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Assessing Food Security and Environmental Sustainability in North Africa: A Composite Indicator Approach Using Data Envelopment Analysis

Muhammad Ikram 

School of Business Administration, Al Akhawayn University in Ifrane, Avenue Hassan II, P.O. Box 104, Ifrane 53 000, Morocco; i.muhammad@au.ma

Abstract

North Africa faces significant challenges of food insecurity and environmental degradation, driven by rapid population growth, ongoing droughts, severe water stress, and increasing rates of undernourishment. Achieving food security and environmental sustainability requires a balanced evaluation of agricultural productivity, resource efficiency, ecosystem health, and climate resilience. Therefore, this study develops a composite food security and environmental sustainability index (FSESI) that encompasses complex relationships via multidimensional indicators. Data analysis was conducted for Egypt, Libya, Algeria, Tunisia, Morocco, Sudan, and Mauritania, covering the period from 2010 to 2022. A comprehensive methodology employing data envelopment analysis (DEA) for objective weighting and geometric mean aggregation was implemented. The findings indicate notable disparities; Sudan presented the highest undernourishment rate (21.8% in 2010, 11.4% in 2022), whereas Libya faced severe water stress (783.12% to 817.14%). Morocco recorded the highest FSESI score of 0.78, reflecting strong performance in both the food security and environmental dimensions, whereas Algeria and Libya each had scores of 0.48, indicating relatively modest outcomes. Finally, sensitivity analysis was employed to check the robustness of the results. This research highlights the need for immediate policy actions focused on equitable resource management, enhanced agricultural methods, and reinforced food security initiatives. This study directly supports Sustainable Development Goal (SDG) 2, Zero Hunger; SDG 6, Clean Water and Sanitation; SDG 13, Climate Action; and SDG 15, Life on Land, by addressing integrated challenges in food security and environmental sustainability in North Africa. The originality of this work lies in its thorough integration of environmental and food security dimensions through innovative aggregation methods, offering a replicable framework that policymakers and researchers can use to address complex environmental and food security issues in North Africa sustainably.

Keywords: food security; environmental sustainability; climate change; food crises; composite indicator; sustainable development



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1. Introduction

Food security is broadly defined as a condition in which all people, at all times, have physical, social, and economic access to sufficient, safe, and nutritious food to meet their dietary needs and food preferences for an active and healthy life FAO, 1996; Pérez-Escamilla, 2017 [1,2]. It encompasses not only the availability of food but also people's ability to access and utilize that food in stable ways over time. On the other hand, environmental

sustainability refers to managing natural resources and ecosystems in a way that meets current needs without compromising the ability of future generations to meet their own needs Goodland, 2017 [3]. In practice, environmental sustainability refers to living within the means of natural resources, for example, consuming water, soil nutrients, and forests at a sustainable rate and safeguarding ecosystem health Salas-Zapata & Ortiz-Muñoz 2019 [4].

Food security and environmental sustainability are fundamental and interlinked challenges in the modern world. A healthy environment underpins long-term food production, whereas unsustainable practices and climate change can undermine food security Kazancoglu et al., 2024; Smith et al., 2020 [5,6]. Conversely, how we pursue food security (through agriculture, fisheries, etc.) impacts environmental health. Global population growth and changing diets are driving up food demand, with agricultural output needing to increase by approximately 60–70% by 2050 to feed nearly 10 billion people Ahmad et al., 2024 [7]. Moreover, climate change and resource degradation threaten food production, making ensuring a stable food supply increasingly difficult for countries Nguyen et al., 2023 [8]. Balancing the goal of feeding growing populations with the imperative of preserving environmental resources has become a pressing concern for sustainable development Ali et al., 2023 [9]. While numerous studies have addressed food security or environmental sustainability in isolation, there remains a need for integrated assessments that capture the trade-offs and synergies between these two domains Hassan et al., 2022; Wang et al., 2021; Moorehead & Wolmer, 2001 [10–12]. The development of a composite indicator that combines food security and environmental metrics can provide valuable insights for policymakers striving to achieve both zero hunger and environmental goals. North Africa exemplifies the food–environment nexus challenges, given its arid climate, severe water scarcity, and reliance on food imports, making it an important case for integrated analysis.

An indicator-based assessment provides a structured means to evaluate food security and environmental sustainability (FSES), as it systematically encapsulates complex interactions among economic conditions, ecological factors, nutritional aspects, and sociopolitical dynamics that might otherwise remain unclear Praveen & Sharma, 2019 [13]. Recognizing the significance and analytical utility of such indicators, international organizations such as the Food and Agriculture Organization (FAO) regularly publish comprehensive datasets comprising multiple indicators of food security and environmental conditions across countries worldwide FAO, 2020 [14]. Although indicator-based evaluations have considerably enhanced understanding, the proliferation of diverse individual indicators, both simplistic and sophisticated, has created certain interpretational ambiguities. Such confusion arises because aggregated indicators frequently overlap, their relative significance often remains uncertain, they sometimes measure similar or correlated dimensions, and their findings occasionally contradict each other. For example, the FAO's suite of food security indicators includes over 30 detailed metrics covering availability, access, stability, and utilization dimensions FAO, 204 [15], whereas recent research by Béné et al., 2020 [16] identified more than 100 potential indicators of food system resilience. Consequently, interpreting and synthesizing such extensive multidimensional data into clear, consistent, and actionable insights becomes challenging. To address these complexities, researchers increasingly attempt to consolidate multiple indicators into unified indices, offering more comprehensible insights Burgass et al., 2017 [17]. Composite indices enable a clearer comparison of national performance over time, facilitate the identification of underlying trends that may otherwise remain obscured, and allow policymakers to visualize interdependencies and trade-offs between different indicator dimensions Ecker & Ecker, 2014; Caccavale & Giuffrida, 2020 [18,19]. Furthermore, developing such indices helps identify critical gaps in national policies and provides guidance

for targeted interventions Cafiero, 2019 [20]. Despite numerous efforts to establish broadly accepted composite indices for food security and environmental sustainability, achieving consensus remains challenging owing to variations in definitions, priorities, and objectives across different regions and stakeholders Allen et al., 2019 [21]. Complications, including spatial considerations (local versus regional or global contexts), variability in data quality and availability, methodological inconsistencies, and inherent interrelationships among indicators, collectively complicate the formulation of an agreed-upon, universally applicable FSES index.

Achieving global food security and environmental sustainability represents a critical intersection in the United Nations' Sustainable Development Goals (SDGs). In particular, SDG 2 (Zero Hunger) and SDG 6 (Clean Water and Sanitation) are closely interlinked, as secure access to adequate water resources underpins sustainable food production Li et al., 2024 [22]. Additionally, addressing climate challenges (SDG 13: Climate Action) and preserving terrestrial ecosystems (SDG 15: Life on Land) are integral to sustaining agricultural productivity and environmental integrity. Recent studies underscore these interdependencies, emphasizing that integrated frameworks addressing multiple SDGs simultaneously offer significant advantages over isolated approaches. Wijerathna and Pathirana, 2022 [23] pointed out that achieving long-term food sustainability requires innovation-driven climate solutions. Against this backdrop, the current study presents an integrated composite index, FSESI, to systematically evaluate and support progress toward these interconnected SDGs within the North African context.

Moreover, within this study, we assigned equal weights to all indicators in this exercise (each indicator weight = $1/N$). The purpose of this comparison was to see how the ranking of countries might differ if one uses a conventional equal-weight index (which assumes all aspects are equally important) versus the DEA optimal-weight index (which lets importance vary per country). SAW is widely used due to its simplicity, and while it lacks the flexibility of DEA, it provides a useful reference point. We followed standard steps for SAW: we normalized each indicator to a 0–100 scale (to avoid tiny decimals), where 100 is the best performance among all countries and years, and then averaged these values (since equal weight) for each country–year pair.

By doing so, this study offers a comprehensive assessment of each country's performance and vulnerabilities at the food–environment nexus. We introduce the composite index approach, the specific indicators chosen for food security and environmental sustainability, how they are weighted and aggregated, the results of comparing countries, and the policy implications. By developing an FSESI composite index, we aim to highlight the multifaceted nature of food security challenges in North Africa and identify key areas where policy intervention can increase both food security and environmental resilience. The FSESI covers the period 2010–2022, a timeframe marked by significant developments in the region's food systems and environmental context. The objectives of this paper are threefold: (1) to construct the FSESI on the basis of carefully selected indicators reflecting the key dimensions of food security and environmental sustainability, (2) to evaluate and compare North African countries' FSESI scores and trends from 2010 to 2022, and (3) to discuss the implications of these findings for policy and practice. By adopting a holistic index approach, this study aims to fill the gap in the literature through integrated assessment and inform strategies that simultaneously advance food security and environmental goals in North Africa.

This study develops a novel FSESI for North African countries, combining multidimensional indicators of food status and environmental conditions into an integrated framework. This integrated index captures the food environment nexus holistically, filling a critical gap in regional assessments. Moreover, this study introduces an objective weighting approach

using data envelopment analysis (DEA) to construct the composite index. This minimizes subjective bias in indicator weighting. In addition, we use a geometric mean aggregation (weighted product) to compute the index, which reduces information loss compared to a simple arithmetic mean. Together, these methodological innovations provide a replicable framework for index construction in sustainability studies.

This study provides a comprehensive comparative analysis of seven North African countries from 2010 to 2022, identifying leaders, laggards, and trends over time. Notably, our results show Morocco leading the region with the highest composite score and Libya trailing due to conflict and resource stress. We validate the index's robustness through sensitivity analysis (varying weighting emphasis), confirming the stability of country rankings. These findings yield new insights into how each nation balances feeding its population versus safeguarding its environment, with direct implications for targeted policy interventions.

2. Materials and Methods

A composite indicator is developed by integrating multiple diverse indicators into one unified measurement. Such indices are particularly valuable for assessing compound phenomena that cannot be sufficiently captured by a single indicator alone Santeramo, 2015 [24]. For a composite index to effectively inform decision-making processes at the national or global level, the methodology behind its creation should be transparent and clearly documented. This transparency ensures that future research efforts can easily replicate, validate, update, or even critically assess the composite indicator Hao & Jin, 2025 [25]. Among the key steps involved in designing an effective composite indicator, the selection of appropriate individual indicators is crucial. Properly selected indicators can yield meaningful insights into critical areas such as food security and environmental sustainability, offering a clear and comprehensive overview of related conditions. Moreover, thoughtfully chosen indicators can serve as dynamic analytical tools for researchers and policymakers, helping them identify evolving trends, compare cross-country situations, and gauge the effectiveness of policy interventions over time Shah et al., 2019 [26]. Given the critical nature of indicator selection, careful attention was devoted to this phase while the food security and environmental sustainability index (FSESI) designed for North African countries was constructed. This study conceptualized FSESI as a two-dimensional index combining food security and environmental sustainability. Each dimension is represented by multiple indicators capturing critical aspects identified from the literature and the regional context. The detailed justification, background, and data sources for each selected subindicator are discussed comprehensively in Sections 2.1, 2.2 and 2.4. Additionally, Figure 1 illustrates the two main categories of indicators employed in this study, namely those related to food security and those addressing environmental sustainability.

