such as Soc Son and Hoang Mai. Points influenced by domestic wastewater, landfills, and industrial zones are more heavily polluted, with some places experiencing severe zinc contamination, such as in the Hoa Khanh industrial zone in Da Nang, with zinc levels reaching up to 260 mg Zn/kg of soil; copper contamination from industrial and urban wastewater, such as in Thu Duc and Binh Chanh - Ho Chi Minh City, with copper levels up to 94 mg/kg of soil. Some monitoring points affected by wastewater from landfills show contamination of copper, lead, and zinc, such as in Soc Son, Hanoi, or wastewater from industrial zones in Thach Son, Phu Tho. The levels of cadmium, mercury, and arsenic in the soil are increasing but still remain within the permitted limits for agricultural production (QCVN 03:2008). However, some specific points with high levels of urban and industrial wastewater, such as Thanh Tri and Hoang Mai in Hanoi, show arsenic levels that are quite high, approaching the permitted threshold (> 10 mg/kg) (Mai Văn Trịnh, 2015).

e. Burning agricultural by-products

The burning of agricultural residues is also a major factor in altering the chemical properties of soil. Research has shown that significant nutrient losses occur during combustion, with 98%–100% of nitrogen, 24% of phosphorus, and 35% of potassium being depleted in the process (Heard, J., 2006). Another study further confirms that rice straw burning leads to the loss of essential soil nutrients, with nitrogen being almost entirely eliminated, approximately 25% of phosphorus, 20% of potassium, and between 5%–60% of sulfur also lost (Dobermann, 2002). Additionally, burning rice straw reduces soil moisture, mineral content, color quality, organic carbon levels, and the humus composition of the top 0–2 cm soil layer.

2.4.3. Causes of deciline in physical indicators

a. Improper irrigation practices

Irrigation practices that are not properly managed can have significant negative impacts on the physical properties of soil, including its structure, porosity, and aeration. These changes reduce water retention capacity and hinder plant growth, leading to broader adverse effects on agricultural ecosystems. Over-irrigation results in waterlogging, which decreases soil porosity and aeration. Essential minerals and nutrients are leached away, accelerating soil degradation. Excess water also contributes to surface erosion, stripping away the nutrient-rich topsoil layer. Conversely, under-irrigation leads to soil dryness, reducing water retention capacity and compromising soil structure. Dry soil becomes compacted and less permeable, restricting water infiltration and root growth. Insufficient water supply also reduces soil porosity and aeration, negatively affecting soil organisms and plant roots (Adejumobi Modupe, 2022; Abhishek Kumar, 2021; John J. Drewry, 2021).

b. Improper tillage

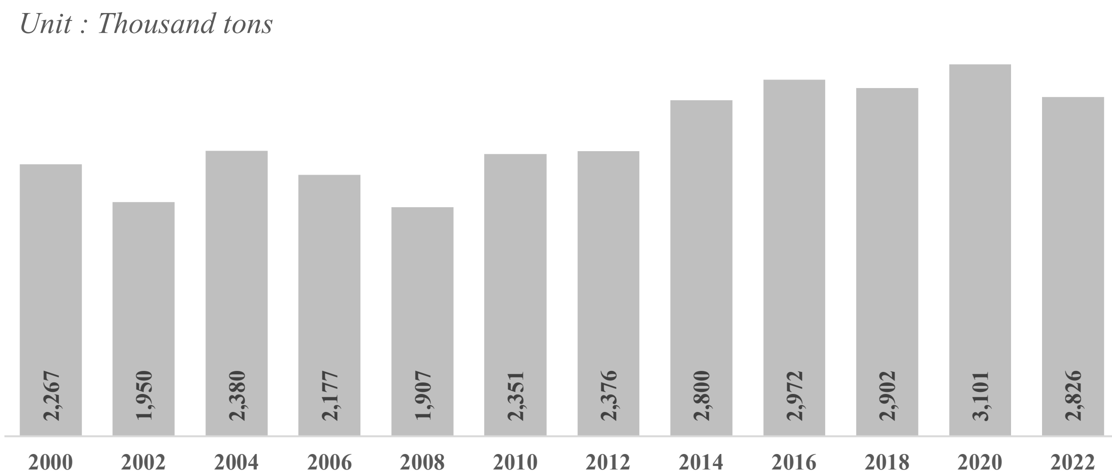
Improper tillage practices can have significant negative impacts on the physical properties of soil. Excessive tillage disrupts soil structure, leading to reduced porosity and aeration. This deterioration lowers the soil's ability to absorb and retain water, increasing the risk of waterlogging or drought, both of which negatively affect plant growth (Younesi Alamouti, 2007; Bertolino, 2023). According to Bertolino (2023), improper tillage increases soil compaction and leads to the formation of a "plough pan"—a compacted layer beneath the soil surface that restricts water infiltration and aeration. This not only hampers root development but also reduces plant growth, agricultural productivity, and increases the risk of soil erosion.

2.4.4. Situation of activities affection soil health in Vietnam

a. Useage of fertilizers

As of 2021, Vietnam has 8,500 fertilizer products circulating on the market, of which more than 4,000 products are inorganic fertilizers. From 2017 to 2020, Vietnam used an average of 10.3 million tons per year, with nearly 90% being inorganic fertilizers, including 2.3-2.4 million tons of urea, 1.3-1.4 million tons of phosphate fertilizers, 4 million tons of NPK, 0.85–0.95 million tons of DAP, potassium, and SA (Ministry of Agriculture and Rural Development, 2021; FPTS, 2021).

Figure 6. Amount of fertilizer used in Vietnam for agriculture in the period 2000-2022

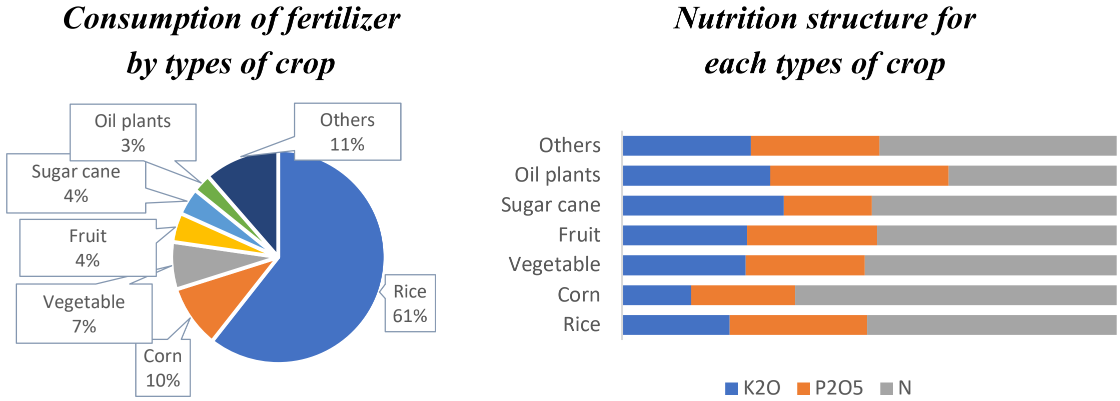


Source: FAO STAT, 2024.

The fertilizer consumption per hectare of agricultural land in Vietnam is relatively high compared to other countries around the world. According to calculations by Nguyễn Văn Bộ (2013) and Đoàn Minh Tín (2015), Vietnam uses 195-200 kg of fertilizer per hectare of cultivated land, which is higher than the global average (138 kg/ha in 2016). Estimates from FAO (2022) also show that all fertilizer usage indicators in Vietnam are higher than the global average. The total nitrogen index in Vietnam is about 151 kg/ha, while the global average is around 65 kg/ha. The phosphate (P2O5) index in Vietnam is 55 kg/ha, compared to 26 kg/ha worldwide, and the potassium (K2O) index in Vietnam is 36 kg/ha, while the global average is approximately 22 kg/ha. Comparing fertilizer use to agricultural production value also reflects Vietnam's reliance on inorganic fertilizers in agriculture. Vietnam's use of K20 is more efficient than the global average, requiring only 7.9 g/Int$ compared to the global 8.5 g/Int$. However, total nitrogen use is 29% higher than the world average (Vietnam: 33.5 g/Int$, World: 25.9 g/Int$), and P2O5 is 22% higher (Vietnam: 12.2 g/Int$, World: 10 g/Int$) (FAOSTAT, 2025).

Overall, Vietnam's fertilizer consumption remains high but is gradually stabilizing. In the future, as the area of cultivated land does not expand further, farming techniques that help save fertilizers are expected to reduce the demand for fertilizers, and consumption is not forecasted to increase significantly as it did in the past.

Figure 7. Fertilizer consumption and nutrient structure for each crop



Source: IFA, FPTS, 2021.

Regarding fertilizer consumption by crop types, rice, coffee, and maize are the three main crops that consume large amounts of fertilizers. Rice is the crop that has the greatest impact on fertilizer demand in the country. Vietnam is one of the world's leading rice producers and exporters. The area of rice cultivation accounts for more than 60% of the total cultivated land in the country. Therefore, changes in planting area and rice variety structure will directly affect annual fertilizer demand.

The Mekong Delta (ĐBSCL) is the region with the highest level of intensive agricultural production and also the largest consumer of chemical fertilizers in the country, with an average use of 1.07 tons/ha (of which 754 kg is inorganic fertilizer), 42% higher than the national average (Ministry of Agriculture and Rural Development, 2021).

For the sweet alluvial soil in the Mekong Delta, which is the main rice-growing area known for very high productivity and a strong response to nitrogen fertilizers, it is recommended to apply about 100-120 kg of N/ha in the Winter-Spring season and 80-100 kg of N/ha in the Summer-Autumn season. However, in practice, farmers often use more than the recommended amount, particularly in the Summer-Autumn season, where the application exceeds even the Winter-Spring season. In contrast, for saline soils in the Long Xuyen Quadrangle, Western Hau River, and Dong Thap Muoi regions, lower nitrogen application is recommended compared to the alluvial regions. The recommended nitrogen application is 80-100 kg N/ha in the Winter-Spring season and 60-80 kg N/ha in the Summer-Autumn season. In addition to these two main rice-growing areas, a small portion of rice cultivated along the coastal areas from Long An to Ca Mau is mainly seasonal rice, with a recommended nitrogen application of 30-50 kg N/ha (Phạm Sỹ Tân, 2005).

It is estimated that each year, around 140,000 tons of nitrogen (N), 82,000 tons of phosphorus (P), and 66,000 tons of potassium (K) are being wasted due to excessive fertilizer use in rice cultivation in the Mekong Delta (Nguyễn Tín Hồng, 2017). Currently, and in the coming years, with the widespread application of advanced farming techniques/technologies, it is expected that the fertilizer use efficiency in Vietnam will improve compared to the previous period.

Table 3. Estimated excess fertilizer use in rice production in the Mekong Delta

(Unit: tons/year)

Province	N	P2O5	K2O
An Giang	20,598	12,034	9,778
Bac Lieu	5,888	3,440	2,795
Ben Tre	2,192	1,281	1,041
Ca Mau	4.1377	2,417	1,964
Can Tho	7,646	4,467	3,630
Dong Thap	17,402	10,167	8,261
Hau Giang	6,757	3,948	3.208
Kien Giang	24,805	14,492	11,775
Long An	17,089	9,984	8,113
Soc Trang	11,978	6,998	5,686
Tien Giang	7,590	4.434	3.603
Tra Vinh	7,761	4,524	3,684
Vinh Long	5,931	3,465	2,816
Total	**139,777**	**1,281**	**66,353**

Source: WB/Nguyen Tin Hong, 2017.

A study in Vietnam's Central Highlands showed that up to 60% of coffee farmers and 45% of pepper farmers use fertilizers improperly and out of balance. Additionally, 70% of farmers apply chemical fertilizers at much higher rates than recommended. The amount of nitrogen fertilizer applied to crops is often very high, sometimes exceeding the recommended amount by 300%; phosphorus is applied at levels 50-200% higher than recommended, while potassium is mostly applied at lower levels than recommended. When the prices of agricultural products such as coffee and pepper are high, over 90% of farmers apply more chemical fertilizers than recommended (Trương Hồng, 2020).

A report from the World Bank on fertilizer use in coffee production in the Central Highlands shows significant discrepancies from technical recommendations, particularly with nitrogen (N) and phosphorus (P_2O_5) fertilizers. On average, farmers in the region use 540 kg of nitrogen per hectare, which is 54.3% higher than the recommended 350 kg/ha. Notably, Lam Dong province has the highest nitrogen application, exceeding the recommended level by 82.6%. The excess nitrogen not only leads to nutritional imbalances but also increases the risk of pests and diseases, reduces the quality of coffee beans, and contributes to long-term soil degradation (Nguyễn Tín Hồng, 2017).

Table 4. Actual fertilizer rates compared to recommended rates in coffee production

(kg/ha/year)

Actual farmer usage			Recommended level	Other		
	Min	Max	Medium	Medium	(kg/ha) [a]	(%) [b]
Gia Lai						
N	114	1,420	458	350	108	30.9
P2O5	0	960	276	85	191	224.7
K2O	48	1.525	335	325	10	3.1
Dak Lak						
N	64	1,980	522	350	172	49.1
P2O5	0	1,504	263	85	178	209.4
K2O	64	1,900	514	325	189	58.2
Lam Dong						
N	64	1,597	639	350	289	82.6
P2O5	0	1,549	489	163	326	200.0
K2O	32	1,700	414	325	89	27.4
Mean						
N	64	1,980	540	350	190	54.3
P2O5	0	1,549	343	111	232	209.0
K2O	32	1,900	421	325	96	29.5

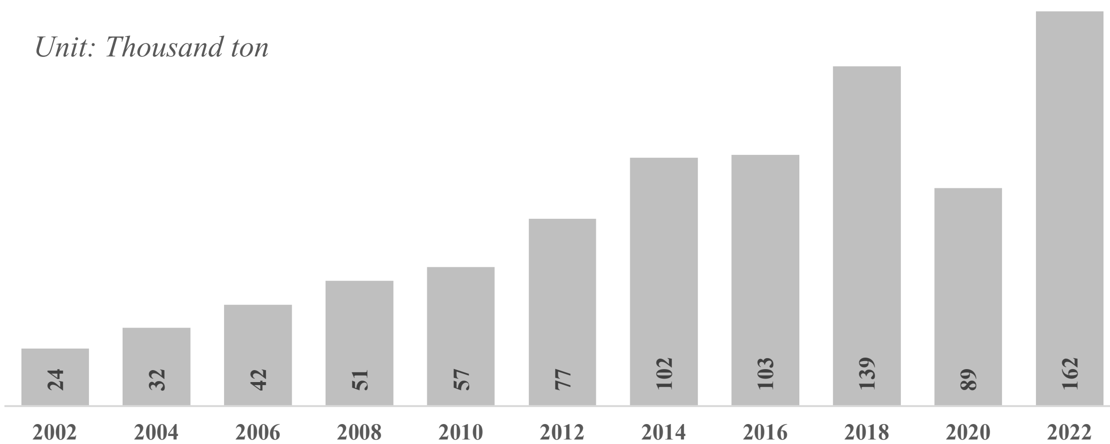
Note: a. Difference between actual and recommended use; b. Percentage increase in actual use over recommended level.
Source: WB/Nguyen Tin Hong, 2017.

The situation of phosphate overuse is even more severe, with an average application rate of 343 kg P_2O_5 per hectare—209% higher than the recommended level of 111 kg/ha. All three provinces of Gia Lai, Đắk Lắk, and Lâm Đồng have phosphate application rates more than double the recommendation, with Gia Lai exceeding the recommended level by the highest margin of 224.7%. Prolonged excess phosphate application can lead to accumulation in the soil, reducing the absorption capacity of trace elements such as iron (Fe) and zinc (Zn), while also increasing the risk of environmental pollution through surface runoff (Nguyễn Tín Hồng, 2017).

b. Useage of plant protection chemicals

Pesticide consumption in Vietnam, similar to fertilizers, has significantly increased over the past decades alongside agricultural intensification. Between 1981 and 1986, Vietnam imported only about 6,500–9,000 tons of active pesticide ingredients (ai), averaging 0.3 kg ai/ha. This figure rose to 13,000–15,000 tons annually during 1986–1990 (0.4–0.5 kg ai/ha), then to 20,000–30,000 tons per year between 1991 and 2000 (0.67–1.0 kg ai/ha). Between 2001 and 2010, pesticide imports surged to 33,000–75,000 tons per year (2.54 kg ai/ha), reaching approximately 100,000 tons annually by 2015. Correspondingly, the value of pesticide imports rose sharply from around $472 million in 2008 to $537 million in 2010 and nearly $700 million in 2015 (World Bank, 2019; FAOSTAT, 2015).

Figure 8. Import value of pesticides into Vietnam in the period 1980–2020



Source: World Bank, 2017; Ministry of Industry and Trade, 2021.

Currently, the average pesticide usage per hectare has decreased from 3.81 kg/ha in 2020 to 3.19 kg/ha in 2022. The global trend is shifting towards biological pesticides, and Vietnam is following suit. Between 2020 and 2023, the number of registered biological pesticides increased from 768 to 810 commercial products. The proportion of biological pesticides used rose from 16.67% in 2021 to 18.49% in 2022. Regions with high biological pesticide usage include Southeast Vietnam (1.49 kg/ha) and the Mekong Delta (0.79 kg/ha). Annual imports of biological pesticides range between 18,000 and 20,000 tons, accounting for 15–20% of total pesticide imports. Major import sources include China, India, the U.S., the EU, and ASEAN countries. The Ministry of Agriculture and Rural Development (MARD) has introduced a development plan for biological pesticide use, targeting 2023 with a long-term vision to 2050.

One major concern associated with excessive and improper pesticide use in Vietnam is the toxicity of pesticide mixtures. A survey in the Red River Delta revealed that one-third of the pesticides used by farmers fall under the "extremely hazardous" category (Class I) as classified by the World Health Organization. These include organophosphates, organochlorines, pyrethroids, and carbamates. Additionally, banned or unregistered pesticides such as methyl parathion, methamidophos, and carbofuran have been detected in use. In general, Vietnamese farmers tend to opt for cheaper, domestically produced, or mixed pesticides that are often more toxic and persistent (Thuy, 2012).

Inspections of traders, vendors, and farmers conducted between 2010 and 2011 found that around 20% of farmers violated pesticide regulations by using illegally imported, banned, or counterfeit pesticides. The continued use of banned pesticides is partly due to their relatively low price (driven by competitive pricing), but also because of their effectiveness against a broad range of pests. Furthermore, enforcement and monitoring of hazardous chemical use remain weak (Van Hoi, 2013).

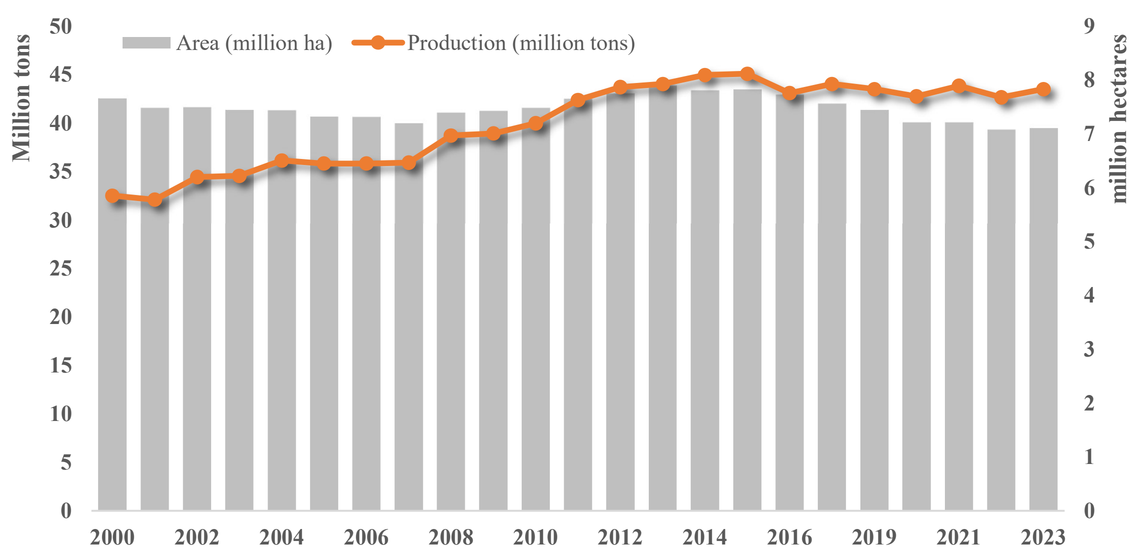
c. Burning agricultural by-products

The Mekong Delta produces about 24 million tons of rice annually (General Statistics Office, 2025), which generates approximately 26–27 million tons of rice straw at harvest (Minh Tuấn & Hải Yến, 2024). Of this, around 70% is either burned in the fields or incorporated into the soil, while only 30% is collected for further use (Lê Cảnh Dũng et al., 2021). Research by Nam et al. (2014) also indicates that straw burning is the most common post-harvest management practice in the Mekong Delta, accounting for 98.2% during the Winter-Spring season, 89.7% during the Summer-Autumn season, and 54.1% during the Autumn-Winter season.

d. Intensification and monoculture

The practices of intensive farming and monoculture are increasingly common in Vietnam's agricultural production, particularly in areas specializing in industrial crops and rice cultivation. These practices have led to significant negative impacts on soil health and the agricultural ecosystem. Intensive farming—aimed at boosting yields by increasing planting density and relying heavily on chemical fertilizers and pesticides—has contributed to the degradation of arable land and nutrient imbalance in soils.

Figure 9. Area and output of rice in Vietnam in the period 2000-2023



Source: FAO STAT, 2024.

Although Vietnam's cultivated area has been decreasing, crop yields have continuously increased, reflecting a trend toward intensification. From 2000 to 2023, the area under rice cultivation declined from 7,666,300 hectares to 7,115,058 hectares, while production remained stable and even tended to increase from 32,529,500 tons to 43,497,624.81 tons

(FAOSTAT, 2024). Calculations based on Household Living Standards Survey data also show that the national average number of rice crops per year increased from 1.6 to 1.75 crops/year.

Monoculture—particularly rice monoculture in the Red River Delta and Mekong Delta, coffee in the Central Highlands, and pepper in the Southeast region—is reducing biodiversity and weakening the resilience of agricultural ecosystems. As a result, soils are becoming increasingly degraded, more prone to erosion, salinization, and contamination by heavy metals. A report by the Institute of Agricultural Environment (2020) indicated that over 60% of agricultural land in the Central Highlands shows signs of declining organic matter and soil fertility due to continuous coffee cultivation over many years without proper crop rotation or soil improvement measures.

e. Industrialization, urbanization and infrastructure development

Vietnam is undergoing rapid industrialization and modernization, driving economic growth. Hundreds of industrial zones have been established, alongside the expansion of traditional craft villages. As of December 2023, the country had 296 operational industrial zones (Nguyễn Hằng, 2023). However, industrial production has generated significant wastewater and solid waste. The national average solid waste output increased from 25,000 tons/day in 1999 to approximately 35,000 tons/day in 2021, with industrial waste making up a substantial portion, particularly in key economic regions in the North and South. Notably, 20% of industrial waste is classified as hazardous, including slag, oil-contaminated wastewater, oil-soaked rags, fluorescent lamps, batteries, lead-acid accumulators, and electronic circuit boards. If not properly collected and treated, hazardous waste mixed with general waste or illegally dumped can lead to severe environmental pollution, particularly heavy metal contamination in soil. Additionally, over 1 million cubic meters of industrial wastewater are discharged daily from industrial zones into water bodies, contributing to the pollution of surface water, groundwater, and soil (Mai Văn Trịnh, 2015).

Using water from polluted rivers for irrigation increases the risk of food insecurity and poses serious threats to human health, due to the potential accumulation of heavy metals in crops and the presence of harmful bacteria such as *E. coli* in vegetables and tubers. Restoring soil quality and ensuring food safety will be extremely challenging if pollution is not effectively controlled (Van Hung, 2024).

In Vietnam, rapid urbanization has been occurring alongside the country's push for industrialization and modernization. The proportion of the urban population increased from 19.5% in 1990 to 38.1% in 2023, corresponding to a rise from 12.9 million to 38.2 million people. This growth has placed significant pressure on urban infrastructure and natural resources, particularly land resources. Accelerated urbanization has had a marked impact on soil quality, evidenced by increasingly widespread soil degradation. The main causes include the accumulation of toxic chemicals, heavy metals, and acidification of soils—primarily driven by wastewater and solid waste from industrial zones and residential areas, a large proportion of which is discharged without proper treatment. As a result, soil in peri-urban and urban areas has become polluted and gradually lost its capacity to regenerate, negatively affecting agricultural production and public health. This poses a major challenge for sustainable urban development and effective land resource management in Vietnam (Mai Van Trinh, 2015).

The rapid development of residential areas, industrial zones, and factories—often without coherent planning—has created mixed-use zones where agricultural land is interspersed with residential and industrial areas. Although the exact area of this farmland has not been comprehensively documented, it is increasing. These areas are often severely polluted by untreated industrial and domestic waste, rendering them completely uncultivable (Thanh Thuy, 2020; Huong An, 2024).

f. Soil health decline due to climate change

Vietnam ranks 159th globally in per capita land area—only about one-sixth of the global average. Changes in weather conditions, including temperature fluctuations, rainfall variations, and extreme climate events, have increasingly led to land degradation issues such as salinization, drought, desertification, waterlogging, erosion, leaching, and landslides. The country's diverse topography, geomorphology, climate, and soil types, combined with economic and social development, have created distinct territorial regions, each experiencing different climate-related impacts.

<u>Drought</u>

The uneven distribution of temperature and rainfall across Vietnam has led to harsh climatic conditions that contribute to soil dryness and semi-arid environments, particularly in the southern regions, the Central Highlands, and South Central Coast. In these areas, prolonged heat and drought significantly increase the risk of land degradation due to aridification, ultimately reducing soil quality. Additionally, hydropower development on upstream rivers further exacerbates the problem by threatening freshwater availability in downstream regions (Phuong Dong, 2022).

The South Central Coast is the driest region in the country, with provinces like Ninh Thuan and Binh Thuan frequently experiencing prolonged droughts during the dry season. Currently, approximately 1,160,306 hectares—or 34.21%—of agricultural land in the region is affected by drought. This figure rose to 1,360,745 hectares in 2020 and is projected to reach 1,366,519 hectares by 2030 and 1,489,193 hectares by 2050. Of the total drought-affected land by 2050, forest land is expected to account for 1,014,962 hectares—an increase of 62,689 hectares from 2030 and 191,551 hectares from the present. Agricultural land (including land for annual and perennial crops) is projected to be 469,300 hectares—up 58,393 hectares from 2030 and 135,250 hectares from the present (Phuong Dong, 2022).

Soil erosion, leaching

Climate change alters rainfall and sunlight patterns, increasing the frequency of heatwaves and intensifying rainfall during the wet season. This leads to greater soil erosion, causing significant nutrient loss, especially during prolonged rainy periods. Systematic soil erosion monitoring since the 1960s indicates that approximately 10–20% of Vietnam's land area is affected by moderate to severe erosion.

Rain-induced soil erosion is the primary cause of land degradation in Vietnam's mountainous regions. About 40% of the country's natural land area—equivalent to 13 million hectares—is at risk of erosion, with the Northwest and Central Highlands being the most vulnerable. In highland areas, soil erosion alters land use patterns and significantly reduces crop productivity. For instance, in Thua Thien Hue province, income losses due to soil erosion are estimated to range from 0.635 to 1.022 million VND per hectare per year, depending on the land-use system (Tung Gia Pham, 2018).

The Northwest region, where sloped land accounts for 98% of the total area, faces a high risk of erosion-induced degradation. During the six-month rainy season, soil loss accounts for 75–100% of the total annual erosion, while the remaining 25% occurs during transitional storm events from the dry to rainy season (March–April) or from the rainy to dry season (November). In Central Vietnam, the rainy season is concentrated in the first four months of the year and the middle of the northeast monsoon season, with torrential rains occurring from September to December. These conditions make soil erosion and runoff particularly severe. Additionally, unsustainable agricultural practices—such as inadequate ground cover, monocropping, and insufficient efforts to replenish and improve soil resources—further contribute to erosion and nutrient depletion (Phuong Dong, 2022).

Landslides along rivers and in highlands

Climate change is exacerbating the risk of soil erosion and landslides by increasing rainfall intensity and flood runoff during the wet season. Landslides not only bury agricultural land but also damage transportation infrastructure, buildings, and even entire villages.

During the rainy and flood seasons, severe soil erosion occurs along river systems, especially in the lower reaches of major rivers such as the Red River, Mekong River, Trà Khúc River, and Ba River. In steep areas with thin soil layers—where rock debris lies just one meter beneath the surface—the soil becomes unstable and detaches due to gravity. In locations such as Mường Tè (Lai Châu), Yên Sơn (Sơn La), and Trạm Tấu (Yên Bái), early-season downpours have triggered landslides that sweep away topsoil from rice and maize fields, leaving the slopes barren. The decline in both the quantity and quality of forests has further intensified soil erosion and landslides, as vegetation loss reduces the land's ability to retain moisture and stabilize slopes.

<u>Flooded land</u>

In recent years, natural disasters, floods, and tidal surges have occurred more frequently, worsening soil waterlogging issues. In northern Vietnam, the convergence of southeastern monsoon winds with cold air masses from the north has led to extreme rainfall, causing severe waterlogging in many areas. In central Vietnam, an average of 120,000 hectares of rice fields are submerged annually, with approximately 40,000 hectares suffering total crop loss and over 70,000 hectares experiencing partial damage. Additionally, more than 62,000 hectares of other crops are affected by flooding. In southern Vietnam, tidal peaks on the Hậu River regularly cause flooding in downtown areas of Cần Thơ. In Ho Chi Minh City, tidal water levels have risen rapidly from 1.22 meters to 1.55 meters, exacerbating urban flooding. Coastal provinces and cities in southern Vietnam are particularly vulnerable to flooding caused by sea level rise, making it one of the most significant threats to land resources in these regions.

2.5. Impact of soil health decline on agricultural production and humans

Nutrient imbalance affects crop productivity. Numerous studies on crop nutrition have demonstrated that, in acid sulfate soils, potassium is a limiting factor after phosphorus due to its low availability in the soil and root leaching during cultivation and land reclamation. Therefore, to achieve potential yields and high product quality in acid sulfate soils, the only viable solution is to supplement potassium through fertilization. Research conducted both globally and in Vietnam has shown that potassium deficiency negatively impacts plant metabolism, weakens enzyme activity, reduces compound exchange processes, and increases sugar consumption for respiration. As a result, older leaves turn yellow prematurely, drying begins at the leaf margins and spreads across the entire leaf. In grain crops, in addition to leaf scorch, potassium deficiency leads to empty grains, reducing both yield and quality (Southern Institute for Agricultural Science and Technology, 2024).

Additionally, several studies have indicated that micronutrient deficiencies affect the uptake of macronutrients and crop productivity (Lê Thị Khánh, 1998; Nguyễn Bá Lộc, 2019). According to Trần Minh Thắng (2017), mineral nutrition plays a crucial role in plant growth and development. The depletion of micronutrients in the soil due to leaching and degradation affects physiological and biochemical processes, as well as macronutrient absorption. Trần Minh Thắng's (2017) research further demonstrated that micronutrients influence a plant's ability to absorb potassium. Moreover, agricultural practices in Vietnam predominantly focus on macronutrient fertilizers (N-P-K), while micronutrients are often neglected, leading to nutrient imbalances. Although macronutrient fertilizers are applied, their efficiency declines, prompting farmers to increase application rates, raising production costs without improving or even reducing crop yields.

Excessive fertilizer application also affects soil pH, indirectly impacting crop productivity. Fungi thrive in highly acidic soils, whereas beneficial bacteria prefer slightly acidic to mildly alkaline conditions. In highly acidic soils, nitrogen conversion and organic matter mineralization slow down. Since nutrient solubility in soil depends on pH, soils with different pH levels will contain varying nutrient concentrations despite undergoing the same reclamation and fertilization practices (Hanna, 2024).

FAO and IPTS (2015) identified ten global threats to soil, including soil erosion, loss of organic matter and soil carbon, nutrient imbalance, acidification, pollution, waterlogging, compaction, sealing, salinization, and loss of soil biodiversity. Many of these threats negatively impact food security by reducing agricultural productivity and limiting the availability of land for food production due to degradation or contamination. While the effects of some types of degradation, such as soil erosion, on food production are well-documented and quantified, the impacts of others remain poorly understood due to insufficient data. For instance, the status and trends of soil biodiversity in Europe are not well comprehended, and its impact on productivity has not been fully quantified. India, which accounts for only 2.4% of the world's land area, supports 18% of the global population and 15% of the world's livestock (Bhattacharyya, 2015). Land degradation in India is leading to declining crop productivity and significant economic losses, threatening food security and farmers' livelihoods. In sub-Saharan Africa, land degradation—particularly nutrient depletion—is reducing crop yields and is linked to poverty (Tully, 2015). In South America, Wingeyer et al. (2015) noted that while the expansion of monoculture has brought some economic benefits, current agricultural practices, even with no-till systems, are detrimental to long-term soil conservation. Monocropping combined with low biodiversity has contributed to land degradation through wind and water erosion, depletion of soil organic matter (SOM), and loss of nutrients. In the EU, it is estimated that around 60–70% of land is no longer in a healthy state due to unsustainable land use and management practices, overexploitation, and pollutant emissions. Specifically, 25–30% of total land area is experiencing organic carbon loss, nutrient overloading, erosion, compaction, secondary salinization, or a combination of these threats, with agricultural land being the most affected. This means that approximately 61–73% of farmland is impacted by these issues (Veerman, 2020). Gardi et al. (2015) estimated that potential agricultural production losses due to soil sealing in 19 EU countries from 1990 to 2006 amounted to approximately six million tons of wheat. While this represents only a -0.81% loss of total potential agricultural production during that period, regions near major cities in Central and Western Europe and the southern European coast were particularly affected, with some losing more than 10% of their agricultural production potential.