To allow aggregation, all indicator data were normalized to a common scale. We applied min–max normalization to the 2010–2022 data for each indicator, transforming values to the [0, 1] range (with 1 = best performance and 0 = worst). This preserves relative performance without altering the underlying trends. For “positive” indicators (where higher is better, e.g., organic farming percentage), normalization is straightforward; for “negative” indicators (where higher is worse, e.g., undernourishment rate, CO₂ emissions), we inverted the values after normalization so that in all cases a higher normalized score indicates better sustainability or security. Equation (1) provides the normalization formula. By normalizing, we ensure that indicators with different units and scales become comparable, as recommended in composite index construction guidelines. We have added text to explicitly reference Equation (1) when discussing this step, to guide the reader.

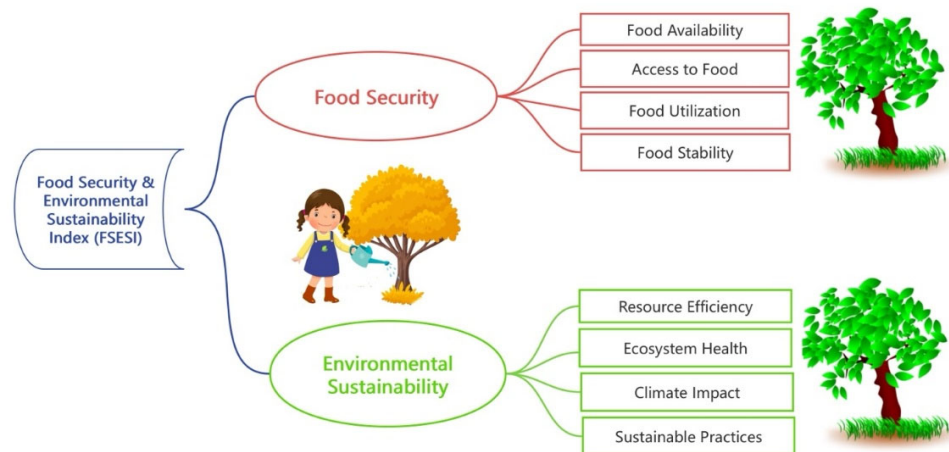


Figure 1. Food security and environmental sustainability indicators for FSESI construction for North Africa (author’s own drawing).

2.1. Food Security Indicators

A composite indicator framework for food security relies on the recognition that food systems are inherently multidimensional. In this context, indicators are chosen not only to capture the aggregate level of food production and distribution but also to reflect the socioeconomic factors that affect household access and nutritional outcomes. The food security component is generally divided into four distinct dimensions: availability, access, utilization, and stability.

Availability: This dimension reflects the supply side of food security, namely whether enough food is physically present in a country to meet the population’s needs. The key indicators under availability include agricultural output and yield metrics, such as cereal yield (kilograms per hectare) and per capita food production, as presented in Equation (1). High crop yields and ample domestic production generally improve food availability, reducing reliance on imports Hu et al., 2024 [27]. In North Africa, where arable land and water are limited, yield improvements are crucial. For example, projections by the IPCC warn that climate change could reduce crop yields in East China and North Africa by 20% by 2050 under a high-emission scenario IPCC, 2022 [28]. Moreover, per capita food supply (calories or tonnage) is used to capture the combined effect of domestic production plus net imports. Overall, availability indicators tell us if the “food basket” for the country is adequate (see Equation (2)).

$$\text{Crop Yield} = \frac{\text{Total Crop Production (tons)}}{\text{Land Area (ha)}} \quad (1)$$

$$\text{Per Capita Food Production} = \frac{\text{Total Food Production (kg)}}{\text{Population}} \quad (2)$$

Access to Food: Even if food is available in aggregate, people must be able to obtain it. Access has both economic and physical aspects. We selected indicators such as poverty rates (e.g., percentage of the population below the national poverty line) and food affordability measures (such as the share of household income spent on food or a food price index relative to incomes). These findings reflect economic access; if a large share of people are poor or if food prices are high, many will struggle to buy sufficient food. North African countries show why access is critical: during the global food price spikes of recent years, even nations with enough food saw increased hunger because people could not afford higher prices. For example, food price inflation in 2022 and 2023, partly due to the Ukraine war, eroded consumers’ purchasing power across the Arab region

Ben Hassen, & El Bilali, 2024 [29]. The formula for the percentage of the population unable to afford a healthy diet is presented in Equation (3). In Tunisia and Egypt, where economic downturns and currency depreciation have occurred, many households face difficulty accessing food despite markets being supplied. We also consider unemployment rates (especially youth unemployment) as an access indicator since joblessness limits people's income from buying food Enriquez et al., 2024 [30]. Another important access metric is infrastructure for distribution, such as the percentage of the population in rural areas with access to markets or transport; however, data on this metric can be scarce, so we use it qualitatively. Access indicators gauge how evenly food is reaching all people. A high poverty rate or high food expenditure share signals that a significant segment of the population is food-insecure despite overall availability Headey et al., 2022 [31]. Indeed, regional analyses classify countries with widespread poverty and inequality as most at risk for food insecurity even when food supplies are sufficient. Equation (4) presents the formula for the poverty rate. Thus, incorporating access metrics ensures that the FSESI captures the socioeconomic side of food security in North Africa.

$$\begin{aligned} &\text{Percentage of Population Unable to Afford a Healthy Diet} \\ &= \left(\frac{\text{number of individuals below affordability threshold}}{\text{Total Population}} \right) \times 100 \end{aligned}$$

Or

$$\text{AHD}_{\text{pop. \%}} = \left(\frac{\text{BAT}_{\text{num.}}}{T_{\text{pop.}}} \right) \times 100 \quad (3)$$

where $\text{AHD}_{\text{pop. \%}}$ is the percentage of the population unable to afford a healthy diet, a variable is the number of individuals below the affordability threshold, and another variable is the total population.

$$\text{Poverty Rate \%} = \left(\frac{N_{\text{poor}}}{T_{\text{pop.}}} \right) \times 100 \quad (4)$$

where N_{poor} is the number of individuals whose income falls below the poverty threshold and a variable is the total population. The poverty threshold, also known as the poverty line, is the minimum level of income deemed adequate in a particular country. It is usually calculated by estimating the total cost of one year's worth of necessities for the average adult.

Food Utilization: Utilization addresses how well individuals can consume and benefit from food, including nutritional quality, food safety, and health conditions necessary for the body to use food. Indicators such as the prevalence of undernourishment (PoU), which is the percentage of people consuming insufficient calories, and child malnutrition rates such as stunting or wasting in children reflect chronic and acute undernutrition, respectively Abegaz, 2018 [32]. In North Africa, undernourishment rates have historically been lower than those in sub-Saharan Africa but have recently been increasing; for example, the Arab region's hunger prevalence was 12.9% in 2022, which is a worrisome increase from previous years Elmighrabi, 2023 [33]. Moreover, access to clean water and sanitation is crucial for the utilization of food. Without safe water, people are prone to waterborne diseases and cannot absorb nutrients properly. Access to improved water sources is commonly used in food security analysis as a proxy for a hygienic utilization environment Wang et al., 2019 [34]. Health indicators such as the prevalence of anemia among women or the incidence of foodborne illnesses can also reflect utilization problems, e.g., a lack of micronutrients or food safety issues Moradiet al., 2018 [35]. Utilization indicators thus ensure that the FSESI rewards not only ample food but also healthy food and effective consumption.

PoU is a metric used to estimate the percentage of a population whose habitual food consumption is insufficient to provide the dietary energy levels required to maintain a normal, active, and healthy life Wanner et al., 2014 [36]. The PoU is calculated via the following formula in Equation (5):

$$\text{PoU} = \int_0^{\text{MDER}} f(x | \mu, \sigma) dx \quad (5)$$

where x represents the probability density function of the habitual dietary energy consumption in the population, characterized by the mean per capita dietary energy consumption; σ is the standard deviation of dietary energy consumption, reflecting the variability in intake among individuals; and MDER is the minimum dietary energy requirement, which is the threshold below which individuals are considered undernourished.

Access to safe drinking water is crucial for food security because waterborne diseases can impair nutrient absorption, leading to malnutrition. Clean water ensures that food can be safely prepared and consumed, reducing the risk of foodborne illnesses. The formula for calculating access to clean water (%) is presented in Equation (6).

$$\text{Access to Clean Water (\%)} = \left(\frac{N_{\text{ew}}}{T_{\text{pop.}}} \right) \times 100 \quad (6)$$

where N_{ew} indicates the number of people in the population with access to clean and safe drinking water and $T_{\text{pop.}}$ represents the total population.

Food Stability: The stability dimension captures the risk of disruptions in availability or access over time. Food security should be secured at all times, meaning that countries and communities can weather shocks such as droughts, price spikes, conflicts, or economic crises. Indicators for stability include food price volatility (e.g., year-on-year variation in staple food prices) and volatile agricultural production variability in domestic output due to rainfall variability. We also incorporate measures of climate and political stability relevant to food systems, such as the frequency of droughts or floods (climate shocks per decade), and an indicator of conflict/insecurity, such as the presence of internal conflict or refugee flows Erb et al., 2012 [37]. Unfortunately, North Africa faces notable stability challenges, from the extreme climate variability of the Sahara and Sahel regions to recent conflicts and social unrest Hzami et al., 2021 [38]. The region's heavy reliance on imports (over 50% of cereal needs in many cases) makes stability a critical concern. According to statistics, approximately 36.6% of the Near East and North Africa population experienced moderate or severe food insecurity in 2022, and acute (severe) food insecurity affected 61 million people, 3.8 million more than in the previous year. By combining these metrics, the stability component of the FSESI gauges how well a country can maintain food security through volatility. A high stability score would mean that food prices are steady, production is reliable or well buffered, and there are institutional measures to handle bad years. A low stability score would be assigned to a country facing frequent shocks and lacking coping capacity, for example, a nation with repeated droughts, no crop insurance or reserves, and political turmoil. The inclusion of stability ensures that the FSESI rewards not only the current status but also the sustainability of food security over time, which is highly pertinent in North Africa's uncertain climate and economic landscape.

Food price volatility (FPVI) impacts household food security by making it harder for consumers, especially low-income groups, to afford basic food items. If the index is high, it indicates greater price fluctuations, which can lead to economic instability and hunger risks Amolegbe et al., 2025 [39]. The formula for FPVI is presented in Equation (7).

$$FPVI = \left(\frac{\sigma}{\mu} \right) \times 100 \quad (7)$$

where σ measures the variability of food prices over time. μ represents the average food price over the same period.

$$CRI = (\omega_1 \times I_A + \omega_2 \times I_E + \omega_3 \times I_S) \quad (8)$$

where I_A is the adaptive capacity index, which measures a country's ability to adjust and respond to climate risks (e.g., investments in climate-smart agriculture, water management, research, education). I_E represents the exposure index, which captures the extent to which a country is exposed to climate-related hazards (e.g., the frequency and severity of droughts, floods, and extreme temperatures). The I_S sensitivity index measures how sensitive a country is to climate impacts (e.g., reliance on rain-fed agriculture, soil degradation, and water scarcity). Finally, ω_1 , ω_2 , and ω_3 indicate the weighting factors, which are typically set to a sum of 1. The climate resilience index (CRI) is key to stability; countries with low resilience are more likely to experience food insecurity due to crop failure, loss of livestock, or water shortages Fang et al., 2024 [40]. The formula for CRI is presented in Equation (8).