Other soil threats, including erosion, loss of organic carbon and soil material, soil biodiversity decline, compaction, salinization, acidification, and desertification, reduce agricultural productivity and food production. For example, erosion caused by water, wind, and harvest damage affects soil function and fertility while transporting sediments and pollutants into water systems, impacting water availability and quality for agriculture and human consumption. In the EU, recent estimates suggest that one-quarter of European land is losing soil at unsustainable rates (more than 2 tons/ha/year in 2016), with over 6.6% of agricultural land experiencing severe erosion (>11 tons/ha/year) (Panagos, 2020). Furthermore, in several countries, soil loss is worsening; between 2010 and 2016, erosion rates increased in eight nations, primarily due to a decline in conservation farming practices. Panagos et al. (2018) estimated that crop yields decrease by -8% in intensively farmed fields with high erosion rates (>11 tons/ha/year). Using 2010 data, they estimated that nearly 3 million tons of wheat and 0.6 million tons of maize are lost annually due to severe erosion in the EU. The highest yield losses were recorded for rice and wheat, as these are the dominant crops in the most erosion-prone Mediterranean countries, such as Italy, Spain, and Greece, with Italy and Slovenia being the most affected nations.

Industrial activities, waste management, and intensive land use have led to the spread of pollutants in the environment, including soil contamination. These pollutants include pesticide residues, industrial emissions, fertilizers, pharmaceuticals, heavy metals, and emerging contaminants such as microplastics, endocrine disruptors, and antibiotics (EEA, 2019). Depending on their properties and concentrations, these pollutants can enter the food chain, threatening soil ecosystem functions, food safety, and human health (Peralta-Videa, 2009). For example, Tóth et al. (2016) found that 137,000 km^2 of agricultural land in the EU has high concentrations of heavy metals, accounting for nearly 8% of total agricultural land. The accumulation of pesticide residues in soil is also an increasing concern. Researchers from Wageningen University analyzed soil samples from 11 EU member states and found that over 80% of soils contained pesticide residues, including glyphosate and its metabolites, as well as several broad-spectrum fungicides. These were the most frequently detected and found at the highest concentrations (up to 2.87 mg/kg) (Silva, 2019). While these pollutants do not directly affect food supply, they impact the quality of agricultural products, thereby posing a threat to food security. Due to their bioaccumulative and biomagnifying nature, long-term human consumption of contaminated food can lead to biochemical disorders and potential carcinogenic effects (Hyun Soo Kim, 2015).

Numerous studies have examined the toxic risks of soil contaminants and their threats to human health. Lead (Pb) is the most widespread heavy metal contaminant in soil, primarily introduced through anthropogenic sources such as leaded gasoline, lead-based paint, mining, and industrial activities. Mass lead poisoning incidents have been reported in Senegal (Haefliger, P., 2009) and Nigeria (Lo, Y. C., 2012). These incidents occurred in villages engaged in informal lead-acid battery recycling and gold ore processing, which contaminated the soil with lead. The resulting lead-laden dust was inhaled or ingested, leading to widespread lead poisoning. Beyond lead, arsenic (As) contamination is also a major concern due to its accumulation in soils near structures made from treated wood (which contains wood preservatives used in pressure-treated timber) (Gardner, D., 2013). Additionally, the use of arsenic-contaminated water for rice cultivation has led to arsenic accumulation in consumers (Kwon, J. C., 2017). Since rice is a staple food for nearly half the global population, it presents a significant source of arsenic exposure. Cadmium (Cd) contamination can result from industrial activities or the application of sewage sludge or phosphate fertilizers (Nordberg, G. F., 2021). High cadmium levels in soil lead to corresponding accumulations in plant tissues, posing toxicity risks to humans consuming food grown in contaminated areas. A well-documented case is the mining operations in Toyama Prefecture, Japan, which discharged large amounts of cadmium into the Jinzu River, a source of irrigation for rice paddies. Rice absorbed cadmium from the water, and those who consumed the contaminated rice developed itai-itai disease, characterized by weak and brittle bones, leg and spine pain, coughing, anemia, and kidney failure (Brevik, 2015).

Pesticides contribute to soil pollution and degradation, negatively impacting human health and ecosystems. These organic chemicals pose significant risks due to their widespread use in both rural and urban areas, with a large proportion seeping into the soil. For instance, when pesticides are applied, only about 25% reach plant foliage, approximately 1% affect target insects, around 30% contact the soil, and the remainder disperses into the atmosphere or water bodies. Due to the long half-life of many organic chemicals, they are classified as persistent organic pollutants (POPs). These pollutants resist degradation in the environment and bioaccumulate as they move up the food chain. A well-known example of a POP is 1,1,1-trichloro-2,2-bis(p-chlorophenyl) ethane (DDT), which has been shown to disrupt avian hormonal systems, causing eggshell thinning that threatens bird populations (Vega, F. A., 2007).

Biodiversity loss leads to soil health deterioration, adversely affecting agricultural productivity. Pollination is one of the critical processes for plant reproduction and long-term survival, with most plants relying on pollination vectors such as animals and wind (Fischer, M., 2018). Globally, over 300,000 flowering plant species (87.5%) depend on animal pollinators. Crop plants are particularly significant, as approximately 85% of the world's leading food crops require animal pollination to some extent for optimal yield and quality (Klein, A. M., 2007). Animal-mediated pollination directly contributes to 3–8% of global agricultural production by volume, meaning that agricultural output would decline without pollinators. In Europe, studies indicate that pollinators enhance the yields of approximately 85% of the 264 cultivated crops, with 12% of the EU’s total agricultural land relying on pollinators for optimal production (Schulp, 2014). Another study suggests that a shortage of pollinating insects could reduce the total yield of pollinator-dependent crops in the EU by 25–32% (Zulian, G., 2013).

Food safety remains a top concern for both the EU and Vietnam, particularly regarding pesticide residues in agricultural products. The EU has established Maximum Residue Limits (MRLs) for food products to ensure consumer safety. According to regulations, the maximum allowable residue level for certain active substances is set at 0.01 mg/kg unless otherwise specified. These MRLs apply to 315 fresh and processed food products, with adjustments reflecting concentration changes during processing. In Vietnam, the Ministry of Health issued Circular No. 50/2016/TT-BYT on December 30, 2016, regulating maximum allowable pesticide residue levels in food, replacing Decision No. 46/2007/QĐ-BYT (USDA, 2017). However, studies indicate that many pesticides found in Vietnamese agricultural products and specialty crops lack specific MRLs or are inconsistent with the list of permitted or banned pesticides in Vietnam. A study assessing pesticide residues in vegetables from Thua Thien Hue and Quang Binh found total pesticide concentrations reaching up to 11.9 mg/kg in scallions and 38.6 mg/kg in mustard greens (Nguyen Dang Giang, 2022). These residue levels far exceed EU MRLs, posing challenges for Vietnam's agricultural exports to European markets.

2.6. Current status of soil health management in Vietnam

2.6.1. Soil health policy

a. Land use policy

The Party and the State have consistently prioritized the development and implementation of policies on land use and management. The Party's directives on land exploitation and utilization are explicitly outlined in Resolution No. 18-NQ/TW (2022) and Resolution No. 19-NQ/TW (2022), which emphasize the establishment of a comprehensive legal framework to enhance land resource management, ensure efficient land use, and mitigate land degradation. Additionally, the Party has advocated for the conversion of low-productivity agricultural land into sustainable land-use models such as agroforestry and organic farming to maintain soil fertility and prevent degradation. Accordingly, legal documents such as the Land Law No. 45/2013/QH13, along with its implementing decrees—including Decree No. 124/QĐ-TTg (2012), which approves the Master Plan for Agricultural Development until 2020 with a vision to 2030, and Decree No. 43/2014/NĐ-CP, which provides guidance on implementing the Land Law—form the legal foundation for agricultural land management. The Planning Law No. 21/2017/QH14 and Decree No. 37/2019/NĐ-CP, which provides guidance on the Planning Law, also relate to land-use planning. This decree specifies procedures for adjusting national land-use plans, regional plans, and national marine spatial plans. However, these regulations are not fully aligned with policies for soil environmental protection, leading to excessive land exploitation and severe degradation in many key agricultural regions. Furthermore, Decree No. 62/2019/NĐ-CP, which amends Decree No. 35/2015/NĐ-CP on the management and use of rice-growing land, introduces provisions on land accumulation and consolidation to promote large-scale agricultural production and encourage modernization. However, gaps in oversight mechanisms have allowed unsustainable land exploitation to persist. The initiative to convert low-productivity agricultural land into sustainable farming models faces challenges due to limited resources and technical support.

In the agricultural sector, several policies have been enacted to improve land-use efficiency. One of the most significant is Decision No. 150/QĐ-TTg, which approves the Strategy for Sustainable Agriculture and Rural Development for the 2021–2030 period, with a vision to 2050. This policy aims to enhance agricultural productivity and product quality while protecting and improving soil and water resources. Decision No. 899/QĐ-TTg (2013), which approves the project on “Restructuring the Agricultural Sector toward Higher Value Addition and Sustainable Development,” and Decision No. 255/QĐ-TTg (2021), which approves the Agricultural Restructuring Plan for 2021–2025, provide strategic directions for restructuring the agricultural sector to optimize land use and promote sustainability. Decision No. 432/QĐ-TTg, which outlines Vietnam’s Sustainable Development Strategy for 2011–2020, also sets objectives for natural resource and environmental protection, particularly concerning land resources.

Despite the issuance of legal documents aimed at improving land use efficiency and protection, excessive land exploitation remains a persistent issue. This is largely due to the lack of a rigorous monitoring system and ineffective enforcement mechanisms. Additionally, public awareness campaigns on soil conservation have not achieved the desired impact, leading to a lack of motivation among farmers and businesses to adopt sustainable farming practices. The increasing use of chemical fertilizers, expansion of industrial crops, and unsustainable land exploitation have placed significant pressure on soil resources. The average chemical fertilizer application rose from 221.3 kg/ha in 2002 to 266.7 kg/ha in 2021, exceeding the regional average in Southeast Asia. At the same time, land accumulation policies remain inconsistent, making it difficult to establish large, stable raw material zones.

Pilot projects for improving soil health have been implemented in some localities but remain experimental and have not been widely replicated nationwide. Decision No. 3458/QĐ-BNN-BVTV (2024), approving the "Project on Enhancing Soil Health and Crop Nutrient Management until 2030, with a Vision to 2050," and Directive No. 6656/CT-BNN-TT (2024) from the Ministry of Agriculture and Rural Development emphasize sustainable land use measures. However, implementation faces challenges due to financial constraints and the lack of strong incentives from local authorities.

Long-standing weaknesses in land-use planning have hindered the transformation of land resources into a true economic driver. Legal provisions on land-use planning still exhibit limitations, leading to impractical and low-feasibility plans in some localities. The integration of different types of planning has not been effectively addressed. Specifically:

1. Regulations on defining the position of land-use planning within the broader "planning layers" of national sectoral plans do not clearly establish land-use planning as a "foundational layer."
2. There are unresolved issues regarding land-use planning for the private sector, as investment projects involving land use often do not align with annual land-use plans and land recovery policies.
3. The conversion of land use according to approved plans has not been effectively implemented.
4. The periodic review and adjustment of land-use plans, as well as localized revisions, have not been thoroughly considered.
5. The authority of the "Standing Committee of the People's Council" at the provincial level remains unclear.

b. Legal framework for land resource protection

To enhance land management efficiency, the legal framework for soil resource protection has been continuously refined by the Party and the government. Since 2013, the Communist Party of Vietnam has issued Resolution No. 24-NQ/TW of the 11th Central Committee on proactively responding to climate change, strengthening resource management, and environmental protection, which set key objectives for environmental protection and, consequently, soil health preservation.

The Party’s policies on land resource protection are reflected in Resolution No. 18-NQ/TW (2022) and Resolution No. 19/NQ-TW (2022), which aim to inprove the legal framework for land protection, pollution control, and land degradation prevention.

Vietnam's soil protection policy is based on legal regulations such as the Land Law No. 45/2013/QH13 and the Crop Law No. 31/2018/QH14. These regulations emphasize the role of soil resource protection in sustainable agricultural development. Accordingly, organizations and individuals are required to use land reasonably, protect topsoil, and apply measures to prevent soil erosion and degradation. Specifically, Clauses 1 and 2 of Article 55 of the Crop Law require that the use of cultivated land must comply with the principles of soil health protection, in order to maintain long-term fertility and productivity.

Measures to protect soil include preventing erosion of steep hillsides, improving acid sulfate soils, saline soils, and restoring degraded land areas. In particular, Decree 35/2015/ND-CP and Decree 62/2019/NĐ-CP on the management and use of rice-growing land requires strict protection of rice-growing land funds and minimizing conversion of land use purposes. Land improvement programs such as the Dong Thap Muoi and Long Xuyen Quadrangle acid sulfate soil improvement projects have achieved some positive results, helping to increase the area of high-quality cultivated land.

Decision No. 3458/QĐ-BNN-BVTV (2024) issued by the Ministry of Agriculture and Rural Development has proposed a plan for soil protection and nutrient management in crops. However, this decision remains an initial step and has yet to establish strong linkages with national-level soil resource protection policies. Soil improvement programs, such as liming and organic matter supplementation, have not been widely implemented due to financial constraints and the lack of specific technical guidance from specialized agencies.

Despite the existence of a relatively comprehensive legal framework, implementation continues to face significant challenges. Local authorities may adopt different measures due to the absence of detailed central guidelines, leading to inconsistencies in soil protection effectiveness. Mechanisms for monitoring soil quality and enforcing violations remain insufficiently robust, making it difficult to prevent pollution caused by chemical fertilizers and pesticides. Furthermore, many localities lack the financial and human resources necessary to fully implement soil protection and restoration measures as required by law.

c. Soil quality monitoring system

The Party's policy on soil quality monitoring is outlined in Resolution No. 18-NQ/TW (2022), which calls for the completion of management mechanisms to ensure the effective and sustainable use of land. The resolution emphasizes the importance of regularly tracking, evaluating, and updating soil quality data to detect early signs of degradation and take timely action. Additionally, Resolution No. 19/NQ-TW (2022) mandates the development of integrated monitoring systems that apply advanced technologies to enhance data accuracy. This direction is crucial in establishing a soil quality monitoring and assessment system, thereby strengthening state management capacity over land resources.

The 2013 Land Law and related decrees, such as Decree No. 43/2014/ND-CP, which details the implementation of the Land Law, have laid the foundation for soil quality monitoring. Under Land Law No. 45/2013/QH13, the Ministry of Natural Resources and Environment (MONRE) is responsible for investigating, assessing, and publishing national soil quality reports every five years. Decree No. 101/2024/ND-CP further regulates the organization of land surveys and assessments, including the formulation and approval of investigation tasks, data collection, and processing. Decision No. 90/QD-TTg (2016) on the national environmental and natural resource monitoring network planning until 2025 has established a nationwide soil quality monitoring system, covering agricultural, forest, and urban land.

However, the current monitoring system remains inconsistent, with incomplete data collection and a lack of modern analytical tools.

MONRE has issued Circular No. 20/2022/TT-BTNMT on economic and technical standards for soil resource monitoring, setting technical requirements for periodic monitoring and evaluating the impact of agricultural production activities. However, implementation faces difficulties due to funding shortages, limited human resources, and uncoordinated processes across localities.

Currently, the soil quality monitoring system encounters several challenges, including fragmented data, outdated analytical tools, and financial and personnel constraints. Although there are plans to build a monitoring network, data collected from monitoring stations have not been fully integrated, reducing its usability for real-time land assessments. The adoption of advanced technologies such as remote sensing, environmental sensors, and big data analytics remains limited, restricting early detection of soil degradation and delaying management responses. Establishing an effective monitoring system requires substantial investment in infrastructure and specialized training for personnel, yet existing resources remain insufficient. Greater investment in remote sensing, environmental sensors, and open data systems is essential to enhance soil quality monitoring efficiency.

d. Soil health assessment tools and management policies

In the current context, soil health is not only a matter of agricultural productivity but also a key indicator of environmental quality and sustainable development potential. Resolution No. 19/NQ-TW (2022) emphasizes the application of science and technology in soil assessment and classification while calling for the establishment of nationwide soil health indicators and evaluation methods. This ensures that land resources are used efficiently and protected for the long term. Additionally, other Party directives propose integrating soil health criteria into the national environmental assessment system to ensure sustainable monitoring and restoration efforts.

The 2013 Land Law and Decree No. 44/2014/ND-CP on land use planning set criteria for soil quality assessment but do not delve deeply into the concept of soil health. Decision No. 3458/QĐ-BNN-BVTV (2024) by the Ministry of Agriculture and Rural Development (MARD) on crop nutrition management and soil protection has introduced an initial evaluation framework. However, there is still no comprehensive national system for soil health assessment. Existing regulations do not cover all soil types or provide detailed methods to assess the impact of various land uses on soil health.

The Ministry of Natural Resources and Environment (MONRE) has issued Circular No. 11/2024/TT-BTNMT, which sets technical guidelines for soil investigation, evaluation, protection, rehabilitation, and restoration. However, the reporting and data collection system for soil health remains inconsistent across provinces, making it difficult to formulate effective soil improvement and restoration strategies at a national scale. Furthermore, regular soil assessment programs still face significant challenges related to funding and personnel shortages.

Despite policy frameworks, several implementation challenges remain. Vietnam lacks a comprehensive soil health index and an effective coordination mechanism between relevant ministries and agencies. There are no clear regulations on the responsibilities of stakeholders in monitoring and reporting soil health, leading to uneven enforcement. Developing specific evaluation standards, establishing a centralized soil health database, and increasing technology adoption in soil monitoring are crucial steps. Notably, incentives should be provided for research institutions and private enterprises to participate in soil data collection and analysis, improving data accuracy and timeliness. To enhance effectiveness, investment in scientific research and collaboration with international organizations such as FAO, GIZ, and ACIAR is essential for developing appropriate tools and standards. Additionally, formulating region-specific soil health assessment criteria tailored to different ecological zones is a vital solution.

e. Training, coaching and communication policy

Public awareness, particularly among farmers and local management officials, plays a crucial role in implementing soil health protection policies. To strengthen these efforts, the Party and the government have issued numerous policies and directives. Resolution No. 19/NQ-TW (2022) mandates enhanced education and training for farmers and management officials on sustainable farming practices, soil protection, and efficient land resource management. Additionally, the Party's directives emphasize the importance of raising community awareness about soil conservation through public campaigns, seminars, and the dissemination of scientific knowledge.

The 2020 Environmental Protection Law and Decree No. 38/2015/ND-CP on waste management and environmental protection outline responsibilities for training and awareness campaigns. However, they lack specific programs dedicated to soil health protection. Current training initiatives primarily focus on general environmental management and do not offer specialized courses on soil health for farmers, cooperatives, and agricultural enterprises. The implementation of training policies remains fragmented, lacking clear priorities and an effective evaluation framework.

The Ministry of Agriculture and Rural Development (MARD) has introduced various policies related to training and capacity-building for sustainable land management. A key initiative is the Agricultural Vocational Training Plan for Rural Workers (2022–2025), approved under Decision No. 3685/QĐ-BNN-KTHT, which aims to enhance farmers' and management officials' capabilities in sustainable land use. Several other policies promoting sustainable agriculture also incorporate training, workshops, and awareness campaigns, such as:

- Decision No. 3417/QĐ-BNN-TT: Sustainable Coffee Industry Development Project (until 2020)
- Decision No. 1648/QĐ-BNN-TT: Planning for Key Fruit Crop Regions in Southern Vietnam (until 2020)
- Decision No. 5018/QĐ-BNN-TT: Sustainable Fruit Tree Development in Northwest Provinces (until 2030)
- Decision No. 431/QĐ-BNN-BNNPTNT: Development of Key Industrial Crops (until 2030) (including coffee, rubber, tea, cashew, pepper, and coconut)
- Decision No. 1115/QĐ-BNN-TT: Sustainable Cassava Industry Development (until 2030, vision to 2050)
- Decision No. 1490/QĐ-TTg: One Million Hectares of High-Quality, Low-Emission Rice in the Mekong Delta (until 2030)
- Decision No. 150/QĐ-TTg: Sustainable Agriculture and Rural Development Strategy (2021–2030, vision to 2050)

Despite these initiatives, local training and awareness programs on soil protection remain scattered, lacking integration and clear focal points. There is no mandatory training program for farmers on soil conservation, nor are there continuous and widespread training policies for key agricultural regions. Furthermore, training programs lack strong partnerships with universities, research institutes, and agricultural technology firms to update farmers on advanced cultivation techniques. To address these challenges, incentives should be provided to encourage farmer participation in training, such as financial support, certification programs, or integration into agricultural extension services. Additionally, investment in digital technology is essential for developing online learning platforms, enabling farmers to access knowledge anytime, anywhere.

f. Policy on standards and regulations

In the context of integration and technological development, establishing a system of standards and technical regulations for soil protection, pollution control, and land restoration plays a crucial role in ensuring the safe and efficient use of land resources. Resolution No. 18-NQ/TW (2022) highlights the need to improve technical regulations on soil protection, pollution control, and the rehabilitation of degraded land. Similarly, Resolution No. 19/NQ-TW (2022) calls for research and the application of advanced standards in land resource management to ensure sustainable soil quality and environmental protection. These directives lay the foundation for developing a comprehensive and consistent national standard system.

The 2006 Law on Standards and Technical Regulations and Decree No. 127/2007/ND-CP provide a general legal framework, but a specific set of standards for soil health has yet to be established. Certain provisions in the 2020 Environmental Protection Law address soil pollution control; however, they remain broad and lack clear thresholds for soil contaminants, as well as standardized scientific methods for assessing soil quality.

The Ministry of Agriculture and Rural Development (MARD) has introduced the Vietnamese National Standard TCVN 11892-1:2017 on sustainable agriculture. However, a comprehensive national standard for soil health assessment and protection has not yet been developed. Additionally, existing standards for fertilizers, pesticides, and organic matter management in soil are inconsistent across sectors, making widespread implementation challenging. Furthermore, many soil-related technical standards have not been updated to reflect environmental changes and the impacts of climate change.

Currently, Vietnam does not have a comprehensive national standard system for assessing soil health. There are no clearly defined biological, chemical, or physical soil indicators to support long-term management and monitoring. Additionally, there is a lack of coordination among relevant ministries in developing a harmonized standard system, leading to overlaps or omissions in implementation. The absence of specific evaluation criteria based on land-use types further complicates efforts to manage and improve soil health. Existing regulations mainly focus on land productivity, without adequately addressing factors such as soil structure, self-recovery capacity, and contamination levels. To support soil quality assessment, soil mapping, and monitoring of soil degradation and pollution in accordance with the Land Law and the Law on Environmental Protection, the Minister of Science and Technology has issued decisions to announce national standards such as TCVN 8409:2012 – Procedures for evaluating agricultural land; TCVN 9487:2012 – Procedures for soil mapping at medium and large scales; QCVN 03:2023/BTNMT – National technical regulation on soil quality; and other standards related to soil sampling and the determination of soil quality parameters. However, these standards and technical regulations still lack comprehensive indicators, testing methods, and rating scales necessary for a robust evaluation of soil health. This lack of standards hinders the effective and coordinated implementation of land management policies. A long-term strategy is needed to update and develop a national soil standard system that integrates modern technologies, ensuring both efficiency and practical applicability. Completing the technical standards and regulations framework will provide a solid foundation for soil health protection and restoration, while also supporting the implementation of sustainable land management policies.

To support fertilizer management in accordance with the Law on Crop Production, the Minister of Agriculture and Rural Development has issued the National Technical Regulation on Fertilizer Quality (QCVN 01-189:2019/BNNPTNT). The Minister of Science and Technology has also issued decisions announcing national standards, including TCVN 12719:2019 for fertilizer trials on annual crops, TCVN 12720:2020 for fertilizer trials on perennial crops, and 93 other TCVNs specifying testing methods for fertilizer quality indicators. In addition, to maximize and efficiently utilize plant nutrients from liquid livestock waste, the Minister of Agriculture and Rural Development has also issued the National Technical Regulation on Livestock Wastewater for Use on Crops (QCVN 01-195:2022/BNNPTNT). As a result, the system of standards and technical regulations supporting fertilizer quality management is now relatively well established. However, several fertilizer quality indicators, particularly those related to microorganisms, still lack corresponding TCVNs for species-specific identification. In the long term, it remains necessary to continue developing national standards for testing methods to ensure better control over fertilizer quality in the future.

g. Policy on database development and management

The database on land and soil quality plays a crucial role in supporting planning, monitoring, and policy development for land resource management. Resolution No. 18-NQ/TW (2022) mandates the completion of the land information system, integrating soil health monitoring data to enhance management efficiency. Additionally, Resolution No. 19/NQ-TW (2022) emphasizes the application of information technology and digital transformation in land management, encouraging the development of a synchronized land database at all levels, from central to local authorities. This approach enhances transparency and facilitates the use of land data for planning, economic development, and land resource protection.

The 2013 Land Law and Decree No. 43/2014/ND-CP regulate land databases but do not include an integrated system for soil health information. These regulations primarily focus on land use rights management, surveying, mapping, registration, and land use certificates without specifying long-term soil quality monitoring. Moreover, the current land database system is not fully digitized, with significant limitations in data storage and updates, especially at the local level. To address these gaps, the Ministry of Natural Resources and Environment issued Circular No. 25/2024/TT-BTNMT on November 26, 2024, outlining the procedures for building the national land database. This circular specifies technical processes for constructing and updating the national land database, including components such as cadastral data, land surveys, soil protection, land rehabilitation, land use planning, land valuation, statistics, inventory, and other relevant land-related data. The database components align with Article 165, Clause 1 of the Land Law.

Vietnam’s soil health database remains underdeveloped and lacks integration across regions and sectors. The land database management system, overseen by the Ministry of Natural

Resources and Environment under Decree No. 102/2014/ND-CP, primarily focuses on land use and ownership data. A comprehensive soil health database should integrate key indicators such as organic carbon content, microbial activity, and pollution levels to support sustainable land management. Developing an integrated soil health database, combined with Geographic Information Systems (GIS), will enhance decision-making and land management effectiveness. Incorporating biological, chemical, and physical indicators into the database will provide a holistic view of soil conditions, enabling policymakers and farmers to leverage this information for practical applications.

In summary, soil health assessment and survey activities have undergone significant changes, including revised evaluation criteria and innovative methodologies using modern technology. Establishing a land database has become an urgent requirement for local authorities, providing a scientific basis for crop structure transformation, efficient land resource management, and modern land administration. However, the current database mainly focuses on improving and operating local land databases (cadastral data, land use planning, land pricing, statistics, and inventory) for land management and public services. Information on soil health and quality has yet to be implemented and integrated into this system.

2.6.2. Actors involved in soil health management

The system of soil health management organizations in Vietnam includes both central and local agencies. Of which, the two main units performing the task of soil health management at the central level are the Ministry of Agriculture and Rural Development and the Ministry of Natural Resources and Environment, in addition to the participation of ministries such as the Ministry of Science and Technology (MOST), the Ministry of Education and Training (MOET), and the Ministry of Labor, Invalids and Social Affairs (MOLISA). The specific roles of the units are as follows:

a. Ministry of Agriculture and Environment

Decree No. 35/2025/NĐ-CP, which stipulates the functions, tasks, powers, and organizational structure of the Ministry of Agriculture and Environment, defines the Ministry's role in crop production and plant protection management: "To direct, guide, and inspect crop production activities; develop crop production zones and ensure the safe production of agricultural food; plan the use, protection, and improvement of agricultural soil fertility; and prevent soil erosion, desertification, and landslides."

Within the Ministry of Agriculture and Environment, several affiliated departments are responsible for managing and improving soil health, including the Department of Crop Production and Plant Protection; the Department of Science and Technology; the Department of International Cooperation; and the National Agricultural Extension Center.

Among these, the Department of Crop Production and Plant Protection plays a key role in the management and use of agricultural land.

Its primary responsibilities include advising the Ministry on criteria for identifying, managing, and providing production guidelines for various soil types such as sloping land, lowland, acid sulfate soils, saline soils, coastal sandy soils, and land at risk of desertification. The Department also develops, directs, guides, and inspects the implementation of plans for the use, protection, and improvement of agricultural soil fertility, and for the prevention of erosion, desertification, and landslides (according to Decision No. 4179/QĐ-BNN-TCCB, dated October 11, 2023).

Additionally, the Department is responsible for state management of plant protection chemicals, including submitting to the Ministry the list of approved plant protection products and the list of banned substances in accordance with legal regulations. It also proposes the removal of harmful plant protection products from the approved list. Moreover, the Department provides guidance on the collection of pesticide packaging after use, helping to minimize the negative impacts of pesticides on soil health.

The Department of Science and Technology is responsible for advising and assisting the Minister in overseeing state management activities related to science and technology, environmental protection, climate change, biodiversity, agricultural extension, information technology, and digital transformation within the Ministry's jurisdiction. The Department leads the development of plans to carry out state management tasks related to environmental protection, climate change, biodiversity, and biosafety within the Ministry's scope of responsibility.

Regarding soil health, the Department also leads the development, guidance, and compilation of results from environmental monitoring programs serving agricultural management, including programs for monitoring water, soil, and sediment for purposes such as irrigation, aquaculture, agriculture, forestry, and salt production in accordance with legal regulations.

The National Agricultural Extension Center is responsible for testing and disseminating knowledge on sustainable agricultural practices that are friendly to soil health. Agricultural extension systems at all levels will organize training programs, workshops, and public awareness campaigns to raise farmers' awareness about the importance of soil health for crop productivity and quality. The extension sector will also provide information on sustainable farming methods, effective land management, and natural resource conservation.

In relation to soil health management, Decree No. 35/2025/NĐ-CP also specifies the areas of responsibility for the Ministry of Agriculture and Rural Development (MARD), which include:

- Guiding and inspecting the periodic statistics and inventory of land, as well as special or ad-hoc land statistics and inventory as per legal regulations.
- Guiding and inspecting the investigation, assessment, and protection, improvement, and restoration of land.
- Organizing periodic and special investigations and assessments of land in various regions and countries, and publishing the results.
- Organizing nationwide soil resource monitoring.
- Organizing the protection, improvement, and restoration of land in areas with severe land degradation, trans-regional or trans-provincial land degradation, and areas with critically polluted land.

Several government agencies under the Ministry of Agriculture and Environment directly participate in soil health management, including the Department of Land Management, the Department of Surveying, Mapping, and Geographic Information of Vietnam, and the Department of Climate Change, among others. Specifically, according to Decision No. 115/QĐ-BNNMT, which outlines the functions, tasks, authority, and organizational structure of the Department of Land Management, the Department is responsible for collecting, summarizing, and managing land information and soil health data. Specifically, the Department is tasked with:

- Developing plans for periodic land statistics and inventory; conducting special or ad-hoc land statistics and inventory, submitting them for approval by the competent authorities, and organizing their implementation after approval; summarizing the results of statistics and inventory nationwide.
- Organizing the construction, management, operation, updating, and exploitation of the national land information system and database.
- Organizing the connection, integration, and sharing of national land data with national databases, databases of ministries, sectors, and localities.
- Performing the archiving and electronic library tasks related to land management, publishing, providing, and sharing land information and data in accordance with legal regulations.
- Guiding and inspecting the construction, management, operation, and exploitation of land information systems, land databases, and the archiving and provision of land information and data in localities.

In addition, the Department of Land Management is also responsible for advising the Ministry of Natural Resources and Environment (MONRE) on issuing circulars that regulate technical procedures for land investigation and assessment; techniques for land protection, improvement, and restoration, including issuing technical regulations on land quality assessment, land potential, land degradation assessment, land pollution assessment, soil quality monitoring, land degradation monitoring, and land pollution monitoring; as well as the protection, improvement, and restoration of land.

b. Ministry of Science and Technology, Ministry of Education and Training

The Ministry of Science and Technology (MOST) plays a crucial role in protecting and restoring soil health by promoting research, technological applications, and policy development. It allocates funding for research projects on soil rehabilitation, fertility conservation, and pollution reduction, including solutions such as biotechnology, new materials, and smart farming models. The ministry also implements projects to develop advanced tools, equipment, and measurement methods for assessing soil quality, degradation levels, and pollution causes. Additionally, MOST evaluates Vietnamese technical regulations related to national soil quality standards.

The Ministry of Education and Training (MOET) contributes to soil health through education, awareness-raising, and workforce training. They provide vocational education related to soil health and promote sustainable agricultural practices that support long-term soil quality.

2.6.3. Research and training on soil health

a. Research institutes

In Vietnam, numerous agencies, organizations, and research institutes are conducting studies on soil health to enhance fertility, protect the environment, and promote sustainable agriculture. Agricultural and environmental research institutes and universities play a central role in carrying out scientific and technological tasks while fostering international collaboration in soil health research, cultivation practices, and soil quality protection across various soil types. Additionally, they work with other sectors to provide training and education on soil health for farmers, businesses, and local authorities.