2.2. Environmental Sustainability Indicators

Sustainable food production cannot be achieved without an accompanying commitment to environmental stewardship. Environmental sustainability indicators help capture how food systems manage natural resources, maintain ecosystem health, and reduce their overall environmental footprint. In the context of food systems, these indicators are grouped into four key categories: resource efficiency, ecosystem health, climate impact, and sustainable practices.

Resource Efficiency: This category examines how efficiently countries use natural resources in their food and agriculture sectors, with a focus on water and soil nutrients, which are especially scarce in North Africa. A flagship indicator here is water use efficiency in agriculture, often measured as agricultural GDP (or crop output) per cubic meter of water withdrawn. Tunisia uses approximately 104% of its renewable water (just above sustainable levels), and Algeria uses approximately 87%, whereas Libya and Egypt astronomically exceed renewable supplies by relying on nonrenewable fossil water or the Nile, Libya's water use is estimated at over 800% of internal renewables, and Egypt's water use is at a staggering 6420% when including Nile waters that originate outside its borders. Equation (9) presents the computation formula for water use efficiency.

Similarly, fertilizer use efficiency, the ratio of crop yield to fertilizer input, or excess fertilizer runoff per hectare, is an important resource metric. The overuse of fertilizers can pollute water and degrade soils, while underuse can limit yields. We look at average fertilizer application rates and nutrient use efficiency. For example, Egypt and Morocco have relatively high fertilizer application rates, ensuring that yield rather than runoff is efficient Abdel-Hakeem & El-Habaak, 2021 [41]. Resource efficiency indicators measure how well North African countries manage the critical inputs for agricultural water and soil nutrients, which directly affect both the immediate productivity and long-term viability of food production.

$$\text{Water Use Efficiency} = \frac{\text{Crop Yield (tons)}}{\text{Water Used (m}^3\text{)}} \quad (9)$$

Water use efficiency measures how much economic output or crop yield is produced per unit of water. The fertilizer use efficiency formula is presented in Equation (10).

$$\text{Fertilizer Use Efficiency} = \frac{\text{Crop Yield (tons)}}{\text{Fertilizer Applied (kg)}} \quad (10)$$

Ecosystem health: This category reflects the condition of the natural ecosystems that support food and agriculture, primarily soil quality and biodiversity. One core indicator we use is the soil organic carbon (SOC) content in agricultural lands. Soil organic carbon is a key indicator of soil health and fertility; higher SOC usually indicates better soil structure, water retention, and nutrient content, which support sustainable yields Beillouin et al., 2022 [42]. Unfortunately, in North Africa’s drylands, SOC levels are naturally low and have been further depleted by overuse. Moreover, the second most important key ecosystem health indicator is biodiversity, which is relevant to food and agriculture. We incorporated an agrobiodiversity index, which could include the number of plant varieties cultivated or the status of pollinator populations, as well as broader biodiversity Bimonte et al., 2021 [43].

The reasoning is that diverse and functioning ecosystems provide services such as pollination, pest control, and genetic resources for crops. A loss of biodiversity can undermine resilience; conversely, maintaining biodiversity (e.g., preserving wild crop relatives and protecting pollinator habitats) can support sustainable agriculture. Across Africa, biodiversity loss is a serious concern, as declines in ecological biodiversity threaten millions of livelihoods and increase food insecurity by disrupting ecosystems.

Overall, the ecosystem health indicators reward countries that conserve soil and biodiversity, e.g., those investing in soil conservation (maintaining SOC) and protecting natural habitats, since these indicators underpin long-term food production capacity. The computational formula for soil organic carbon is shown in Equation (11).

$$\text{Soil Organic Carbon (\%)} = \left(\frac{C_{\text{organic}}}{M_{\text{soil}}} \right) \times 100 \quad (11)$$

where C_{organic} indicates the mass of organic carbon in the soil sample (g or mg) and M_{soil} represents the total mass of the soil sample (g or mg). A relatively high SOC percentage improves soil fertility, water retention, and resilience against droughts, benefiting long-term food production. Low SOC% indicates soil degradation, loss of fertility, and increased vulnerability to erosion and desertification. Sustainable agricultural practices such as crop rotation, cover cropping, conservation tillage, and organic matter addition help increase SOC Payen et al., 2021 [44].

$$\text{Biodiversity Index (BI)} = 1 - D \quad (12)$$

$$D = \sum_{i=1}^s p_i^2$$

where D measures the probability that two randomly selected individuals belong to the same species and a variable represents the proportion of individuals of species i relative to the total population (see Equation (12)). A high BI (~ 1) indicates rich and balanced biodiversity, supporting ecosystem services such as pollination, pest control, and soil fertility. A low BI (~ 0) indicates a loss of species, making ecosystems vulnerable to disease, climate shock, and reduced agricultural productivity Simpson, 1949 [45].

Climate Impact: This category measures how the food and agriculture sector in each country contributes to climate change and other environmental externalities, as well as how efficiently the system is operating in terms of waste. Indicators here include greenhouse gas (GHG) emissions from agriculture (typically measured in CO₂-equivalent emissions per year or per unit of agricultural GDP). Agriculture (including land use change and forestry) is a notable source of emissions globally, and approximately 24% of GHG emissions worldwide are attributed to agriculture, forestry, and land use Verma et al., 2024 [46].

Moreover, the second crucial indicator is food loss and waste. This area is highly important for both food security and sustainable food, which is lost or wasted, resulting in unnecessary pressure on land and water resources and avoidable GHG emissions through the production and decomposition of wasted food Somlai, 2022 [47]. It is estimated that approximately one-third of the food produced globally is lost or wasted, and in Africa, 40% of food output is lost or wasted, representing considerable inefficiency Mmerek et al., 2024 [48]. In North Africa, food losses often occur in early stages (harvest and storage) for staples and at the consumer level for perishable foods, partly because of inadequate cold chains and consumer habits. We use an indicator for food loss percentage postharvest and food waste per capita at the consumer level.

A country that emits fewer GHGs, wastes less food, and minimizes the amount of food it produces will score well, indicating a more sustainable and efficient system. This is particularly pertinent for North Africa; as countries develop, they have the opportunity to adopt sustainable practices to avoid high-emission trajectories even as they increase food production. The formula for GHG emissions from agriculture is presented in Equation (13).

$$\begin{aligned} \text{GHG Emissions from Agriculture (GHG}_{\text{agri}}) \\ = \frac{\sum (E_{\text{CO}_2} + E_{\text{CH}_4} + E_{\text{N}_2\text{O}})}{L_{\text{agriculture}}} \end{aligned} \quad (13)$$

where GHG_{agri} represents greenhouse gas emissions from agriculture (measured in CO_2 equivalents per hectare). $E_{\text{CO}_2} + E_{\text{CH}_4} + E_{\text{N}_2\text{O}}$ represents total carbon dioxide (CO_2) and methane (CH_4) emissions and nitrous oxide (N_2O) from agriculture. $L_{\text{agriculture}}$ represents the total agricultural land area (hectares). A high GHG_{agri} indicates high emission intensity, requiring sustainable practices such as precision farming, reduced fertilizer use, and methane-reducing feed for livestock. A low GHG_{agri} signifies more climate-friendly agriculture with better efficiency in terms of resource use.

$$\text{Food Loss/Waste Rate (FLW\%)} = \left(\frac{F_{\text{lost or wasted}}}{F_{\text{produced}}} \right) \times 100 \quad (14)$$

where $F_{\text{lost or wasted}}$ represents the amount of food lost or wasted (kg, tons, or kcal) and F_{produced} represents the total amount of food produced (kg, tons, or kcal). The higher the FLW%, the more inefficient the food system is, contributing to hunger, economic losses, and environmental damage. The formula for the food loss/waste rate is presented in Equation (14).

Sustainable Practices: This category looks at the presence of forward-looking, sustainable agricultural practices and policies, which act as positive indicators that a country is moving toward long-term sustainability in food security. We include metrics such as the area under organic farming (as a percentage of total agricultural land) and the adoption of agroforestry or conservation agriculture. Organic agriculture avoids synthetic chemicals, thereby reducing environmental harm and often improving soil health. North Africa has been a leader in organic farming within Africa: Tunisia, for example, now has the largest area of certified organic land in Africa (approximately 336,000 hectares) and has seen the number of organic farms soar from under 500 two decades ago to nearly 8000 by 2018 Benabdelkader et al., 2021 [49]. Egypt also has a growing organic sector (approximately 3% of its agricultural land is organic as of 2018).

By including sustainable practices, the FSESI captures whether countries are on a sustainable trajectory. It is not only about the current state but also about efforts being made for future sustainability. Countries that embrace organic farming, agroforestry, water-saving technology, and other agroecological methods are essentially investing in

both near-term and long-term food security. This component can therefore differentiate between two countries that currently may have similar outcomes by highlighting which is better prepared for the future. In North Africa, where climate change looms large, such forward-looking measures are especially pertinent.

$$\text{Farmland Under Organic Agriculture} = \left(\frac{A_{\text{organic}}}{L_{\text{total}}} \right) \times 100 \quad (15)$$

where A_{organic} is the total area of farmland under organic agriculture (hectares or acres). L_{total} represents the total agricultural land area (hectares or acres), as presented in Equation (15). A relatively high percentage of organic farmland indicates sustainable agricultural practices that promote biodiversity and soil health and reduce chemical input use Gamage et al., 2023 [50]. However, a lower percentage of organic farmland suggests a high reliance on conventional farming, which may involve synthetic fertilizers and pesticides.

$$\text{Agroforestry Adoption Rate (\%)} = \left(\frac{A_{\text{agroforestry}}}{L_{\text{ftotal}}} \right) \times 100 \quad (16)$$

where $A_{\text{agroforestry}}$ represents the area of farmland that uses agroforestry (hectares or acres) and L_{ftotal} represents the total farmland area (hectares or acres) used. Higher adoption rates indicate a stronger commitment to sustainable agricultural practices, leading to benefits such as improved soil health, biodiversity, climate resilience, and long-term food security. Lower adoption rates suggest the potential to increase awareness, training, or incentives for agroforestry. The computational formula for the agroforestry adoption rate is presented in Equation (16).

2.3. Weighting and Aggregation

After the indicators are selected, the next step is to assign weights and aggregate them into the composite FSESI. Weighting is needed because not all indicators are equally significant, and they are measured in different units, so there is a need for weights to reflect their relative importance in the index. We approach weighting with objectivity and transparency to minimize bias. First, we assigned equal weights to the major pillars (food security and environmental sustainability) to ensure that neither dimension dominated the index. Within each pillar, we also started with an equal weighting for each subdimension (for example, within food security: availability, access, utilization, and stability, each initially given 25% of the food security subindex). This equal weighting approach is common in composite index construction, especially when there is no clear, empirically justified reason to prioritize one component over others Zhou et al., 2010 [51]. Equal weights treat all variables as worth the same value in the absence of a consensus on alternatives. This helps to avoid injecting subjective bias (e.g., considering that availability is twice as important as utilization, which might undervalue nutrition, or that water is more important than biodiversity, which might be disputed) Zhou et al., 2006 [52]. By considering, for example, that crop yield and undernourishment indicators have equal influences, we ensure a balance between the quantity and quality aspects of food security.

The DEA model allows each country to have its own optimal set of indicator weights subject to the efficiency constraints. In practical terms, this means a country's FSESI score is weighted more heavily by the indicators where it performs relatively well. For instance, Morocco's DEA solution gave considerable weight to water efficiency and sustainable practices, reflecting its strengths in those areas, whereas Sudan's solution placed more weight on low emissions since Sudan had very low per capita CO₂ emissions to maximize its score. Conversely, Libya could not benefit much from any indicator weight emphasis due to uniformly poor performance in both food and environmental metrics, which is why

its score remained low. We support these observations with data: e.g., in 2022, Morocco had the highest organic farming share in the region and relatively moderate undernourishment, so it could boost its score by emphasizing those indicators, whereas Libya's high undernourishment and extreme water stress meant no weighting could substantially raise its composite score without violating efficiency constraints. No arbitrary weight restrictions were imposed; the DEA was allowed full flexibility within the only constraints that weights be non-negative and common for comparison. This ensures the weighting is entirely data-driven.

One novel aspect of our approach is the use of DEA to determine indicator weights objectively. Rather than assigning arbitrary or subjective weights, we implemented a benefit-of-the-doubt DEA model. In this model, each country-year observation is treated as a decision-making unit (DMU) that chooses the most favorable weights for itself, subject to the constraint that no other DMU's index score exceeds 1 under those same weights. This linear programming approach endogenously calculates weights that maximize each country's composite score while keeping all scores on a common efficiency scale (0 to 1).

However, we also tested the robustness of this assumption. We performed a sensitivity analysis with slightly varying weights to determine whether country rankings changed significantly. The results were stable, indicating that no single indicator or subindex unduly skewed the overall outcome, an important check of objectivity. In a few cases, we adjusted the weights on the basis of the data quality. Indicators with very limited or low-quality data (or those serving as proxy placeholders) were given a somewhat lower weight to reduce noise in the index. For example, if reliable data on agroforestry adoption are sparse, the indicator's weight in the sustainable practices subindex might be slightly lower than that in organic farming areas, which have robust data. These adjustments were kept minimal and documented clearly. With the weights set, we aggregated the indicators into subindex scores (food security subindex and environmental subindex) and then into the final FSESI score. We chose a geometric mean aggregation for combining subindices (and, in some cases, within subindices) rather than a simple arithmetic mean. The multiplicative aggregation (geometric mean) has the effect of reducing substitutability between components Chiclana et al., 2004 [53].

Step 1: Min–Max Normalization (Rescaling)

Each indicator is first normalized into a common range [0, 1] via min–max normalization. This process ensures comparability across indicators measured in different units.

Benefit indicators (higher = better):

These indicators positively contribute to food security or environmental sustainability. The normalization formula is presented in Equation (17):

$$x_{\text{nom}} = \frac{x - \min(x)}{\max(x) - \min(x)} \quad (17)$$

where x_{nom} represents the normalized indicator (0–1 scale) and $\min(x)$ and $\max(x)$ represent the minimum and maximum observed values of the indicator across countries.

Cost indicators (lower = better):

The cost indicators presented negatively impact food security or environmental sustainability (e.g., poverty rate, food price volatility, and GHG emissions). The normalization formula is inverted and presented in Equation (18).

$$x_{\text{nom}} = \frac{\max(x) - x}{\max(x) - \min(x)} \quad (18)$$

Here, a higher normalized score (closer to 1) indicates better performance (lower cost).

Step 2: DEA-Like Weighting (Data Envelopment Analysis)

DEA is a mathematical approach used to assign weights objectively and minimize subjectivity. It identifies optimal indicator weights for each country to maximize or minimize the composite index.

Best score model (optimistic scenario):

The goal is to find weights that maximize the composite index for each country. This is expressed as a weighted product, which is presented in Equation (19).

$$CI_i^{max} = \max \prod_{k=1}^n (x_{ik})^{w_k} \quad (19)$$

subject to

$$\sum_{k=1}^n w_k = 1 \text{ and } 0.05 \leq w_k \leq 0.20 \forall k$$

CI_i^{max} is the maximum composite index for country i . x_{ik} is the normalized value of indicator k for country i . w_k is the weight assigned to indicator k . n represents the total number of indicators.

Worst score model (pessimistic scenario)

This model assigns weights to minimize the composite index, representing a pessimistic scenario (see Equation (20)):

$$CI_i^{min} = \min \prod_{k=1}^n (x_{ik})^{w_k} \quad (20)$$

subject to the same constraints.

Step 3: Logarithmic Transformation

Since the multiplicative (weighted product) model is nonlinear, it is converted to a linear model using logarithms. This simplifies the computational implementation, which is presented in Equations (21) and (22).

$$CI_i^{max} = \max \sum_{k=1}^n w_k \ln(x_{ik}) \quad (\text{Best Score}) \quad (21)$$

$$CI_i^{min} = \min \sum_{k=1}^n w_k \ln(x_{ik}) \quad (\text{Worst Score}) \quad (22)$$

Step 4: Aggregation (Weighted Product Method)

After the optimal weights are determined, the normalized indicators are aggregated into a composite index via the weighted product method (see Equation (23)):

$$\text{FSESI}(CI_i) = \prod_{k=1}^n (x_{ik})^{w_k} \quad (23)$$

A higher composite index $\text{FSESI}(CI_i)$ reflects better overall performance in terms of food security and environmental sustainability.

Step 5: Sensitivity Analysis (Robustness Check)

Robustness is tested by varying the control parameter λ to balance food security (FS) and environmental sustainability (ENV subindices):

$$\text{FSESI}(\lambda) = (\text{FS}_i)^\lambda + \text{ENV}_i^{(1-\lambda)} \quad (24)$$

where FSESI is the food security and environmental sustainability index. FS_i and ENV_i are the food security and environmental sustainability subindices (0–1), respectively. λ is the control parameter, which ranges between 0 and 1. If $\lambda = 1$, 100% weight is given to food

security (see Equation (24)). In the case of $\lambda = 0$, 100% weight is given to environmental sustainability. $\Lambda = 0.5$ provides equal balance between both dimensions.

2.4. Data

Data for the period from 2010 to 2022 were taken from the Food and Agriculture Organization of the United Nations, the World Bank, the United Nations Sustainable Development Goals, Our World in Data, and various country-specific sources. For example, we obtained Morocco's data from the Haut Commissariat au Plan or Higher Planning Commission (<https://www.hcp.ma>; accessed on 2 December 2024) in Morocco; for Algeria, the data are available from the Ministry of Environment and Renewable Energy (<https://bawabatic.dz>; accessed on 11 December 2024); for Egypt, data were obtained from the Ministry of Agriculture and Land Reclamation (<https://moa.gov.eg>; accessed on 4 December 2024); for Libya, data were acquired from the National Monitoring Program for Biodiversity (<https://www.rac-spa.org>; accessed on 2 January 2025); Mauritania data are available from the Ministry of Environment and Sustainable Development (<http://www.environnement.gov.mr>; accessed on 22 December 2024); Sudan data are available from the Ministry of Agriculture and Forests (<https://moaf.gov.sd>; accessed on 5 December 2024); and data for Tunisia were collected from the Ministry of Environment and Sustainable Development (<http://www.environnement.gov.tn>; accessed on 10 December 2024).

3. Results

3.1. Nexus of Regional Food Security and Environmental Vulnerability

Before constructing the composite index, we first examined two key indicators, the prevalence of undernourishment and the level of water stress, to contextualize North Africa's food security and environmental sustainability status over 2010–2022. North Africa's current food security status and environmental vulnerability can be understood through a range of indicators that underpin the FSESI. In terms of food security, the region has achieved relatively low levels of undernourishment compared with other parts of Africa, yet hidden vulnerabilities persist Eini-Zinab et al., 2020 [54]. Most North African countries have single-digit undernourishment rates; for example, Tunisia and Algeria report that approximately 3% or less of their population is undernourished Elmighrabi et al., 2023 [55]. These low hunger levels reflect decades of investments in food subsidies, imports, and social programs. Nevertheless, food availability and access remain fragile in the face of shocks. Domestic food production covers only a portion of demand, with staples such as cereals being heavily imported. North African nations are net food importers, making them susceptible to global supply and price fluctuations. When international grain prices spiked or supply chains were disrupted (as seen during the COVID-19 pandemic), the region experienced increased food inflation and pressure on access to food Ben Amara & Qiao, 2024 [56].

North African countries exhibited varied levels of food security, as indicated by the prevalence of undernourishment between 2010 and 2013. Egypt and Libya experienced slight increases from 5.2% to 5.8% and from 6.6% to 7%, respectively, highlighting a mild deterioration in nutritional outcomes. Algeria, Tunisia, and Morocco displayed moderate improvements, with Algeria's undernourishment dropping significantly from 4.1% to 2.9%. Sudan saw a substantial reduction in undernourishment from an alarming 21.8% in 2010 to 9.2% by 2013 Eini-Zinab et al., 2020 [54], whereas Mauritania's levels improved modestly from 7% to 6.2%. From 2014 to 2017, Egypt and Libya showed continued increases in undernourishment, increasing to 6.9% and 8.4%, respectively, indicating increasing food security challenges FAO, 2023 [57]. Algeria and Tunisia remained relatively stable, fluctuating slightly from approximately 2.5% to 3.3%, reflecting consistent progress in managing nutri-

tional deficiencies. Morocco experienced a steady improvement from 4% to 3.5%, indicating modest success in food security policies. Sudan’s situation, however, worsened slightly from 8.8% to 10.5%, whereas Mauritania remained almost unchanged, marginally rising to 6.9% Domguia et al., 2023 [58]. Between 2018 and 2021, Egypt’s undernourishment level rose gradually to 7.6%, suggesting emerging vulnerabilities in food systems, and Libya’s undernourishment level increased notably to 11.9%, reflecting sustained instability. Algeria maintained its robust performance at a consistent 2.5%, whereas Tunisia and Morocco faced an uptick in undernourishment, reaching 3.4% and 6.4%, respectively, by 2021. In Sudan, undernourishment peaked at 11.1% in 2020 but marginally declined to 11% in 2021. The level of Mauritania increased steadily, reaching 8.3% in 2021, highlighting rising nutritional risks. In 2022, Egypt (8.5%), Libya (11.4%), Morocco (6.9%), Sudan (11.4%), and Mauritania (9.3%) experienced higher undernourishment levels, emphasizing urgent policy attention, whereas Algeria (2.5%) and Tunisia (3.2%) sustained lower, stable rates, demonstrating more resilient food security frameworks World Bank, 2023 [59]. These results are illustrated comprehensively in Figure 2.