Several key research institutes in Vietnam specialize in soil science, land management, and soil mapping, including:

- The Soils and Fertilizers Research Insitute (under the Vietnam Academy of Agricultural Sciences), which leads research on soil science, plant nutrition, and soil improvement for agriculture.
- The National Institute of Agricultural Planning and Projection, which focuses on land-use planning and sustainable agricultural development.
- The Central Institute for Natural Resources and Environmental Studies (Vietnam National University), which conducts research on land resource management and environmental protection.
- Other institutes under the Vietnam Academy of Agricultural Sciences, such as the Institute of Soils and Agrochemistry, the Institute for Agricultural Environment, the Northern Mountainous Agriculture and Forestry Science Institute, the South-Central Coast Agricultural Science Institute, and the North Central Agricultural Science Institute. These institutes not only conduct scientific research but also provide policy

advice, support effective land resource management, and contribute to sustainable agricultural development in Vietnam.

b. Training facilities

In addition to research institutes, universities across different regions of Vietnam offer programs related to soil science, land management, agriculture, and environmental protection. In the northern region, the Vietnam National University of Agriculture (Hanoi) specializes in soil science and agricultural chemistry, while the Hanoi University of Natural Resources and Environment focuses on land management. Other universities in the North with programs related to soil health include the University of Science (Vietnam National University, Hanoi), the Vietnam National University of Forestry (Hanoi), the Thai Nguyen University of Agriculture and Forestry, and the Bac Giang University of Agriculture and Forestry.

In the central region, Hue University of Agriculture and Forestry is known for its expertise in soil science and resource management. In the southern region, the University of Agriculture and Forestry in Ho Chi Minh City, Can Tho University, and Tay Nguyen University (Dak Lak) focus on sustainable agriculture and development. These universities not only provide a strong academic foundation but also contribute significantly to scientific research and the sustainable management of soil resources in Vietnam.

c. Associations

In Vietnam, several associations support their members in enhancing research, teaching, investigation, surveying, application, management, planning, land use, protection, and restoration. These associations also engage in scientific, technical, and socio-economic activities, including soil investigation, classification, mapping, and evaluation; fertilizers and plant nutrition; soil and water environment management; land-use planning and sustainable resource management; poverty reduction; and sustainable agricultural and forestry development. Additionally, they collaborate with ministries and local agencies to provide technical assistance to communities in improving, maintaining, and strengthening soil health. Notable associations include the Vietnam Soil Science Society (VSSS), the Vietnam Fertilizer Association, the Vietnam Organic Agriculture Association, the Vietnam Gardeners' Association (VACVINA), and the Vietnam Farmers' Union.

2.7. International experience in soil health management

2.7.1. United Kingdom

Recognizing the crucial role of soil in food production, food security, environmental protection, and climate change mitigation, England has developed the "Safeguarding our Soils" strategy. This new soil strategy builds upon and replaces the Soil Action Plan 2004–2006.

The strategy outlines the UK Government's long-term approach to soil protection, providing a clear vision to guide future policy development across various sectors. It also identifies practical actions to prevent soil degradation, enhance and restore soil resilience, and raise public awareness of soil-related threats and best practices for addressing them. The strategy's vision is that by 2030, all soils in England will be managed sustainably, and degradation threats will be effectively addressed. This will improve soil quality and safeguard its ability to provide essential services for future generations.

The soil protection strategy focuses on key areas of action, including:

- Better protection for agricultural land
- Conservation and enhancement of soil carbon stocks
- Strengthening soil resilience to climate change
- Preventing soil pollution
- Effective soil management during construction and development
- Remediation of contaminated land
- Research and monitoring of future soil quality

2.7.2. Scotland

To prepare for future challenges and enhance soil resilience under increasing pressures from climate change, the Scottish Soil Framework was developed to raise awareness of soil's role in sustaining life and the pressures it faces. The framework aims to foster collaboration among key stakeholders to improve soil protection. Given the multifunctionality of soil, effective cooperation and coordination among various stakeholders are essential. The Scottish Government recognizes soil as one of the nation's greatest natural assets, providing significant ecological, economic, and social benefits while remaining highly vulnerable. Identifying effective solutions for sustainable soil use is crucial. The Scottish Soil Framework represents an important step toward achieving the National Objective of Protecting Natural Resources.

The framework envisions soil as a vital component of Scotland's economy, environment, and heritage, requiring protection for both present and future generations. Its core purpose is to promote sustainable soil management and protection in alignment with Scotland's economic, social, and environmental needs.

The framework outlines a series of actions contributing to 13 key objectives:

- SO1 – Protect and enhance soil organic carbon stocks where appropriate.
- SO2 – Reduce and, where possible, remediate soil erosion.
- SO3 – Maintain soil structure.
- SO4 – Minimize greenhouse gas emissions from soil to an optimal balance.
- SO5 – Protect soil biodiversity and its contribution to above-ground biodiversity.
- SO6 – Support sustainable flood management through soil conservation.

- SO7 – Improve water quality through enhanced soil management.
- SO8 – Sustain and enhance soil productivity for food, timber, and biomass production.
- SO9 – Reduce soil contamination.
- SO10 – Decrease pressures on soil.
- SO11 – Protect soil with significant historical and cultural value.
- SO12 – Improve knowledge and understanding of soil to strengthen policy development.
- SO13 – Ensure effective coordination of roles, responsibilities, and actions among all stakeholders.

The implementation of the Scottish Soil Framework is a critical first step in raising awareness of sustainable soil management and promoting better policy integration. It establishes a training process to identify and implement future activities in collaboration with key delivery partners.

2.7.3. Australia

The Australian government recognizes soil as an integral part of the country's landscape, providing essential production and ecosystem services that support and contribute to Australia’s economic, environmental, and social prosperity. Healthy soils are key to building resilience against climate change and natural disasters, meeting emissions reduction targets, developing the agricultural sector, and ensuring human health, food and water security, biodiversity, and economic growth.

In 2021, the Australian Department of Agriculture, Water, and the Environment introduced the National Soil Strategy, a 20-year plan outlining how Australia will assess, manage, and improve its soils. Developed in collaboration with state and territory governments, the National Soil Advocate, and key stakeholders in soil science and land management, the strategy’s goals focus on restoring and protecting soils nationwide through coordinated action, research, education, monitoring, and governance. It emphasizes the role of all levels of government, industries, research institutions, private soil scientists, and land managers in safeguarding soil resources.

This long-term strategy sets the direction for sustainable soil science innovation and national soil management while allowing flexibility for regional and local priorities, as soil management challenges vary across different areas. The strategy ensures that soil quality is prioritized in government decision-making processes. It also equips government and non-government land managers with the knowledge, tools, networks, and capabilities to preserve soil while maintaining and enhancing productivity. By strengthening knowledge and expertise in soil health, the strategy ensures that research is conducted in a coordinated manner and its findings are shared with those who need them. The strategy is supported by the Commonwealth Interim Action Plan, which will be followed by and replaced with the National Soil Action Plan.

The strategy sets out three key objectives:

- Prioritizing soil health
- Empowering land managers and fostering innovation
- Enhancing soil knowledge and capability

It also outlines 12 goals:

- Collaboration – Effective decision-making, aligned efforts, and partnerships contribute to successful research, policy planning, and implementation.
- Science and Innovation – Delivering world-class research, innovation, monitoring, and evaluation.
- Traditional Knowledge – Recognizing, respecting, and incorporating the culture, values, knowledge, innovations, and practices of First Nations Peoples into land planning, management, and conservation where appropriate.
- Knowledge Sharing – Promoting information exchange to support evidence-based and cost-effective decision-making.
- Future Soil Security – Ensuring sustainable land use meets current needs without compromising those of future generations.
- Immediate Action – Taking prompt steps to manage, prevent, or remediate soil degradation and environmental risks that could cause severe or irreversible damage.
- Prioritization and Integration – Incorporating soil considerations into all relevant decisions to enhance agricultural productivity and ecosystem services.
- Ownership and Responsibility – Addressing soil degradation impacts that extend beyond legal property boundaries through cooperative management solutions.
- Practical, Site-Based Adaptability – Utilizing regional and local knowledge to develop and implement location-specific, adaptable solutions.

By June 2022, the Australian government worked with states and territories to develop and implement the National Soil Action Plan. This plan details specific programs and activities required to achieve the strategy’s vision and objectives. These actions follow SMART principles—Specific, Measurable, Achievable, Relevant, and Time-bound. Before its full implementation in June 2022, the government took interim soil-related measures through the Commonwealth Interim Action Plan to contribute to the strategy’s goals.

2.7.4. USA

In the United States, the Soil Science Interagency Working Group (SSIWG) was established to facilitate cross-agency coordination in soil research activities and ensure the long-term sustainable use of soil resources. In 2016, the working group developed the Federal Strategic Plan Framework for Soil Science, outlining five key federal science and technology priorities that, if implemented, could significantly support government-wide efforts to ensure the long-term sustainability of U.S. soils.

The framework prioritizes:

- Advancing applied social science research in soil science and increasing public awareness of soil science and its importance.
- Enhancing national research infrastructure for soil data storage, analysis, and sharing.
- Supporting coordinated research efforts on soil and global climate interactions.
- Expanding and strengthening investment in long-term, collaborative research programs to better understand, document, and manage the impacts of land use and land cover change on soils.
- Prioritizing programs and technical support designed to promote sustainable land management practices and mitigate unsustainable soil management activities.

The United States Department of Agriculture (USDA) plays a key role in addressing soil health through conservation programs and educational resources. The Natural Resources Conservation Service (NRCS), along with its Soil Health Division, leads efforts to improve soil management. USDA collaborates with states and other partners to provide training and technical guidance, ensuring that soil health assessments are effectively used and that soil health management systems are developed and implemented. At the federal level, soil health initiatives are primarily addressed through conservation programs, most of which are administered by the USDA.

2.7.5. Canada

In 2021/2022, the Soil Conservation Council of Canada (SCCC) collaborated with the Compost Council of Canada to develop the roadmap "Recruiting Soil to Tackle Climate Change." This roadmap was created by a multidisciplinary team with input from various stakeholders in the agri-food sector. It proposes a range of solutions to improve soil quality, with a key recommendation calling for the development of a "National Soil Health Strategy." This initiative aims to enhance soil health, promote sustainable agricultural practices, and ensure environmental resilience for Canada’s future.

The National Soil Health Strategy is designed to maintain and enhance soil health while addressing climate change, contributing to Canada's climate goals for 2030 and the long-term vision for 2050. The SCCC plays a leading role in convening and connecting agri-food stakeholders to develop an action plan for soil health in Canada, aligning with the country’s climate mitigation goals.

The strategy includes a framework and action plan for sustaining and improving soil health, with short-term and long-term goals for the agri-food sector. Although Canada is in the early stages of developing this strategy, several initiatives have already been launched:

- The Senate is conducting a study on soil health in Canada.
- Agriculture and Agri-Food Canada (AAFC) is leading the development of the Sustainable Agriculture Strategy, where soil health is a priority.

- The Canadian Roundtable on Sustainable Crops is finalizing a Sustainable Grain Production Initiative, with soil and crop nutrient management as one of four key components.
- Several provinces have implemented measures to improve soil quality, including:
  - Ontario: Implementing a provincial soil health strategy in collaboration with stakeholders.
  - Prince Edward Island: Launching the "Soil First Farming" initiative as a joint effort between farm organizations and the provincial government.
  - Québec: Developing the 2020-2030 Sustainable Agriculture Plan, which includes soil quality targets and increased investment in agricultural extension services.

2.7.6. European Union (EU)

The European Commission has adopted the Thematic Strategy for Soil Protection in response to concerns about the level of soil protection in Member States. The Commission also proposed the EU Soil Framework Directive, which includes legal measures to prevent soil degradation, preserve soil functions, and restore degraded and contaminated soils.

Recognizing the importance of soil for people, food production, nature, and climate, the EU identified the need for a new Soil Strategy to establish a framework and specific measures for soil protection, restoration, and sustainable use. This strategy also aims to mobilize societal participation, financial resources, knowledge sharing, sustainable practices, and monitoring to achieve common goals.

In November 2021, the new EU Soil Strategy for 2030 was adopted. It provides a framework and concrete measures to protect and restore soil while ensuring its sustainable use. The strategy sets a vision and objectives to achieve healthy soils by 2050, with specific actions to be taken by 2030. In 2023, the EU also introduced the new Soil Health Law to ensure a level playing field and a high level of environmental and health protection.

The new EU Soil Strategy for 2030 is a key outcome of the EU Biodiversity Strategy for 2030 and contributes to the objectives of the European Green Deal. Healthy soils are essential for achieving climate neutrality, a clean and circular economy, and preventing desertification and land degradation. They are also crucial for reversing biodiversity loss, ensuring safe food production, and protecting human health.

Under the 2050 vision for soil, all soil ecosystems in the EU will be in a healthy and more resilient state, requiring decisive changes within this decade. By then, soil protection, sustainable use, and restoration will have become the standard. As a critical solution, healthy soil contributes to addressing major challenges, including achieving climate balance and resilience, advancing a clean and circular (bio)economy, reversing biodiversity loss, protecting human health, preventing desertification, and halting land degradation.

The new EU Soil Strategy for 2030 identifies soil as a key solution to major challenges:

- Soil for climate change mitigation and adaptation
- Soil and the circular economy
- Soil biodiversity for the health of humans, animals, and plants
- Soil for clean water sources

The strategy also outlines several priorities for preventing soil degradation and restoring healthy soils:

- Making sustainable soil management the new standard
- Preventing desertification
- Preventing soil pollution
- Restoring degraded soils and remediating contaminated areas

2.7.7. Southeast Asian countries

The ASEAN Guidelines on Soil and Nutrient Management (SNM) were initiated as a policy tool to support the implementation of the ASEAN Integrated Food Security (AIFS) Framework and the Strategic Plan of Action on Food Security (SPA-FS). These guidelines were completed through the commitment and voluntary work of the ASEAN Expert Group on Soil and Nutrient Management.

The Guidelines on Soil and Nutrient Management, along with their accompanying policy recommendations, provide guidance for agricultural decision-makers. These decision-makers may be individuals or groups with the authority to formulate or influence policy decisions, including ASEAN Ministers of Agriculture and Forestry, national representatives of ASEAN Member States, members of the ASEAN Sectoral Working Group on Crops (ASWGC), project steering committees, or authorized institutions managing soil and nutrients at the international, regional, and national levels. The policy recommendations aim to provide evidence-based and scientifically grounded guidance on climate-adaptive soil and nutrient management to support informed decision-making, contributing to sustainable agricultural production and enhanced food security.

Soil and nutrient management is an integrated system for the sustainable management of soil, nutrients, water, and crops to optimize crop yields while maintaining or improving soil health. These guidelines provide regionally relevant directions as a key component of the Strategic Plan of Action for the ASEAN Integrated Food Security (AIFS) Framework. The ultimate goal of the AIFS Framework is to achieve food security in the region by promoting climate-smart and resilient agricultural systems. These systems serve as the foundation for a productive and profitable rural sector while maintaining soil resources to support essential ecosystem functions, often described as 'soil health,' including greenhouse gas mitigation. Climate-smart agricultural systems must be underpinned by the principles of Good Agricultural Practices (GAP), a relationship acknowledged in the Guidelines.

The ASEAN Framework for the Implementation of Soil and Nutrient Management contributes to achieving key objectives outlined in the ASEAN Vision and Strategic Plan for Cooperation in Food, Agriculture, and Forestry (2016-2025): 'Ensuring food security, food safety, and improved nutrition' and 'Enhancing resilience and contributing to climate change mitigation and adaptation, disaster risk reduction, and other shocks.' Specifically, the implementation framework aligns with the Program of Action for the 'Effective Implementation of the ASEAN Integrated Food Security (AIFS) Framework and the Strategic Plan of Action on Food Security in the ASEAN Region (SPA-FS, 2015-2020).

3. FUTURE CONTEXT

3.1. Opportunites

The Vietnamese government has made strong commitments to green growth, emissions reduction, and sustainable agricultural development, creating a favorable policy environment for soil health protection and restoration. At COP 26, the Prime Minister pledged to achieve net-zero emissions by 2050, transition from fossil fuels to renewable energy, and reduce environmental pollution, including soil contamination. The National Green Growth Strategy for 2021-2030, with a vision to 2050, emphasizes efficient resource use, greenhouse gas emissions reduction, the promotion of organic and sustainable agriculture, minimizing negative impacts on soil, and integrating soil protection objectives into socio-economic development planning. In 2020, the National Assembly enacted the Law on Environmental Protection, which clearly defines the responsibilities of businesses and individuals in waste management, soil pollution prevention, and strict enforcement against environmental violations affecting soil, water, and air quality. The agricultural sector's development strategy prioritizes sustainability, ecological balance, and soil health as key directions, consistently reflected in sectoral development strategies, restructuring plans, the national green growth action plan for agriculture, and strategies for subsector restructuring.

The global market for sustainably produced agricultural products has been growing significantly, and Vietnam is part of this trend. This growth has both direct and indirect positive impacts on soil health in Vietnam. According to the Research Institute of Organic Agriculture and the International Federation of Organic Agriculture Movements, the global organic products market was valued at USD 18 billion in 2000, surpassed USD 100 billion in 2018, surged to USD 188 billion in 2021, and was estimated at USD 208 billion in 2022. In Vietnam, nearly 80% of consumers are concerned about chemicals in their food, and 86% prefer organic food products (AC Nielsen, 2021).