Food utilization and nutrition indicators reveal a dual burden: while outright hunger is low, malnutrition in other forms is evident. The prevalence of child stunting (chronic malnutrition) in North Africa is approximately 21.4% on average, which is slightly below the global average Elmighrabi et al., 2023 [55]. This finding indicates that approximately one in five children suffers from growth retardation due to nutritional deficiencies, despite the overall number of calories being sufficient. Moreover, rising rates of obesity and overweight, even among young children, point to emerging diet-related health issues. These patterns highlight that food security concerns not only avoiding hunger but also ensuring high-quality nutrition and stability. Food stability in North Africa is challenged by recurrent social, economic, and climatic shocks. Conflict has been a major destabilizer in countries such as Libya, where civil war since 2011 has shattered food distribution systems. The prolonged instability in Libya led to spikes in undernourishment and one of the highest child stunting rates in the Arab region (exceeding 50% in 2022), exemplifying how quickly food security gains can be reversed Joulaei et al., 2021 [60]. Overall, the region’s food status is a mix of measured progress and latent risk; basic food access has improved, but resilience to disruptions remains weak. Low undernourishment rates, defined as rates less than 5%, indicate stable food access in accordance with global targets. In contrast, moderate levels ranging from 5% to 14.9% suggest the presence of emerging risks that necessitate preventive measures. Severe rates of 15–24.9% necessitate an urgent response to mitigate the escalation of hunger, whereas critical thresholds of 25% or higher require immediate assistance to prevent famine. A detailed description of the undernourishment rates is presented in Table 1.

Table 1. Prevalence of undernourishment ranges with color codes and interpretations.

Range	Status	Color Code	Interpretation
<5%	Low / OK	Green 	Considered acceptable, meeting SDG 2 (Zero Hunger) targets. Minimal food insecurity.
5–14.9%	Moderate to serious	Yellow / Orange  / 	Requires attention. Reflects moderate food insecurity, signaling emerging challenges.
15–24.9%	Serious to high	Orange / Red  / 	Significant food insecurity. Urgent interventions needed to prevent worsening conditions.
≥25%	Critical	Red 	Emergency-level undernourishment. Immediate humanitarian action needed.

FAO, 2023 [61].

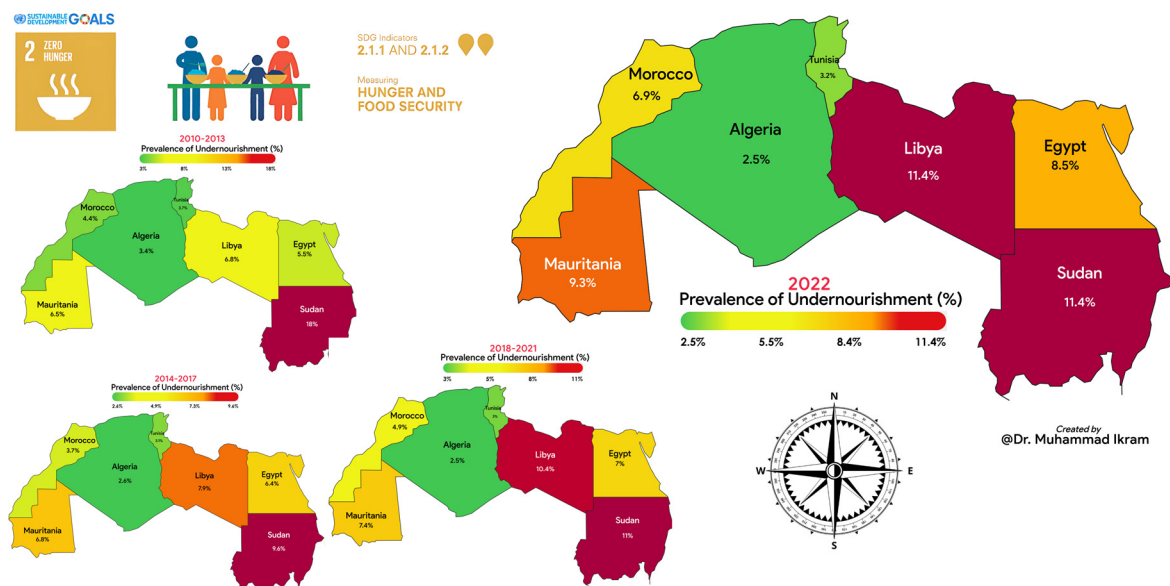


Figure 2. Spatial mapping of the prevalence of the undernourishment rate of North Africa from 2010 to 2022 FAO, 2023 [61].

The environmental vulnerability of North Africa is a critical factor that directly affects its food security prospects. A defining feature of the region is water stress. Water stress, defined as freshwater withdrawal as a percentage of renewable resources, serves as a critical indicator of environmental sustainability. It directly impacts the ecological balance, resilience against climate extremes, and agricultural productivity, making it integral to assessing environmental vulnerability and sustainability in water-scarce regions Salman Abdou & Rajab 2023; United Nations Sustainable Development Goals, 2024 [62,63].

North African countries are collectively among the driest in the world, with MENA having the lowest per capita water availability globally Schilling et al., 2020 [64]. Renewable water resources are not only limited but also unevenly distributed and inefficiently managed. Groundwater overextraction, reservoir siltation, and outdated irrigation practices exacerbate water stress. Agriculture in North Africa consumes a large share of water resources, yet frequent droughts mean that rainfed yields are highly variable. In Morocco, Algeria, and Tunisia, where the Atlas Mountains provide some rainfall, consecutive drought years have sharply reduced crop outputs, necessitating greater food imports. The 2022 drought across the Maghreb, for instance, significantly reduced grain harvests and pasture availability, underscoring the climate vulnerability of the region's food supply Gumus et al., 2024 [65]. In addition to water, land and soil constraints pose additional challenges. Arable land per capita is low, and much of the region's territory is threatened by desertification. Only a narrow band of the North African coast and certain valley areas receive enough rainfall to support dense agriculture; south of that, Sahara encroachment is a constant threat. For example, forest cover is sparse; forest areas constitute approximately 12.9% of land in Morocco but under 5% in Tunisia and are minimal in Egypt and Libya Santoro, 2023 [66]. This limited vegetation contributes to soil erosion and reduces ecosystem services such as watershed protection. North African countries also face environmental pollution and climate change impacts. Rapid urbanization and fossil fuel use (especially in oil- and gas-producing economies) have led to rising carbon emissions; Egypt and Algeria are among Africa's top CO₂ emitters Engo, 2021 [67], although the region's share of global emissions remains relatively small. The greater concern is that North Africa is warming faster than the global average, with more frequent heatwaves and extreme weather events recorded. Coastal areas, including the Nile Delta in Egypt

and low-lying parts of Tunisia and Libya, are increasingly at risk from sea level rise and storm surges. These environmental vulnerabilities of water scarcity, land degradation, and climate extremes directly threaten agricultural productivity and food stability. They also complicate efforts to improve sustainability; for example, the overuse of groundwater for irrigation can secure food production in the short term but is unsustainable in the long term. In summary, North Africa's environmental challenges significantly heighten the risk profile for food security. Therefore, any integrated assessment of the region's food status must account for these vulnerabilities, which the FSESI does by incorporating key environmental indicators alongside food security metrics.

The environmental vulnerability in North Africa measured through freshwater withdrawal as a percentage of total available freshwater resources (SDG Indicator 6.4.2) revealed substantial variation. Between 2010 and 2013, Libya consistently presented the highest levels of water stress, increasing sharply from 783.12% to 817.14%, indicating severe over-exploitation of scarce water resources. Egypt exhibited a moderate decrease from 134.43% to 132.97%, although it was still significantly above sustainable thresholds, highlighting persistent water stress issues. Algeria's water stress steadily increased from 104.92% to 115.16%, demonstrating increasing pressure on water resources. Tunisia experienced an increase from 79.12% to 86.85%, indicating increasing environmental vulnerability. Morocco, Sudan, and Mauritania maintained consistent values of 50.75%, 118.66%, and 13.25%, respectively, over this period, reflecting varying but stable levels of water usage pressure Belhassan, 2023 [68].

From 2014 to 2017, Libya remained severely stressed at a constant 817.14%, emphasizing critical, unsustainable freshwater usage. Egypt initially experienced reduced water stress, which decreased notably to approximately 110.47% by 2016 before spiking sharply back to 141.17% in 2017. Algeria showed a continuous upward trend from 120.58% to 137.92%, highlighting intensified water-related environmental challenges. Tunisia's water stress increased steadily from 89.44% to a peak of 94.61% in 2016 but slightly decreased in 2017 (89.53%). Morocco, Sudan, and Mauritania continue to exhibit stability with unchanged water stress levels, reinforcing the persistent nature of their environmental profiles Mahjoub et al., 2021 [69]. A detailed description of the water stress level is presented in Table 2.

Between 2018 and 2021, Egypt's water stress stabilized at a high level of 141.17%, reflecting persistent pressure and limited improvement. Libya maintained an exceedingly high value of 817.14%, indicating extreme and chronic water vulnerability. Algeria's environmental stress escalated further, reaching a peak of 149.56% in 2020 before slightly dropping to 140.59% in 2021, underscoring significant environmental risk. Tunisia witnessed a gradual rise to 98.11%, highlighting increasing vulnerability and resource constraints. Morocco, Sudan, and Mauritania remained unchanged at 50.75%, 118.66%, and 13.25%, respectively, suggesting consistency in their environmental challenges. In 2022, the environmental vulnerability situation remained critical in Libya (817.14%) and significantly high in Egypt (141.17%) and Algeria (144.81%). Tunisia sustained elevated water stress at 98.11%, indicating that the strain continued to respond. Morocco, Sudan, and Mauritania maintained previous levels (50.75%, 118.66%, and 13.25%, respectively), underscoring the persistent and differing environmental vulnerabilities within the region FAO, 2018 [70]. Figure 3 presents the environmental vulnerability across North African countries from 2010 to 2022.

To capture the complex, multidimensional nature of food security and environmental sustainability in one measure, we adopt a composite index approach. Composite indices combine multiple indicators into a single score, providing an overview of performance across different dimensions. In this case, the FSESI brings together indicators of food

security (covering the availability, access, utilization, and stability of food) and of environmental sustainability (covering resource use, ecosystem health, climate impact, and farming practices). The rationale for using a composite index is to enable a holistic assessment: countries can be ranked and compared in terms of overall progress toward secure and sustainable food systems while also tracking their performance in each subcomponent. This approach aligns with established methodologies in the literature. As recommended by the OECD and other bodies, constructing a composite index involves several steps: defining a conceptual framework, selecting relevant indicators, normalizing data, weighting the indicators, and choosing an aggregation method to compute the index. We ground our methodology in prior work on food security indices (such as *The Economist's* Global Food Security Index, which assesses affordability, availability, quality and safety, and natural resource resilience) and sustainability indices, adapting them to the North African context.

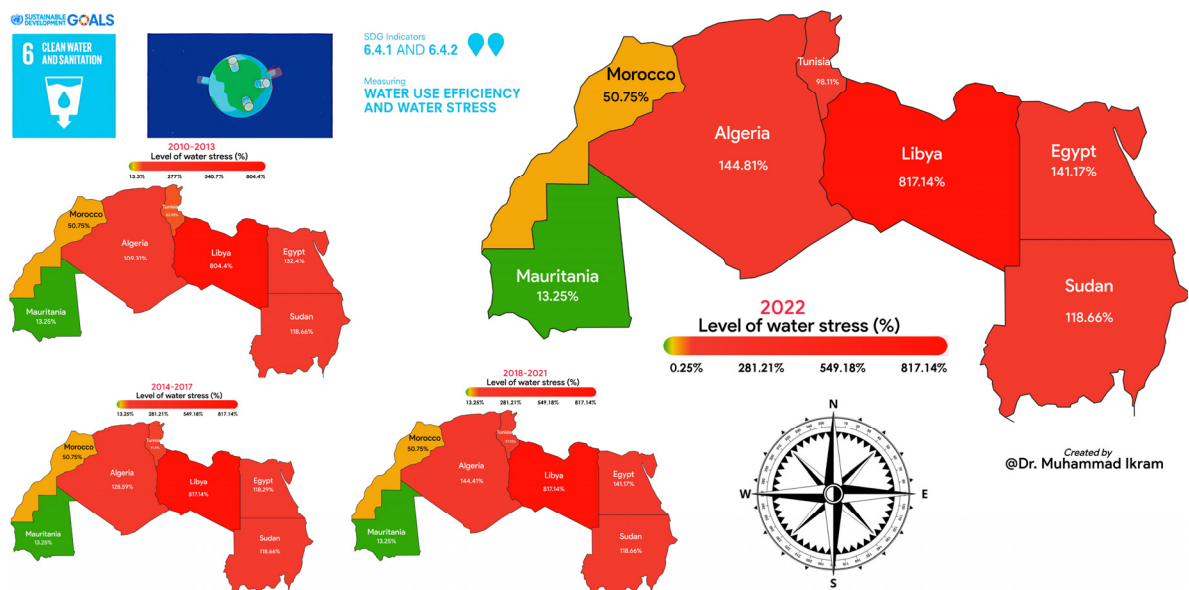


Figure 3. Spatial mapping of the water stress level of North Africa from 2010 to 2022 FAO, 2024 [71].

Table 2. Level of water stress ranges with color codes and interpretations.

Freshwater Withdrawal (%)	Status	Color Code	Interpretation
<25%	Low Stress	Green ●	Sustainable water use. No significant risk to availability.
25–50%	Moderate Stress	Yellow ●	Emerging scarcity; requires improved efficiency and management.
50–75%	High Stress	Orange ●	Severe pressure on water resources; risks to agriculture, industry, and ecosystems.
≥75%	Critical Stress	Red ●	Extreme scarcity: unsustainable use, often relying on nonrenewable reserves (e.g., fossil groundwater).

FAO, 2024 [71].

3.2. Analysis of Subindicators

3.2.1. Food Availability

Food availability in this study is evaluated via two key indicators: cereal production (kg/ha) and per capita food production (kg/person).

As illustrated in Figure 4, Egypt consistently reported the highest cereal yields, increasing from 6504.3 kg/ha in 2010 to 7418.5 kg/ha in 2022, which was largely attributed to its intensive irrigation systems and sustained investment in agricultural inputs. In contrast,

Morocco exhibits considerable fluctuations: yields can exceed 2000 kg/ha during favorable seasons but can decrease to approximately 943.3 kg/ha under severe drought, as observed in 2022. The yields of Algeria, which typically range between 990.3 and 1952 kg/ha, reflect moderate gains tempered by variable rainfall, whereas Tunisia maintains a steadier output of approximately 1640.8 kg/ha in 2022, which is supported by targeted water resource management. Libya, constrained by ongoing conflict, seldom surpasses 700–800 kg/ha, highlighting disruptions to farming inputs and land rehabilitation. Sudan remains below 800 kg/ha in most years, hindered by recurrent environmental shocks and limited infrastructure, whereas Mauritania, despite harsh arid conditions, saw yields increase from 955.2 kg/ha in 2010 to 1720.5 kg/ha in 2022, suggesting incremental improvements.

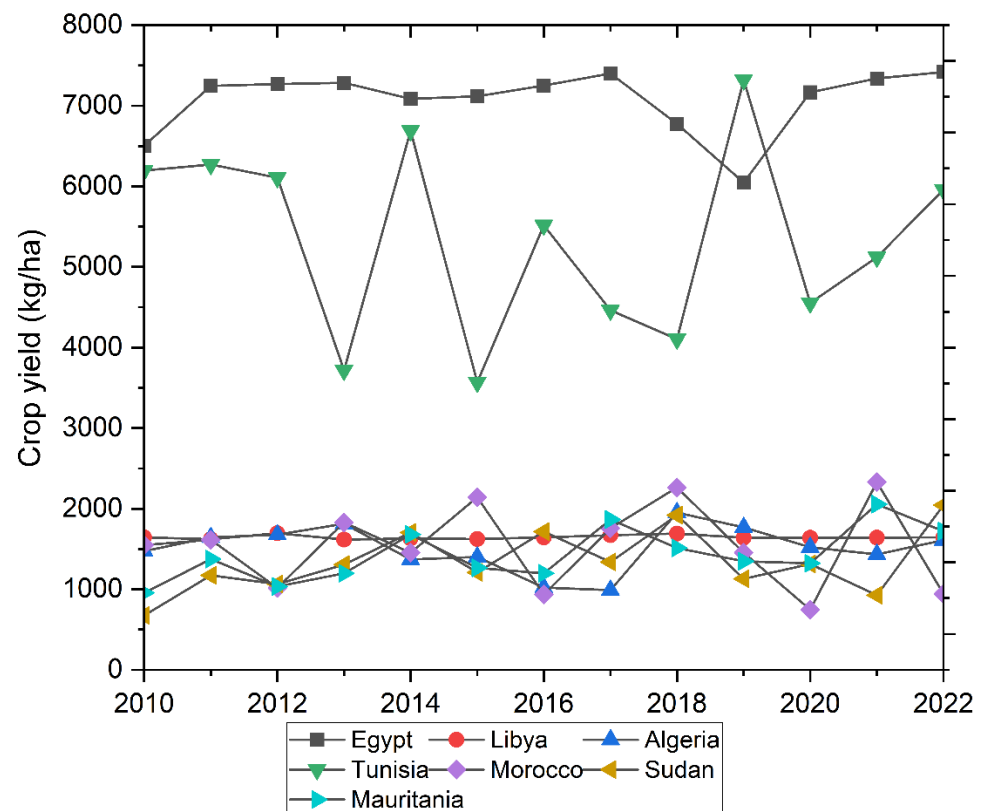


Figure 4. Crop yield (kg/ha) of North Africa from 2010 to 2022 The World Bank, 2025 [72].

Figure 5 depicts per capita food production. Egypt again leads the region with values hovering at approximately 3000 kg/person, although a modest dip from 3219 kg/person in 2010 to 3071 kg/person in 2022 indicates demographic pressures and shifts in production strategies. Libya's per capita figure fluctuates between approximately 3000 and 3100 kg/person, reflecting the toll of political instability on domestic food output. Algeria and Tunisia both trend upward, surpassing 3400 kg/person and 3500 kg/person, respectively, by 2022, suggesting gradual expansions in production capacity relative to population growth. Morocco's per capita availability oscillates near 3300 kg/person, partly mirroring the volatility in cereal yields. Sudan, although improved from 2396 kg/person to 2513 kg/person, still faces persistent resource constraints and rapid population increases. Mauritania, which is consistently under 3000 kg/person, registered 2914 kg/person in 2022, underscoring the impact of limited arable land and reliance on external food sources. These outcomes collectively underscore the uneven nature of food availability across North Africa and highlight the importance of context-specific strategies ranging from drought mitigation measures to infrastructure upgrades that can increase both aggregate yields and per capita supply.

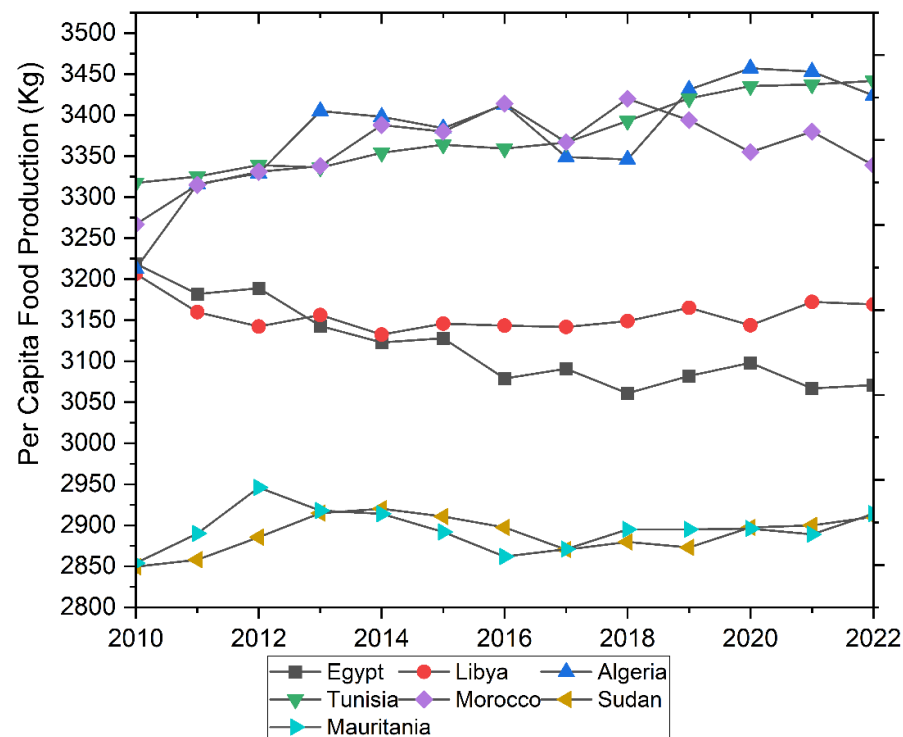


Figure 5. Food production per capita (kg) of North Africa from 2010 to 2022 FAO, 2023 [73].

3.2.2. Access to Food

Figure 6 shows that access to food in this study comprises two main indicators: the percentage of the population unable to afford a healthy diet and the poverty rate (%).

Egypt has experienced a gradual decrease in the proportion of individuals unable to afford a healthy diet, dropping from 58.0% in 2010 to 44.4% in 2022. However, the country's poverty rate remains relatively high, fluctuating between 25.2% and 32.5% over the same period before settling at 28% in 2022. In contrast, Libya experiences a troubling increase in the share of those unable to afford a healthy diet, increasing from 62.0% to 70.0%, coupled with an increase in poverty from 21.6% to 25.8%, reflecting the impacts of prolonged conflict on household purchasing power. Algeria's figures show an overall improvement in affordability from 22.5% to 19.7%, whereas the poverty rate moves from 5.5% in 2010 to 3.9% in 2022, underscoring relatively robust social programs and economic stability. Tunisia records a notable decline in both indicators, with affordability challenges shrinking from 12.0% to 7.3% and poverty receding from 20.5% to 13.7%, indicative of policy efforts to address cost-of-living and unemployment pressures.