The development of the global and Vietnamese carbon credit market presents a crucial opportunity to enhance the economic efficiency of sustainable agricultural solutions that promote soil health. The carbon credit market provides financial incentives for adopting sustainable soil management and farming practices that improve soil carbon sequestration, such as reducing fertilizer and pesticide use, implementing alternate wetting and drying irrigation, soil cover and crop rotation to enhance soil structure, agroforestry, organic fertilization, composting, and other organic waste treatments. These practices improve soil fertility, reduce greenhouse gas emissions from soil, and strengthen soil health. Revenue from carbon credit sales will also support projects for preserving primary forests, afforestation, and restoring degraded forests, contributing to enhanced carbon sequestration in forest ecosystems, thereby indirectly protecting forest soil from erosion and degradation.

Advancements in technologies such as IoT (Internet of Things), AI (Artificial Intelligence), and GIS (Geographic Information Systems) are significantly improving soil management, particularly through real-time soil quality monitoring and agricultural optimization. IoT sensors placed in soil, mini weather stations, or monitoring drones can measure key parameters such as moisture, temperature, pH, nutrient levels (N, P, K), salinity, air temperature, humidity, rainfall, wind speed, solar radiation, and pest populations. These sensors collect real-time data and transmit it to a central system, enabling producers to make informed decisions regarding optimal fertilizer and pesticide use, thereby enhancing soil health. IoT-collected data, integrated with GIS systems and AI-driven image analysis, enables the creation of detailed digital soil maps. These maps provide insights into soil quality, topography, irrigation systems, and other factors, facilitating spatial analysis to identify nutrient-deficient areas, flood-prone zones, and pest-vulnerable regions, allowing for targeted interventions to protect and restore soil health.

3.2. Challenges

In the future, the expansion of industrial zones, urban areas, and infrastructure will not only reduce agricultural land but also increase the risk of soil pollution and create isolated agricultural zones. According to the National Land Use Plan for 2021-2030, with a vision to 2045, by 2030, non-agricultural land is expected to increase by 965.37 thousand hectares, industrial land by 120.10 thousand hectares, and transportation land (excluding traffic corridor areas) by 199.55 thousand hectares compared to 2020. This expansion will primarily come from unused land and partially from agricultural land, with agricultural land projected to decrease by 251.22 thousand hectares by 2030. However, the greatest risks posed by the development of industrial zones, urban areas, and infrastructure are the fragmentation of agricultural land and the pollution threats from household and industrial waste. Urbanization and industrialization often involve land leveling, destruction of the topsoil layer, and loss of soil's natural structure.

Climate change will accelerate and have widespread impacts on soil health, degrading and altering its natural properties. According to the Ministry of Natural Resources and Environment (2021), key climate indicators—including average annual air temperature, extreme temperatures, annual rainfall, extreme rainfall, and extreme weather events (heatwaves, droughts), as well as rising sea levels—are all projected to increase, posing direct threats to soil health. Increased extreme rainfall and flooding will heighten the risk of soil erosion, particularly in mountainous and barren areas, washing away the topsoil and reducing soil fertility. Rising temperatures will accelerate water evaporation, leading to drought and decreased soil moisture, resulting in desertification in semi-arid regions or overexploited lands. Prolonged heat and drought will also reduce vegetation cover, decreasing the organic matter supply to soil and disrupting soil microbial activity, which will affect the entire food chain and natural soil processes. Rising sea levels, combined with upstream activities, particularly in the Mekong Delta, will exacerbate soil salinization, breaking down soil structure, destroying microbial habitats, disrupting soil biological cycles, and causing reverse osmosis, which severely impacts crop growth.

The growing population and increasing demand for food, both domestically and from countries importing agricultural products from Vietnam, exert additional pressure on soil health. These impacts stem primarily from the overexploitation of agricultural land to meet food production demands. Continuous land use without recovery time depletes soil organic matter and nutrients. This depletion leads to the increased use of chemical fertilizers to maintain high yields, disrupting soil nutrient balance. Additionally, monoculture farming increases the risk of pests and diseases, necessitating higher pesticide usage, which accumulates harmful substances in the soil, disrupts microbial activity, and contributes to soil pollution from agricultural waste.

4. VIEWPOINTS, OBJECTIVES, ORIENTATIONS AND SOLUTIONS

4.1. VIEWPOINTS

- Protecting and restoring soil health is the foundation of a sustainable ecosystem, ensuring responsible, efficient and economically - socially - environmentally sustainable agricultural development towards ecological, organic, circular, low carbon emission, environmentally friendly and climate change adaptation.
- Protecting soil health is an important part of environmental protection, and therefore human health, and should be given priority in development decisions; long-term soil health should not be sacrificed for economic benefits.
- Protecting soil health is the responsibility of the entire political system, the entire population as well as each land user. Strengthening the mobilization of social resources combined with increasing budget expenditure to protect and restore soil health.

4.2. OBJECTIVES

4.2.1. Overall objective

- Protect, restore and improve soil health to ensure people's health, increase agricultural productivity and output, enhance climate change adaptation and balance ecosystems, thereby contributing to ensuring national food security, contributing to economic growth and improving and restoring environmental quality, preventing biodiversity loss.

4.2.2. Specific objectives

- Soil quality is protected and improved, the percentage of degraded agricultural land is reduce to below 10%;
- Maintain the organic matter level in the soil meets the minimum standard of 3-5% in major agricultural production areas; agricultural land areas contaminated by chemicals or heavy metals are restored.
- Organic and low-emission agricultural practices acount for at least 2% of total agricultural land area.
- Suitable farming practices, combined with efficient fertilizer use to reduce nutrient loss and efficient pesticide use for key crops in major ecological regions are developed and published on digital platforms to ensure public accessibility.
- A national digital database on soil quality and health in harmony with the international soil health database is built. Smart soil health monitoring systems are piloted and deployed directly through remote sensing images and AI image interpretation tools and indirectly through periodic quality inspection of agricultural products.
- Awareness of state management officials and people about soil health is raised; Quality of human resources participating in soil health protection and restoration activities are maintained and improved.

4.3. ORIENTATIONS

- Improving and enhancing the effectiveness of the policy system with the coordination across all levels of management, from central to local authorities. At the same time, it is essential to establish a stable legal framework with a long-term vision, creating favorable conditions for investment in soil restoration technologies and solutions.
- Maintaining and protecting fertile land areas, ensuring agricultural productivity and product quality. Simultaneously, it should allow for flexible conversion of land areas unsuitable for agricultural production to other land uses such as industrial development, services, or urbanization, but in compliance with approved land use planning and plans. This conversion needs to be conducted in a controlled manner, avoiding land resource waste and ensuring environmental sustainability.
- Enhancing training, workshops, and advisory activities to raise awareness among government officials and the public about the current state and importance of soil health,

as well as measures to improve it. Strengthening the capacity of technical staff in soil health management and researchers involved in soil health from the central to the local level. Establishing incentive mechanisms to attract lecturers and students to formal education programs in soil health.

- Promoting research activities to assess soil health status, test, and scale up soil health protection and improvement solutions for key crops in different ecological zones; expanding existing soil health protection and restoration initiatives. Enhancing the economic efficiency of agricultural products from soil-friendly farming models. Investing in infrastructure development, particularly irrigation systems, to mitigate the impact of non-agricultural factors such as pollution, drought, and salinity intrusion on soil health.
- Mobilizing resources from the entire society to implement soil health protection and restoration efforts. Establishing appropriate financial solutions to help farmers avoid unsustainable agricultural practices driven by risk pressures or living costs. Encouraging both horizontal and vertical linkages in value chains for soil-friendly agricultural production models, promoting private sector investment in organic inputs, and providing technical support to farmers engaged in organic and sustainable production. Actively mobilizing and maximizing international funding for soil health protection and restoration initiatives.
- Enhancing the efficiency of state management in soil health by developing a comprehensive, detailed, and timely soil health database to support decision-making by policymakers. Conducting deeper and long-term evaluations of soil health aspects in environmental impact assessments of investment projects that may pose risks to soil health. Studying appropriate land-use planning to prevent agricultural land from becoming fragmented within residential or industrial zones. Strengthening the regulation of waste discharge, monitoring operational procedures, and ensuring wastewater treatment quality; developing wastewater treatment stations along river segments to meet environmental standards before discharge into main waterways.
- Accelerating digital transformation in soil health management, including soil health monitoring activities and improving soil health management capacity.

4.4. SOLUTIONS

4.4.1. Improving the effectiveness of state management of soil health

- Developing a national soil database utilizing multiple sources, including land surveys, scientific research, and data from government agencies. Creating detailed soil health maps with periodic updates on physical, chemical, and biological indicators such as fertility, pH levels, organic matter content, and microbial composition. Analyzing the risks of soil degradation, chemical contamination, and heavy metal pollution to develop risk maps that support decision-making.

- Regularly updating soil health data through a network of monitoring stations in key ecological regions and remote sensing image analysis.
- Enhancing the application of digital technology in soil management, including the use of AI and machine learning to analyze soil health data and predict degradation trends. Integrating soil health data into decision-support systems. Applying blockchain technology to soil health data management to ensure transparency and accuracy.
- Standardizing national soil health data by adopting international standards for data collection, classification, and management to ensure consistency and ease of sharing. Using open data formats to enhance accessibility and usability.
- Updating the Environmental Protection Law and relevant regulations to mandate soil health assessments as a required component of environmental impact assessments (EIAs) for projects that pose risks to soil. Requiring EIAs to include soil health indicators such as organic matter content, pH levels, heavy metal contamination, fertility, and microbial activity. Mandating projects to provide short-term, medium-term (5–10 years), and long-term (over 20 years) impact scenarios on soil. Applying Life Cycle Assessment (LCA) methodologies for a comprehensive evaluation of soil impact from project initiation to completion. Requiring projects to establish soil health monitoring plans post-implementation, with a minimum inspection frequency of once per year, and enforcing post-project reviews to assess compliance with soil health commitments outlined in EIAs.
- Reviewing land-use plans to prevent agricultural zones from being encroached upon by residential, industrial, or public infrastructure developments. Clearly defining functional areas (residential, industrial, agricultural, green spaces) and delineating specific boundaries. Consulting local communities and businesses during planning processes to prevent conflicts of interest and promptly address inconsistencies.
- Updating and expanding national wastewater quality standards, particularly for high-pollution industries such as manufacturing, food processing, and livestock farming. Imposing strict penalties, including criminal liability, for illegal or non-compliant waste discharge. Installing automatic wastewater monitoring systems at large-scale production facilities, industrial zones, and wastewater treatment plants. Connecting monitoring data to government agencies for real-time supervision and rapid violation detection.
- Developing and upgrading wastewater treatment systems, including the construction of centralized treatment stations along key river segments with high discharge concentrations. Encouraging the adoption of advanced wastewater treatment technologies such as biological filtration, nanotechnology, and microbial treatment to ensure wastewater meets environmental standards before discharge. Investing in the modernization of existing treatment plants to improve efficiency and compliance with updated environmental standards, preventing residual chemical contamination that could harm soil health. Publicizing water quality data for rivers, canals, and irrigation

systems to inform farmers and provide recommendations on safe water use for agriculture.

- Establishing and refining national standards and regulations for soil quality, fertilizers, and pesticides. Issuing national soil quality standards for agricultural, forestry, industrial, and urban lands, tailored to regional characteristics. Setting safety thresholds for heavy metal content, chemical residues, and organic matter levels in soil. Defining fertilizer quality standards and updating the list of approved pesticides to ensure only safe and environmentally friendly products are available on the market. Aligning national regulations with international standards to meet global trade requirements.
- Strengthening market oversight and regulatory enforcement by tightening licensing requirements for fertilizer and pesticide manufacturers, importers, and distributors. Increasing inspections of production, importation, distribution, and usage to detect and strictly penalize counterfeit and substandard products.

4.4.2. Solutions to improve awareness and quality of human resources

- Design and implement regular training programs on soil health management, prioritizing topics such as soil degradation prevention, pollution reduction, and fertility conservation. Utilize a blended learning approach that combines online and in-person training to reach a wide range of participants at different levels.
- Collaborate with international organizations such as UNEP, FAO, and IRRI to invite experts for training programs, capacity-building workshops, and specialized seminars aimed at enhancing the knowledge and skills of government agencies, research institutes, and universities. Establish a networking environment for researchers and experts, particularly those from Southeast Asia and countries with agricultural conditions similar to Vietnam, to facilitate knowledge exchange.
- Organize short- and long-term training courses to improve the expertise of local technical staff, particularly community agricultural extension officers, equipping them with soil health knowledge so they can further train and advise farmers.
- Integrate soil health training sessions into other ongoing programs and projects, educating farmers on soil conservation and restoration techniques and the role of soil health in crop growth. Develop demonstration models showcasing effective soil health management practices for farmers to observe, learn from, and apply.
- Conduct public awareness campaigns through television, newspapers, social media, and community workshops to enhance understanding of soil importance. Incorporate fundamental soil health concepts into educational curricula at all levels, from elementary to university. Collaborate with social organizations and local groups to promote and encourage public participation in soil health protection efforts.
- Increase financial support and improve working conditions for soil health educators, especially in disadvantaged areas. Establish research and teaching funds to encourage

faculty engagement in the field. Develop policies that incentivize educational institutions to introduce new academic programs related to soil health.

- Provide full or partial scholarships for students specializing in soil health, particularly those committed to working in local communities after graduation. Partner with businesses and international organizations to offer internships and job opportunities for soil health graduates. Encourage collaboration between universities and employers, such as organic fertilizer manufacturers and companies investing in ecological and organic agriculture, to enhance workforce readiness.

4.4.3. Technical solutions

- Increase budget allocation for research and trials on cultivation practices such as crop rotation, intercropping, soil cover, minimal tillage, organic fertilizers, microbial fertilizers, and integrated pest management, ensuring suitability for specific crops and ecological regions.
- Develop demonstration models showcasing soil health-friendly farming practices for farmers to observe, learn from, and adopt. Scale up successful models and support farmers in implementing effective cultivation practices through agricultural extension programs, training sessions, technical assistance, and credit support.
- Conduct market research to assess demand for agricultural products produced using soil health-friendly methods. Establish branding for such products to create a competitive advantage in the market. Connect producers with businesses, supermarkets, and organic food stores to facilitate product distribution. Assist producers in obtaining certifications for quality, food safety, and organic standards.
- Upgrade and construct new irrigation canal systems to ensure adequate water supply for crops while improving drainage to prevent waterlogging. Develop water storage infrastructure such as reservoirs, ponds, and dams to support irrigation during dry seasons. Improve sluices, dams, and closed dike systems to prevent saltwater intrusion in designated rice, vegetable, and fruit-growing areas in coastal regions. Implement policies to support the adoption of advanced irrigation technologies, such as drip irrigation and sprinkler systems, to conserve water and enhance irrigation efficiency.

4.4.4. Financial solutions

- Attract private sector investment by expanding the scope and actively implementing incentive policies, including tax benefits, preferential loans, and technical support for organizations and individuals engaged in sustainable land use and land restoration models. Provide support for enterprises producing agricultural inputs that promote soil health, such as organic fertilizers and biological pesticides.
- Develop public-private partnership (PPP) models for land restoration projects, establishing appropriate benefit-sharing mechanisms to attract private sector participation. Allow sustainable resource utilization on restored land, such as

ecotourism development or carbon credit generation from afforestation and reforestation initiatives.

- Actively implement Decree 58/2018/ND-CP on agricultural insurance to minimize risks for farmers adopting soil health-friendly farming practices. Explore increasing insurance premium support for farms practicing ecological and organic agriculture.
- Develop strategies to maximize international support for soil health protection and restoration in Vietnam. Prepare well-defined project proposals and implementation plans aligned with the Sustainable Development Goals (SDGs), such as soil resource conservation, greenhouse gas emission reduction, and livelihood improvement for local communities. Prioritize degraded lands and areas with high biodiversity value to attract international attention and funding.

5. LIST OF REFERENCES

Vietnameses references

Bảo Thắng, Quỳnh Anh, 2024. *Đa dạng sinh học trong đất - Năng lượng bền vững cho cây trồng*. Báo Nông Nghiệp Việt Nam.

Bộ Nông nghiệp và Phát triển Nông thôn, 2023. Báo cáo tổng kết thực hiện Kế hoạch phát triển nông nghiệp, nông thôn năm 2023 và triển khai kế hoạch năm 2024

Bộ Nông nghiệp và Phát triển Nông thôn, 2021. Hội thảo *Thực trạng và giải pháp quản lý sử dụng phân bón, thuốc bảo vệ thực vật, vùng trồng, cơ sở đóng gói nông sản tại Đồng bằng sông Cửu Long*. Cần Thơ: 27/08/2021.