Similarly, Morocco reduces affordability issues from 18.0% to 12.7%, whereas poverty remains comparatively low, hovering near 6.2% in 2010 and easing to 5.2% by 2022, suggesting incremental gains in household incomes (see Figure 7). Sudan, on the other hand, exhibited a significant decrease in the inability to afford a healthy diet from 55.0% to 33.7%, yet poverty increased from 46.5% to 66.1%, highlighting that improvements in food costs have not been matched by stable incomes. Mauritania presents a mixed picture, with the share of individuals unable to afford healthy food rising from 46.0% to 55.2%, even as poverty rates decline from 42% to 34.5%, pointing to persistent structural vulnerabilities that limit equitable access to nutritious diets. These findings highlight the region's varied capacity to protect vulnerable populations against income shocks and food price volatility.

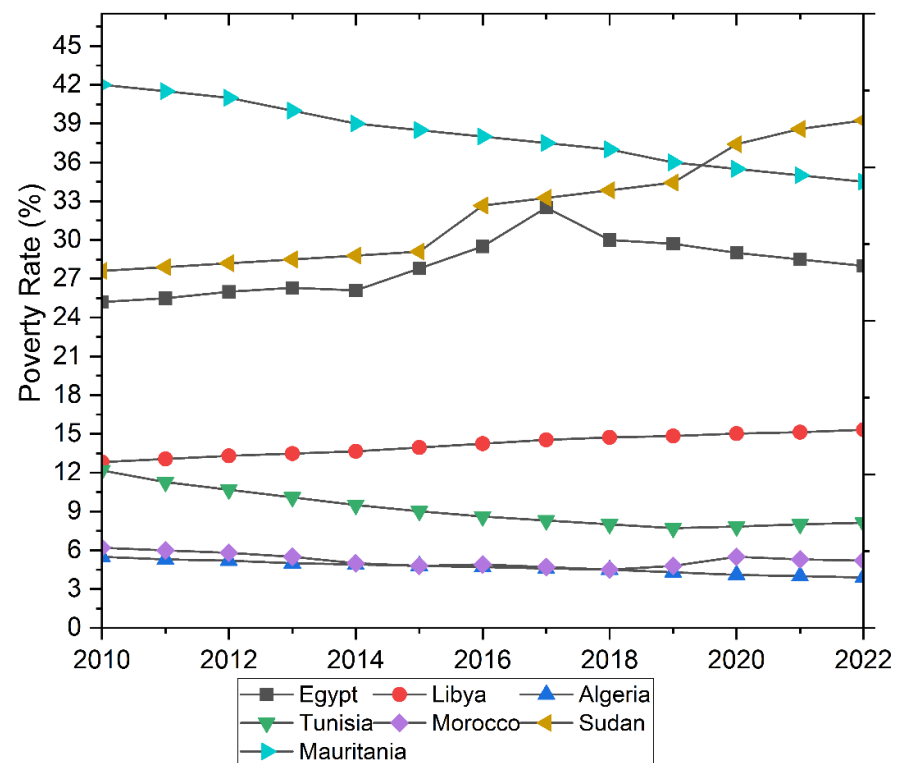


Figure 6. Poverty rates (%) in North Africa from 2010 to 2022 The World Bank, 2024 [74].

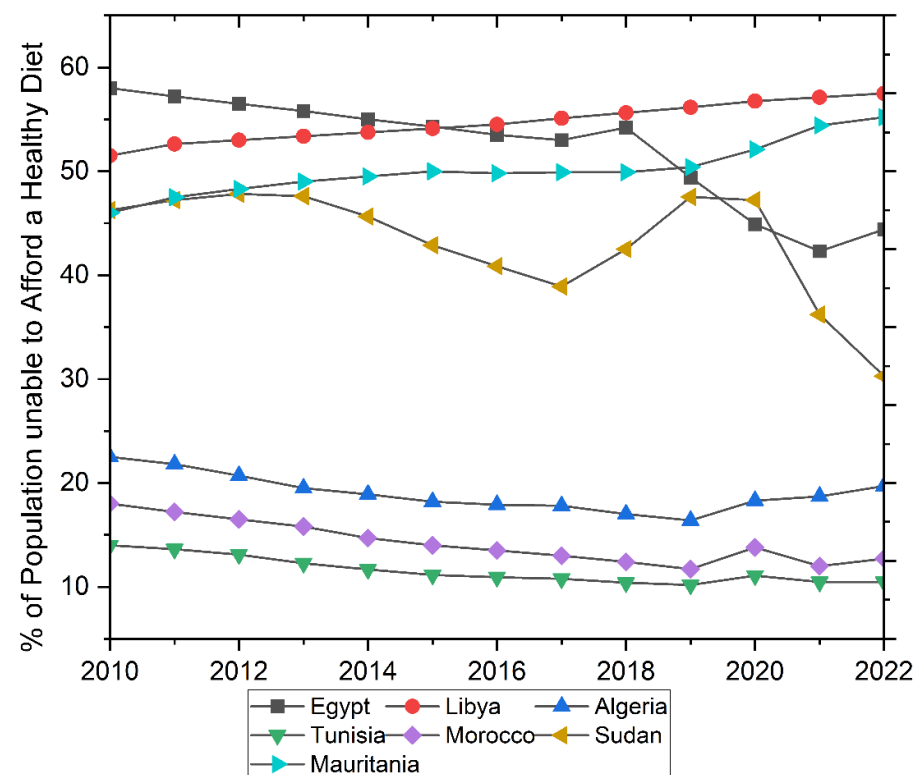


Figure 7. Percentage of population unable to afford a healthy diet in North Africa from 2010 to 2022 Our World in Data, 2024 [75].

3.2.3. Food Utilization

Food utilization in this study is captured through two indicators: the prevalence of undernourishment (PoU) and access to clean water (%).

As shown in Figure 8, Egypt's PoU increased from 5.2% in 2010 to 8.5% in 2022, indicating a reversal in nutritional outcomes despite overall food availability. Libya's PoU rose from 6.6% to 11.4% over the same period, reflecting the impact of ongoing conflict on food access and distribution. Algeria demonstrated steady improvement, with PoU declining from 4.1% to 2.5%, signifying effective nutritional interventions. Tunisia's PoU remained relatively stable, shifting marginally from 3.7% to 3.2%, while Morocco saw an increase from 4.8% to 6.9%, highlighting emerging undernourishment concerns despite other gains. Sudan recorded the highest PoU in the region, rising from 8.9% to 11.4%, and Mauritania's PoU increased from 7.0% to 9.3%, underscoring persistent nutritional challenges across the region.

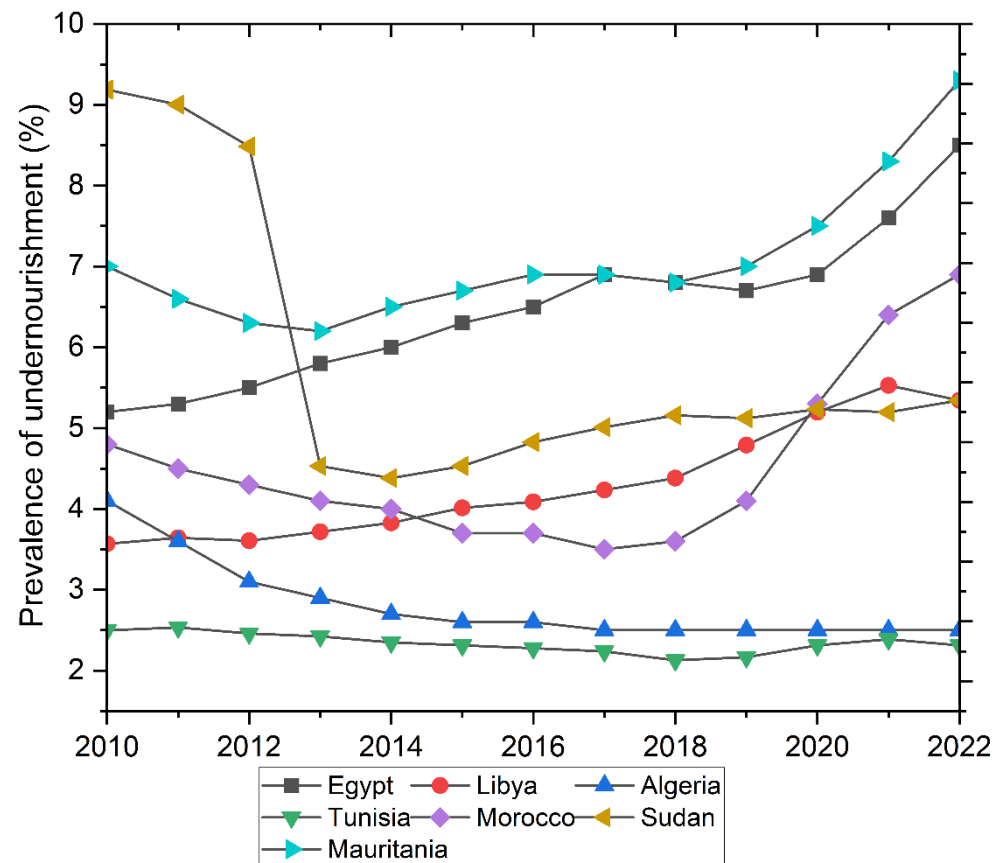


Figure 8. Prevalence of undernourishment (PoU) in North Africa from 2010 to 2022 FAO, 2023 [76].

Figure 9 illustrates that Egypt's access to safe drinking water remained nearly universal at 99% throughout 2010–2022, indicating strong infrastructure but limited translation into improved nutritional status. Libya's water access improved modestly from 54.9% to 58.5%, though conflict-related damage hindered broader coverage. Algeria experienced a rise in water access from 75.1% to 79.1%, reflecting incremental infrastructure gains. Tunisia's clean water coverage increased from 93.0% to 95.4%, while Morocco expanded access from 78.0% to 81.6%, demonstrating moderate progress. Sudan's water access rose from 55.0% to 58.6%, and Mauritania's from 52.1% to 56.9%, pointing to gradual improvements in service delivery amid challenging contexts.