Bộ Nông nghiệp và Phát triển Nông thôn, 2024. *Báo cáo thuyết minh Đề án nâng cao sức khỏe đất và quản lý dinh dưỡng cây trồng đến năm 2030, tầm nhìn đến năm 2050.*

Bộ Tài nguyên và Môi trường, 2016. *Kịch bản biến đổi khí hậu và nước biển dâng cho Việt Nam*. Nhà xuất bản tài nguyên môi trường và bản đồ Việt Nam.

Bộ Tài Nguyên và Môi Trường, 2021a. *Kịch bản biến đổi khí hậu*. Nhà xuất bản Tài nguyên - Môi trường và Bản đồ Việt Nam.

Bộ Tài nguyên và Môi trường, 2021b. *Quyết định 1432 ngày 21/7/2021 công bố kết quả điều tra, đánh giá đất đai cả nước, các vùng kinh tế - xã hội*

Bộ Tài nguyên và Môi trường, 2022, *Báo cáo đa dạng sinh học quốc gia*.

Bộ Tài nguyên và Môi trường, 2023. *Quyết định số 3048/QĐ-BTNMT ngày 18/10/2023 phê duyệt và công bố kết quả thống kê diện tích đất đai năm 2022*.

Bộ Tài nguyên và Môi trường, 2023. *Quyết định số 719/QĐ-BTNMT ngày 24/3/2023 phê duyệt và công bố kết quả thống kê diện tích đất đai của cả nước năm 2021*

Bùi Hải An, Trần Minh Tiến, Nguyễn Văn Bộ, 2016. *Nghiên cứu xác định yếu tố hạn chế độ phì nhiêu của đất lúa đồng bằng sông Cửu Long*. Hà Nội: Viện khoa học Nông nghiệp Việt Nam.

Bùi Lương, 2024. *Thực trạng độ phì đất lúa ĐBSCL và giải pháp nâng cao hiệu quả canh tác*, Báo Nông nghiệp Việt Nam.

Bùi Thị Nga, Hưng Xuân Võ và Nhan Phan Nguyen, 2013. Hiện trạng và giải pháp cho các cơ quan quản lý chất thải rắn trong trồng lúa ở tỉnh Hậu Giang. *Tạp chí Khoa học trường Đại học Cần Thơ*. 29: 83-88.

Bộ Nông nghiệp và Phát triển Nông thôn, 2006. *Đất và dinh dưỡng đất - Cẩm nang ngành lâm nghiệp*.

Đinh Thị Ngọc Hạnh, Võ Chí Cường, Nguyễn Đô, Nguyễn Văn Long, 2023. *Thâm canh cà phê tác động đến pH đất tại Tây Nguyên*. Trung tâm Nghiên cứu và Phát triển Cây Hồ Tiêu.

Đỗ Thu Hà, Hà Mạnh Thắng, Lê Hồng Lịch, Phạm Quang Hà, 2016. *Ảnh hưởng của thâm canh đến hàm lượng một số chỉ tiêu dinh dưỡng trong đất tại Lâm Đồng*. Hội thảo Quốc gia về Khoa học Cây trồng lần thứ hai - Viện Khoa Học Nông Nghiệp Việt Nam.

FPTS, 2020. *Báo cáo ngành phân bón Tháng 09/2020*

Hồ Quang Đức và Nguyễn Văn Đạo, 2011. Đánh giá sự biến động đất mặn và đất phèn vùng Đồng bằng sông Cửu Long sau 30 năm sử dụng. *Tạp chí Khoa học và Công nghệ Nông nghiệp Việt Nam.* 01(13)

Hương An, 2024. *Nguồn nước ô nhiễm ảnh hưởng đến sản xuất nông nghiệp*. Báo Hải Phòng.

IPCC, 2010. *Các báo cáo về phương pháp nghiên cứu và đánh giá biến đổi khí hậu*

Kim Anh, 2024. *Đất lúa ĐBSCL đang chịu nhiều áp lực do thâm canh tăng vụ*. Báo Nông nghiệp. https://s.net.vn/OaMz

Lê Thị Khánh, 1998. Bước đầu nghiên cứu ảnh hưởng của GA3, B, Zn đến tỷ lệ đậu quả và phẩm chất ớt Thừa Thiên - Huế. *Tạp chí Nông nghiệp và Công nghiệp Thực phẩm*. 2, p.78-80.

Lê Văn Khoa, 2004. *Sinh thái và môi trường đất*. Nxb Đại học Quốc gia Hà Nội.

Trần Minh Tiến, 2015. *Nghiên cứu nâng cao hiệu quả sử dụng tài nguyên đất nông nghiệp vùng miền núi Tây Bắc Việt Nam*. Viện Thổ Nhưỡng Nông hóa.

Lưu Thế Anh, 2017. Hiện trạng và biến động các chất dinh dưỡng đa lượng đạm, lân và kali trong đất trồng lúa tỉnh Thái Bình. *Tạp chí Khoa học ĐHQGHN: Các Khoa học Trái đất và Môi trường*, 33 (3) (2017): 1-10.

Mai Hạnh Nguyên, 2010. *Đánh giá tổng quát tác động của biến đổi khí hậu đối với tài nguyên đất đai và các biện pháp ứng phó*. Tổng hợp báo cáo khoa học, Kỷ niệm 65 năm Ngành Quản lý đất đai Việt Nam. Tổng cục Quản lý đất đai, Bộ Tài nguyên và Môi trường, tr. 273 – 283

Mai Hạnh Nguyên, Trần Văn Thụy, Võ Tử Can, Mai Văn Trịnh, 2015. Giải pháp quản lý, sử dụng đất nông nghiệp ứng phó với biến đổi khí hậu, nước biển dâng cho vùng Duyên hải Nam trung Bộ. *Tạp chí Khoa học Đại học quốc gia Hà Nội: Khoa học tự nhiên và Công nghệ*, tập 31, Số 3 (2015).

Mai Chiến, 2019. *Cả nước có 1.3 triệu ha đất bị suy thoái*. Báo Nông nghiệp Việt Nam, 14/6/2019. https://nongnghiep.vn/ca-nuoc-co-13-trieu-ha-dat-bi-suy-thoai-d243456.html.

Mai Văn Trịnh, Hà Mạnh Thắng, Đỗ Thu Hà, Bùi Thị Phương Loan, Lương Hữu Thành, Phạm Quang Hà, 2015. *Thực trạng môi trường đất Việt Nam*. Tuyển tập báo cáo Hội thảo Quốc gia "Đất Việt Nam – Hiện trạng sử dụng và thách thức" 11/2015. NXB Nông nghiệp.

Minh An, 2024. *Báo động tình trạng đất nông nghiệp ở Việt Nam bị suy thoái nghiêm trọng*. Tạp chí điện tử Môi trường và Cuộc sống.

Nam, T. S., Ingvorsen, K.., Việt, L. H., Như, N. T. H., Chiếm, N. H., & Ngân, 2014. *Ước tính lượng và các biện pháp xử lý rơm rạ ở một số tỉnh Đồng bằng sông Cửu Long*. Tạp chí Khoa học Trường Đại học Cần Thơ, Tập 32, tr. 87-93

Ngô Thị Dung, Cao Việt Hà, Vũ Thị Xuân, 2020. Nghiên cứu các yếu tố hạn chế của đất trồng cam ở huyện Hàm Yên, tỉnh Tuyên Quang. Tạp chí Khoa học Nông nghiệp Việt Nam (18)4

Nguyễn Bá Lộc & Nguyễn Thị Quỳnh Trang, 2009. Ảnh hưởng của Mn và GA3 đến năng suất và phẩm chất ngô rau LVN23 trên đất phù sa thành phố Huế. *Tạp chí khoa học Đại học Huế*, 52, 25-31

Nguyễn Đức Dũng, Nguyễn Xuân Lai, Trần Minh Tiến, Hồ Công Trực, Nguyễn Thu Hà, Nguyễn Viết Hiệp, Nguyễn Thị Thu Hoài, & Nguyễn Trần Quyện, 2019. Hiện trạng độ phì nhiêu đất trồng cà phê, hồ tiêu vùng Tây Nguyên. *Tạp chí Nông nghiệp & Phát triển Nông thôn*, 50 năm Viện Thổ nhưỡng Nông hóa, 3-9.

Nguyễn Hằng, 2023. *Năm 2023 các khu công nghiệp, khu kinh tế Việt Nam phát triển mạnh mẽ*. Tạp chí Kinh tế và Dự báo.

Nguyễn Minh Phượng, Hubert Verplancke, Lê Văn Khoa và Võ Thị Gương, 2009. Sự nén dẽ của đất canh tác lúa ba vụ ở Đồng bằng sông Cửu Long và hiệu quả của luân canh trong cải thiện độ bền đoàn lạp. *Tạp chí Khoa học Đại học Cần Thơ*. 2009:11 194-199.

Nguyễn Thị Ngọc Anh, 2019. Tiềm năng giảm phát thải khí nhà kính thông qua thay đổi nhận thức và hành vi của người nông dân về việc áp dụng các tiến bộ kỹ thuật trong trồng lúa tại ô bao thủy lợi xã Vị Thanh, huyện Vị Thủy, tỉnh Hậu Giang. *Tạp chí Khoa học và công nghệ thủy lợi.* Số 55-2019

Nguyễn Tử Siêm và Thái Phiên, 1999. *Đất đồi núi Việt Nam–Thoái hóa và phục hồi*. NXB Nông nghiệp, Hà Nội.

Nguyễn Văn Bộ, Bùi Hải An, Trần Minh Tiến, Hồ Quang Đức, 2015. *Xu thế biến động độ phì nhiêu đất sản xuất nông nghiệp*. Tuyển tập báo cáo Hội thảo Quốc gia "Đất Việt Nam – Hiện trạng sử dụng và thách thức" 11/2015. NXB Nông nghiệp.

Nguyễn Tín Hồng, 2017. *Tổng quan về Ô nhiễm Nông nghiệp ở Việt Nam: Ngành trồng trọt*. Ngân Hàng Thế Giới.

Nhật Trịnh, 2023. *Tác động của biến đổi khí hậu đối với tài nguyên rừng. Tạp chí điện tử Môi trường và Cuộc sống*. Truy cập tại https://moitruong.net.vn/tac-dong-cua-bien-doi-khi-hau-doi-voi-tai-nguyen-rung-68212.html ngày 20/01/2025.

Phạm Sỹ Tân, 2005. *Kết quả nghiên cứu nâng cao hiệu quả phân bón cho lúa cao sản ở Đồng bằng sông Cửu Long*. Sách 'Khoa học công nghệ nông nghiệp và phát triển nông thôn 20 năm đổi mới'. Tập 3, trg: 315-327. NXB Chính trị Quốc gia, Hà Nội.

Phạm Văn Linh, Trần Thị Quỳnh Nga, Trần Đình Hợp Mai Sỹ Cường, Giáp Thị Luân, 2017. Đánh giá đặc điểm một số tính chất đất vùng trồng cây có múi tại Phủ Quỳ. *Tạp chí Khoa học và Công nghệ Nghệ An.*

Phương Đông, 2022. *Nhận diện các ảnh hưởng của biến đổi khí hậu đến tài nguyên đất*. Báo Nông nghiệp và Môi trường

Phương Anh, 2020. *Nỗi lo sa mạc hóa*. Báo Nông nghiệp. Truy cập tại https://nongnghiepmoitruong.vn/noi-lo-sa-mac-hoa-d666115.html ngày 18/01/2025.

Quang Thuần, 2023. *Ưu tiên phê duyệt thuốc bảo vệ thực vật sinh học hơn thuốc hóa học*. Báo Thanh Niên.

Sfarm, 2019. *Suy giảm chất lượng đất: hiện trạng, nguyên nhân và giải pháp*. Truy cập tại https://sfarm.vn/suy-giam-chat-luong-dat-hien-trang-nguyen-nhan-va-giai-phap ngày 20/6/2019.

Sở KH&CN Bắc Giang, 2024. *Nghiệm thu đề tài cấp quốc gia về sản xuất và sử dụng phân bón chuyên dùng cho cây vải thiều Bắc Giang*

Tổ chức Hợp tác và Phát triển Kinh tế, 2015. *Báo cáo rà soát Nông nghiệp và Lương thực của OECD: Chính sách nông nghiệp Việt Nam 2015*

Tổng cục thống kê, 2022. *Báo cáo tình hình kinh tế – xã hội quý III và 9 tháng năm 2022.*

Tổng cục thống kê, 2024. *Sản xuất nông, lâm nghiệp và thủy sản năm 2023.*

Tổng cục Thống kê, 2023. *Niên giám Thống kê 2022.*

Trần Minh Thắng, Nguyễn Tấn Lê, 2017. Ảnh hưởng của mo, b, cu và gibberellin đến sự tăng trưởng và phẩm chất của cây củ đậu (pachyrhizus erosus l.) trồng trên đất cát pha có bón mức phân kali khác nhau tại Quảng Nam. Tạp chí khoa học Yersin. 03(9.2017). 33-39.

Trần Minh Tiến, Hồ Quang Đức, Hoàng Trọng Quý, 2014. *Biến động một số tính chất đất trồng lúa vùng Đồng bằng sông Hồng và Đồng bằng sông Cửu Long*. Viện Thổ nhưỡng Nông hóa.

Trần Minh Tiến, Bùi hải An, Lê Thị Mỹ Hảo, Nguyễn Toàn Thắng, Nguyễn Văn Bộ, 2021. *Yếu tố hạn chế độ phì nhiêu đất trồng lúa ở Đồng bằng sông Hồng và Đồng bằng sông Cửu*

Long. Kết quả nghiên cứu và chuyển giao công nghệ, 50 năm xây dựng và phát triển, Viện Thổ nhưỡng nông hóa.

Trần Thị Thu Trang, 2023. *Sản xuất lúa năm 2022 - Kết quả từ sự thay đổi*. Tạp chí Con số & Sự kiện.

Trần Thị Tuyết Thu, Phạm Mạnh Hùng, Nguyễn Thị Thảo, Nguyễn Xuân Huân, Nguyễn Thị Phương Loan, Trần Vũ Diễm Huyền, Cao Văn Chí & Trịnh Quang Pháp, 2018. *Nghiên cứu nguyên nhân suy thoái chất lượng đất trong cam Cao Phong, tỉnh Hoà Bình và đề xuất biện pháp cải tạo phục hồi*, Hội thảo Khoa học Đất, phân bón và nông nghiệp hữu cơ, Bộ NN và PTNT, Hội KHĐ Việt Nam, TP HCM, tháng 12/2018

Trần Thị Ngọc Lan, Nguyễn Phượng Lê và Nguyễn Thanh Phong, 2014. Quản lý Nhà nước về sử dụng thuốc bảo vệ thực vật của hộ nông dân tỉnh Thái Bình. *Tạp chí Khoa học và Phát triển*. 12.

Trương Hồng, 2020. *Trên 1.1 triệu ha đất Nông nghiệp Tây Nguyên đã bị thoái hoá nặng*. Báo Hội Nông dân Việt Nam, ngày 18/11/2020.

Văn Hùng, 2024. *Đất nông nghiệp bị 'bức tử'*. Báo Nông nghiệp Việt Nam.

Viện Khoa Học Kỹ Thuật Nông Nghiệp Miền Nam, 2024. *Suy giảm kali trong đất đe dọa năng suất cây trồng* https://iasvn.org/homepage/Suy-giam-kali-trong-dat-de-doa-nang-suat-cay-trong-18167.html

Viện Thổ nhưỡng Nông hóa, 2010. Báo cáo kết quả thực hiện đề tài: "*Nghiên cứu thực trạng đất phèn và đất mặn vùng đồng bằng sông Cửu Long và ĐBSH sau 30 năm khai thác sử dụng*".

Viện Thổ nhưỡng Nông hóa, 2015. Báo cáo kết quả thực hiện đề tài: "*Nghiên cứu nâng cao hiệu quả sử dụng tài nguyên đất nông nghiệp vùng miền núi Tây Bắc Việt Nam*"

Viện Thổ nhưỡng Nông hóa, 2015. Báo cáo kết quả thực hiện đề tài: "*Nghiên cứu xác định yếu tố hạn chế của độ phì nhiêu đất trồng lúa ở ĐBSH và đồng bằng sông Cửu Long và đề xuất giải pháp khắc phục*".

Võ Thị Gương, 2021. Sự suy thoái hóa học và vật lý đất vườn trồng cam ở đồng bằng sông Cửu Long. *Tạp chí Khoa học đất*.

Vũ Năng Dũng, 2015. Biến động sử dụng đất và những thách thức trong những năm tới ở nước ta. Tuyển tập báo cáo Hội thảo Quốc gia "Đất Việt Nam – Hiện trạng sử dụng và thách thức" 11/2015. NXB Nông nghiệp.

International references

Bertolino, A., 2023. Effects of the Periodic Plowing on Soil Physical Properties. *Agrotechnology*, 12:299. DOI: 10.35248/2168-9881.23.12.299.

Abhishek Kumar, Varinder Singh Saimbhi and Jagjeet Singh. Effect of irrigation on physical properties of different soil types. *The Pharma Innovation Journal*. 2021; 10(4S): 437-443. DOI: 10.22271/tpi.2021.v10.i4Sg.6108

Altieri, M. A., 1999. The ecological role of biodiversity in agroecosystems. *Agriculture, Ecosystems & Environment*, 74(1-3), 19-31.

Australian Department of Agriculture, Water and the Environment, 2021. *National Soil Strategy*, Canberra, April. CC BY 4.0.

Bhattacharyya, R.; Ghosh, B.N.; Mishra, P.K.; Mandal, B.; Rao, C.S.; Sarkar, D.; Das, K.; Anil, K.S.; Lalitha, M.; Hati, K.M.; et al, 2015. Soil Degradation in India: Challenges and Potential Solutions. *Sustainability*, 7, 3528–3570.

Bouma, J., Van Ittersum, M. K., Stoorvogel, J. J., Batjes, N. H., Droogers, P., & Pulleman, M. M., 2017. Soil capability: exploring the functional potentials of soils. *Global soil security*, 27-44.

Brevik, E. C., & Sauer, T. J., 2015. The past, present, and future of soils and human health studies. *Soil*, 1(1), 35-46

Cassou, E., D. N. Tran, T. H. Nguyen, T. X. Dinh, C. V. Nguyen, B. T. Cao, S. Jaffee, and J. Ru. 2017. *An Overview of Agricultural Pollution in Vietnam: Summary Report*. Prepared for the World Bank, Washington, DC.

Chandini & Kumar, Randeep & Kumar, Ravendra & Prakash, Om., 2019. *The Impact of Chemical Fertilizers on our Environment and Ecosystem*. Research Trends in Environmental Sciences (2).

Chenu, C., Amiraslani, F., Garcia Cardenas, M., Soussana, J. F., Kaonga, M., Koutika, L. S.,... & Wollenberg, L., 2018. *The «4 per 1000» initiative*. Soils for food security and climate.

Choudhury, B. U., Fiyaz, A. R., Mohapatra, K. P., & Ngachan, S., 2016. Impact of land uses, agrophysical variables and altitudinal gradient on soil organic carbon concentration of North-Eastern Himalayan Region of India. *Land Degradation & Development*, 27(4), 1163-1174.

Dessureault-Rompré, J., 2022. Restoring soil functions and agroecosystem services through phytotechnologies. *Frontiers in Soil Science*, 2, 927148.

Dincă, L. C., Grenni, P., Onet, C., & Onet, A., 2022. Fertilization and Soil Microbial Community: A Review. *Applied Sciences*, 12(3), 1198.

Dobermann, A. T. H. F., & Fairhurst, T. H., 2002. Rice straw management. *Better crops international*, 16(1), 7-11.

EEA, 2019. *The European environment — State and outlook 2020: knowledge for transition to a sustainable Europe*. European Environment Agency, Copenhagen.

EU legislation on MRLs https://food.ec.europa.eu/plants/pesticides/maximum-residue-levels_en

Eurofins Scientific, 2024. *Soil health*. https://www.eurofins.vn/en/news/knowledge-of-testing-industry/soil-health/

F. A. Shafie and D. Rennie, 2012. Consumer perceptions towards organic food, *ProcediaSocial Behavioral Sciences*, vol. 49, pp.360-367, 2012.

FAO, 2020. *Towards a definition of soil health*. ITPS – Soil letters #1. September 2020.

FAO, 2025. *FAOSTAT*. https://www.fao.org/faostat/en/#data/RFN

FAO, ITPS, GSBI, CBD and EC. 2020. *State of knowledge of soil biodiversity - Status, challenges and potentialities*, Report 2020. Rome, FAO.

Fischer, M., Rounsevell, M., Rando, A. T. M., Mader, A., Church, A., Elbakidze, M.,... & Ring, I., 2018. *The regional assessment report on biodiversity and ecosystem services for Europe and Central Asia: Summary for policymakers*. IPBES Secretariat.

Gardi, C, Panagos, P, Van Liedekerke, M, Bosco, C and De Brogniez, D, 2015. Land take and food security: assessment of land take on the agricultural production in Europe. *Journal of Environmental Planning and Management,* 58 (5), 898-912.

Gardner, D., Weindorf, D. C., & Flynn, M., 2013. Presence of chromium, copper, and arsenic in schoolyard soils. *Soil Horizons*, 54(2), 1-5.

Gattinger, A., Jawtusch, J., Muller, A., & Mäder, P., 2012. *No-till agriculture–a climate smart solution*. Royal Society, Science Policy Centre Report.

Guo, L., Zhao, J, 2021. Effect of burning straw in rural areas on ecological environment quality. *Arab J Geosci* 14, 1357.

Haefliger, P., Mathieu-Nolf, M., Lociciro, S., Ndiaye, C., Coly, M., Diouf, A.,... & Neira, M., 2009. Mass lead intoxication from informal used lead-acid battery recycling in Dakar, Senegal. *Environmental health perspectives*, 117(10), 1535-1540.

Hai-Lin Zhang, Rattan Lal, Xin Zhao, Jian-Fu Xue, Fu Chen, 2014. Chapter One - Opportunities and Challenges of Soil Carbon Sequestration by Conservation Agriculture in China, *Advances in Agronomy*, Volume 124, 2014, Pages 1-36.

Heard, J., Cavers, C., & Adrian, G., 2006. *Up in smoke-nutrient loss with straw burning.*

Hyun Soo Kim, Yeo Jin Kim, Young Rok Seo, 2015. An Overview of Carcinogenic Heavy Metal: Molecular Toxicity Mechanism and Prevention, *Journal of Cancer Prevention*. 20(4):232-40.

Jansson, J. K., & Hofmockel, K. S., 2020. Soil microbiomes and climate change. *Nature Reviews Microbiology*, 18(1), 35-46.

Jodi Boe, 2023. *Soils, Pesticides, and pH: Interactions and Management*. 2023 AGVISE Soil Fertility Seminars

John J. Drewry, Sam Carrick, Veronica Penny, David J. Houlbrooke, Seth Laurenson & Nicole L. Mesman, 2021) Effects of irrigation on soil physical properties in predominantly pastoral farming systems: a review, *New Zealand Journal of Agricultural Research*, 64:4, 483-507, DOI: 10.1080/00288233.2020.1742745

Klein, A. M., Vaissière, B. E., Cane, J. H., Steffan-Dewenter, I., Cunningham, S. A., Kremen, C., & Tscharntke, T., 2007. *Importance of pollinators in changing landscapes for world crops.* Proceedings of the royal society B: biological sciences, 274(1608), 303-313.

Kumar, A., Kushwaha, K. K., Singh, S., Shivay, Y. S., Meena, M. C., & Nain, L. 2019. Effect of paddy straw burning on soil microbial dynamics in sandy loam soil of Indo-Gangetic plains. *Environmental Technology & Innovation*, 16, 100469.

Kwon, J. C., Nejad, Z. D., & Jung, M. C., 2017. *Arsenic and heavy metals in paddy soil and polished rice contaminated by mining activities in Korea*. Catena, 148, 92-100.

Lal, R., 2016. Soil health and carbon management. *Food and energy security*, 5(4), 212-222.

Lê Cảnh Dũng, Nguyễn Phú Son, Võ Văn Tuấn, Nguyễn Thị Kim Thoa, 2021. *The rice value chain in the Mekong Delta*, Vietnam. Dự án GIZ.

Lehmann, J., Bossio, D. A., Kögel-Knabner, I., & Rillig, M. C., 2020. The concept and future prospects of soil health. *Nature Reviews Earth & Environment*, 1(10), 544-553.

Liang, C., Amelung, W., Lehmann, J., & Kästner, M., 2019. Quantitative assessment of microbial necromass contribution to soil organic matter. *Global change biology*, 25(11), 3578-3590.

Lo, Y. C., Dooyema, C. A., Neri, A., Durant, J., Jefferies, T., Medina-Marino, A.,... & Brown, M. J., 2012. Childhood lead poisoning associated with gold ore processing: a village-level investigation—Zamfara State, Nigeria, October–November 2010. *Environmental Health Perspectives*, 120(10), 1450-1455.

Lopes, G. R., Lima, M. G. B., & Dos Reis, T. N., 2021. Maldevelopment revisited: Inclusiveness and social impacts of soy expansion over Brazil's Cerrado in Matopiba. *World Development*, 139, 105316.

M. Younesi Alamouti and M. Navabzadeh, 2007. Investigation of Plowing Depth Effect on Some Soil Physical Properties. *Pakistan Journal of Biological Sciences*, 10: 4510-4514.

Manuchehri & Arnall, 2018. *How Does Soil pH Impact Herbicides*. Division of Agricultural Sciences and Natural Resources. Accessed at https://extension.okstate.edu/fact-sheets/how-does-soil-ph-impact-herbicides.html on 12th Jan 2025.

Modupe, Adejumobi & O., Ojediran & Onofua, Oluwaseun., 2022. Impact of Irrigation Practices on Soil Physicochemical Properties of Josepdam Irrigation Scheme. *Journal of Engineering Research and Reports*. 23. 29-39. 10.9734/JERR/2022/v23i217594.

Mohammadi Galangash, M., Ghasemi Zolpirani, R., Askari Tappeh, F., & Forouhar Vajargah, M., 2022. A Review on the Effects of Rice Straw Burning on the Rice Paddy Fields, Guilan Province Iran. *Austin Environmental Sciences*, 7(1), 1068.

Nguyen Dang Giang, C., Le, D. B. C., Nguyen, V. H., Hoang, T. L., Tran, T. V. T., Huynh, T. P. L., & Nguyen, T. Q. T., 2022. Assessment of pesticide use and pesticide residues in vegetables from two provinces in Central Vietnam. *PloS one*, 17(6), e0269789.

Nordberg, G. F., & Costa, M. (Eds.)., 2021. H*andbook on the Toxicology of Metals: Volume II: Specific Metals*. Academic press.

NRCS, U., 2019. *Soil health*. United States Department of Agriculture Natural Resources Conservation Service.

Pahalvi, H.N., Rafiya, L., Rashid, S., Nisar, B., Kamili, A.N., 2021. Chemical Fertilizers and Their Impact on Soil Health. In: Dar, G.H., Bhat, R.A., Mehmood, M.A., Hakeem, K.R. (eds) *Microbiota and Biofertilizers*, Vol 2. Springer, Cham. https://doi.org/10.1007/978-3-030-61010-4_1

Panagos, P, Ballabio, C, Poesen, J, Lugato, E, Scarpa, S, Montanarella, L and Borrelli, P, 2020) A soil ero- sion indicator for supporting agricultural, environmental and climate policies in the European Union. *Remote Sensing* No 12 (9), 1365.

Panagos, P, Standardi, G, Borrelli, P, Lugato, E, Montanarella, L and Bosello, F, 2018) Cost of agricul- tural productivity loss due to soil erosion in the European Union: From direct cost evaluation ap- proaches to the use of macroeconomic models. *Land Degradation & Development,* No 29 (3), 471-484.

Pat H. Bellamy, P.H et al, 2003. Carbon losses from all soils across England and Wales 1978–2003. *Nature*, Vol 437|8 September 2005|doi:10.1038/nature04038.

Pelczar, M. J., Chan, E. C. S., & Kriec, N. R., 2017. *Microbiology*. Mc Graw Hill Education

Peralta-Videa, J R, Lopez, M L, Narayan, M, Saupe, G and Gardea-Torresdey, J, 2009) The biochemistry of environmental heavy metal uptake by plants: implications for the food chain. *The international journal of biochemistry & cell biology,* No 41 (8-9), 1665-1677

Schulp, C. J. E., Lautenbach, S., & Verburg, P. H., 2014. Quantifying and mapping ecosystem services: Demand and supply of pollination in the European Union. *Ecological Indicators*, 36, 131-141.

Scottish Government, 2009. *The Scottish Soil Framework.*

Seymour, N. P., 2005. *Impacts of pesticides and fertilisers on soil biota*. Department of Primary Industries and Fisheries.

Silva, V, Mol, H G J, Zomer, P, Tienstra, M, Ritsema, C J and Geissen, V, 2019) Pesticide residues in Euro- pean agricultural soils - A hidden reality unfolded. *Science of the Total Environment*, No 653, 1532- 1545.

Sokol, N. W., Slessarev, E., Marschmann, G. L., Nicolas, A., Blazewicz, S. J., Brodie, E. L.,... & Pett-Ridge, J., 2022. Life and death in the soil microbiome: how ecological processes influence biogeochemistry. *Nature Reviews Microbiology*, 20(7), 415-430.

Tayyab, M., Yang, Z., Zhang, C., Islam, W., Lin, W., & Zhang, H., 2021. Sugarcane monoculture drives microbial community composition, activity and abundance of agricultural-related microorganisms. *Environmental Science and Pollution Research*, 28, 48080-48096.

The ASEAN Secretariat, 2022. *ASEAN Regional Guidelines for Sustainable Agriculture in ASEAN*

The ASEAN Sectoral Working Group on Crops, 2017. *ASEAN Guidelines on Soil and Nutrient Management*

The Soil Conservation Council of Canada, 2023. *Towards a National Soil Health Strategy*

Thuy, P. T., Van Geluwe, S., Nguyen, V. A., & Van der Bruggen, B., 2012. Current pesticide practices and environmental issues in Vietnam: management challenges for sustainable use of pesticides for tropical crops in (South-East) Asia to avoid environmental pollution. *Journal of Material Cycles and Waste Management*, 14, 379-387.

Tilman, D., Cassman, K. G., Matson, P. A., Naylor, R., & Polasky, S., 2002. Agricultural sustainability and intensive production practices. *Nature*, 418(6898), 671-677.

Tóth, G, Hermann, T, Da Silva, M R and Montanarella, L, 2016) Heavy metals in agricultural soils of the European Union with implications for food safety. *Environment International*, No 88, 299-309

Tully, K.; Sullivan, C.; Weil, R.; Sanchez, P, 2015. The State of Soil Degradation in Sub-Saharan Africa: Baselines, Trajectories, and Solutions. *Sustainability*, 7, 6523–6552.

Tung Gia Pham, Jan Degener, Martin Kappas, 2018. *Integrated universal soil loss equation (USLE) and Geographical Information System (GIS) for soil erosion estimation in A Sap basin: Central Vietnam*, International Soil and Water Conservation Research, Volume 6, Issue 2, June 2018, Pages 99-110.

USDA, 2017. *Vietnam: MOH revises MRLs for Pesticides in Foods.*

USDA, 2021. *Vietnam Organic Market.*

USDA, 2024. *What is Soil Health?* https://www.nrcs.usda.gov/conservation-basics/natural-resource-concerns/soils/soil-health

USDA. https://www.nrcs.usda.gov/conservation-basics/natural-resource-concerns/soils/soil-health

Van Hoi, P., Mol, A., & Oosterveer, P., 2013. State governance of pesticide use and trade in Vietnam. NJAS: *Wageningen Journal of Life Sciences*, 67(1), 19-26.

Veerman, C, Pinto Correia, T, Bastioli, C, Biro, B, Bouma, J, Cienciala, E, Emmett, B, Frison, E A, Grand, A, Hristov, L, Kriauciũniené, Z, Pogrzeba, M, Soussana, J-F, Vela, C and Wittkowski, R, 2020) *Caring for soil is caring for life.* Interim report of the Soil Health and Food Mission Board. Independent expert report to European Commission, Publications Office of the European Union.

Vega, F. A., Covelo, E. F., & Andrade, M. L., 2007. Accidental organochlorine pesticide contamination of soil in Porrino, Spain. *Journal of environmental quality*, 36(1), 272-279.

Vietnam Soil Association (Vietsoil), 1996. *Vietnam soil*. Agriculture publishing house. Ha Noi, p. 168.

Widyati, E., Nuroniah, H. S., Tata, H. L., Mindawati, N., Lisnawati, Y., Darwo,... & van Noordwijk, M., 2022. Soil degradation due to conversion from natural to plantation forests in Indonesia. *Forests,* 13(11), 1913.

Wingeyer, A.B.; Amado, T.J.C.; Pérez-Bidegain, M.; Studdert, G.A.; Perdomo Varela, C.H.; Garcia, F.O.; Karlen, D.L, 2015. Soil Quality Impacts of Current South American Agricultural Practices. *Sustainability*, 7, 2213–2242.

World Bank, 2025. *World Bank Open Data*. Access at https://data.worldbank.org/ on 14th Jan 2025.

World Bank. 2019. *Vietnam: Toward a Safe, Clean, and Resilient Water System*. World Bank, Washington, DC.

Yi Huang, Keisuke Miyauchi, Ginro Endo, Le Dinh Don, Nguyen Cong Manh & Chihiro Inoue, 2016. Arsenic contamination of groundwater and agricultural soil irrigated with the groundwater in Mekong Delta, Vietnam, *Environmental Earth Sciences*, Volume 75, article number 757.

Zulian, G., Maes, J., & Paracchini, M. L., 2013. Linking land cover data and crop yields for mapping and assessment of pollination services in Europe. *Land*, 2(3), 472-492.