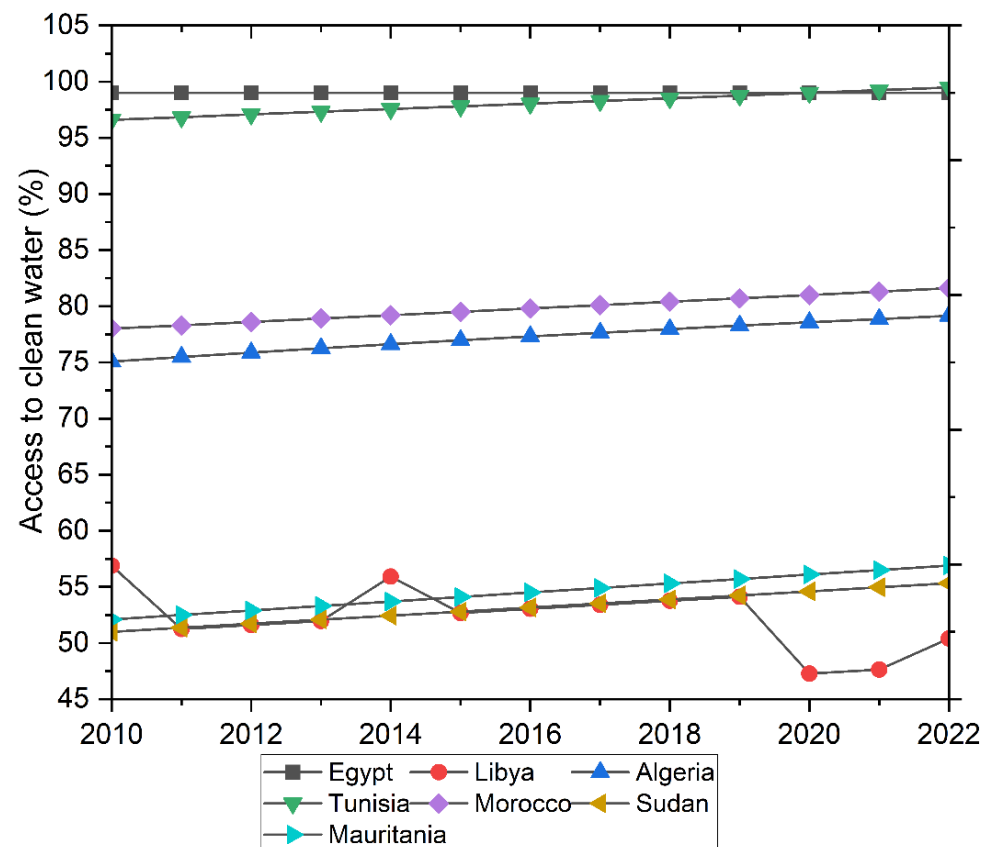


Figure 9. Access to water (%) in North Africa from 2010 to 2022 FAO, 2023 [77].

3.2.4. Stability

Food stability in this study is evaluated through the food price volatility index (FPVI), which reflects year-to-year fluctuations in staple food prices. Figure 10 shows that Sudan records some of the most pronounced volatility, surging from 16.12% in 2010 to over 100% in 2020, underscoring the impact of recurrent political and economic crises on market stability. Egypt's FPVI initially hovered at approximately 19.85% in 2010, decreased to less than 10% by 2012–2013, then spiked to 37.88% in 2017, and finally settled at 25.38% in 2022, indicating cyclical fluctuations tied to currency shifts and broader economic reforms. Libya experienced moderate to high volatility swings, ranging from as low as 0.04% in 2020 to 34.54% in 2017, reflecting the influence of ongoing conflict on supply chain disruptions. Algeria's FPVI mostly remains under 6%, except for a peak of 11.23% in 2012 and a notable increase to 13.24% in 2022, highlighting occasional market shocks. Tunisia fluctuates between approximately 3% and 7% but climbs to 11.4% in 2022, indicating renewed pressure on food costs. Morocco's index is relatively low, occasionally decreasing below zero (e.g., 0.83% in 2019) but increasing to 12.56% by 2022, suggesting heightened sensitivity to external price movements. Mauritania's volatility mostly remains modest, approximately 2–6% for much of the period, yet jumps to 15.38% in 2022, reflecting emerging market disruptions. Overall, these figures emphasize that while certain countries maintain relatively stable food prices, sudden economic or climatic shocks can trigger substantial volatility, posing challenges to food security and requiring responsive policy measures.

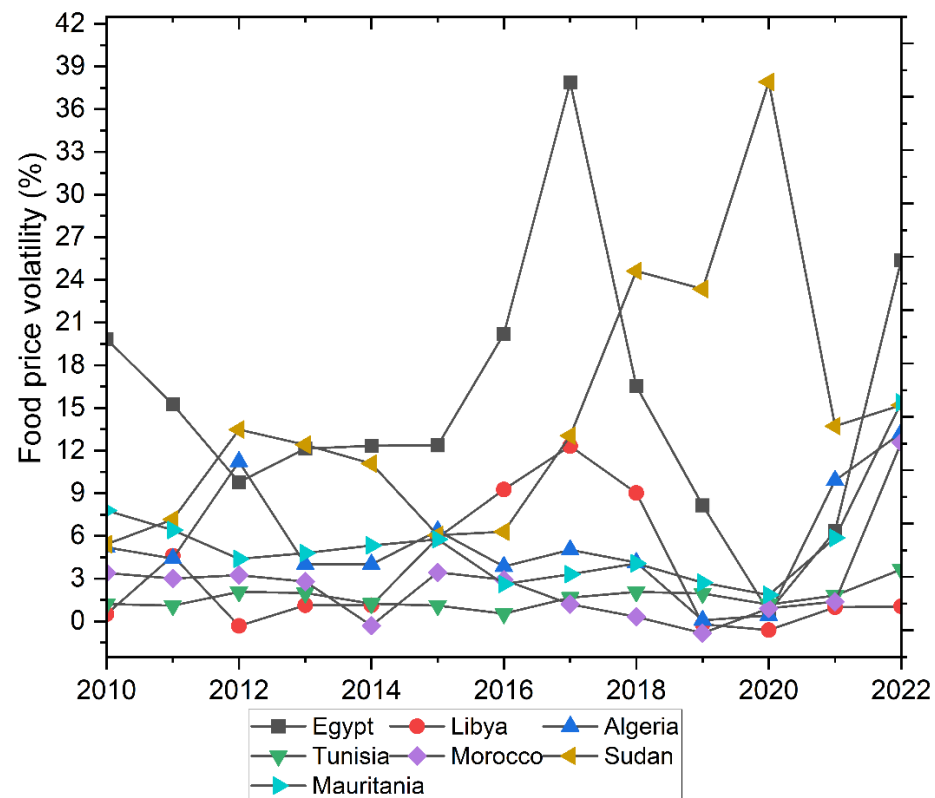


Figure 10. Food price volatility index (FPVI) of North Africa from 2010 to 2022 FAO, 2024 [78].

3.3. Environmental Sustainability Indicator Analysis

3.3.1. Resource Efficiency

Water use efficiency and fertilizer use efficiency are used to assess resource efficiency. As presented in Figure 11, Egypt's water use efficiency began at 116.52 in 2010 and then stabilized near 106.70 from 2017 onward, reflecting moderate refinements in irrigation methods over time. Libya consistently reported higher water use efficiency values, exceeding 650, underscoring an unconventional balance between limited arable land and substantial water extraction for agriculture. Algeria shows a steady increase, increasing from approximately 40.45 to 57.18 by 2022, suggesting incremental improvements in water resource management. Tunisia remains static at approximately 31.57 throughout the period, suggesting stable but modest water efficiency gains. Morocco hovered near 68.55, indicating relatively consistent irrigation practices with little reported change, whereas Sudan's low water use efficiency, averaging just above 10, reflected chronic underinvestment and infrastructural gaps in water delivery systems. Mauritania transitioned from approximately 56.63 in 2010 to approximately 58–64 in the middle of the decade before settling near 58.72, signifying limited but ongoing adaptations to water-scarce conditions.

Figure 12 depicts fertilizer use efficiency in Egypt, with values ranging from 0.010591 in 2010 to approximately 0.085424 by 2022, underscoring periodic spikes in input usage that raise questions about sustainability. Libya fluctuates approximately from 0.003 to 0.005, indicating a comparatively low reliance on chemical fertilizers. Algeria's fertilizer use efficiency increases from 0.010247 to 0.037687, suggesting the progressive optimization of fertilizer application. Tunisia, with values between 0.19 and 0.29, consistently records some of the region's highest fertilizer use efficiency, suggesting a deliberate push toward more efficient nutrient management. Morocco shows modest changes, generally below 0.006, implying relatively cautious fertilizer practices. Sudan's fertilizer use efficiency surges notably from 0.008764 to 0.071002 by 2022, indicating a shift toward intensification but raising concerns about potential environmental trade-offs. Mauritania demonstrates moderate

variability, peaking at 0.023098 in 2020 and then decreasing to 0.016761 in 2022, reflecting fluctuating fertilizer availability and evolving agronomic practices. Overall, these findings highlight that while several North African countries have made strides in resource efficiency, uneven progress persists, emphasizing the need for region-specific strategies that address both water and soil management. These differences highlight the need for targeted resource management that aligns with local agroecological realities and sustainable growth objectives.

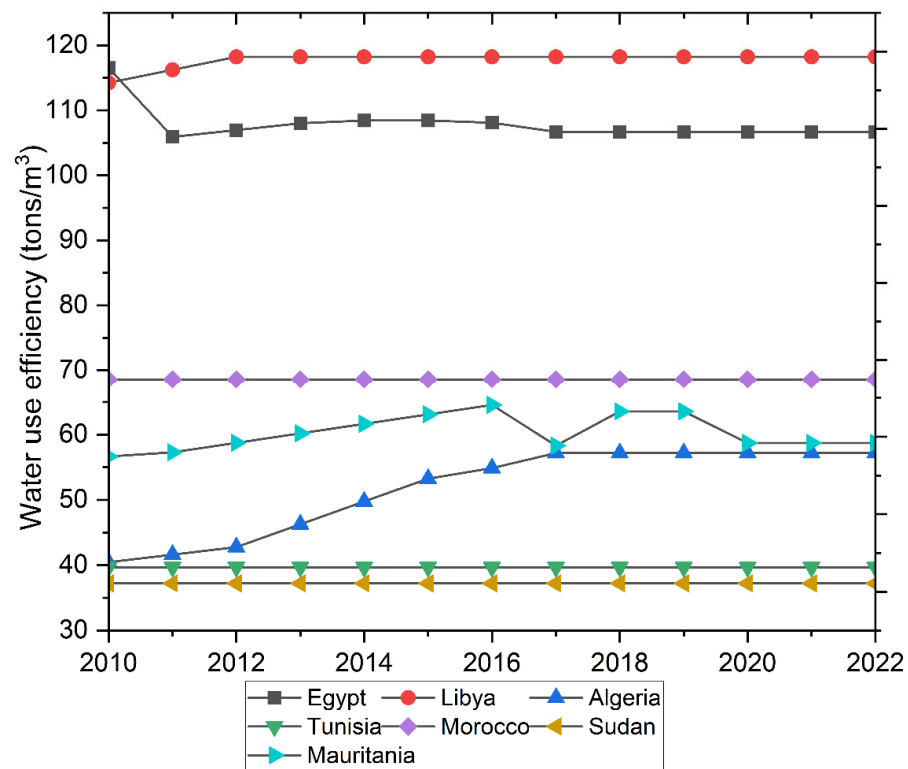


Figure 11. Water use efficiency (tons·m³) of North Africa from 2010 to 2022 United Nations, 2024 [79].

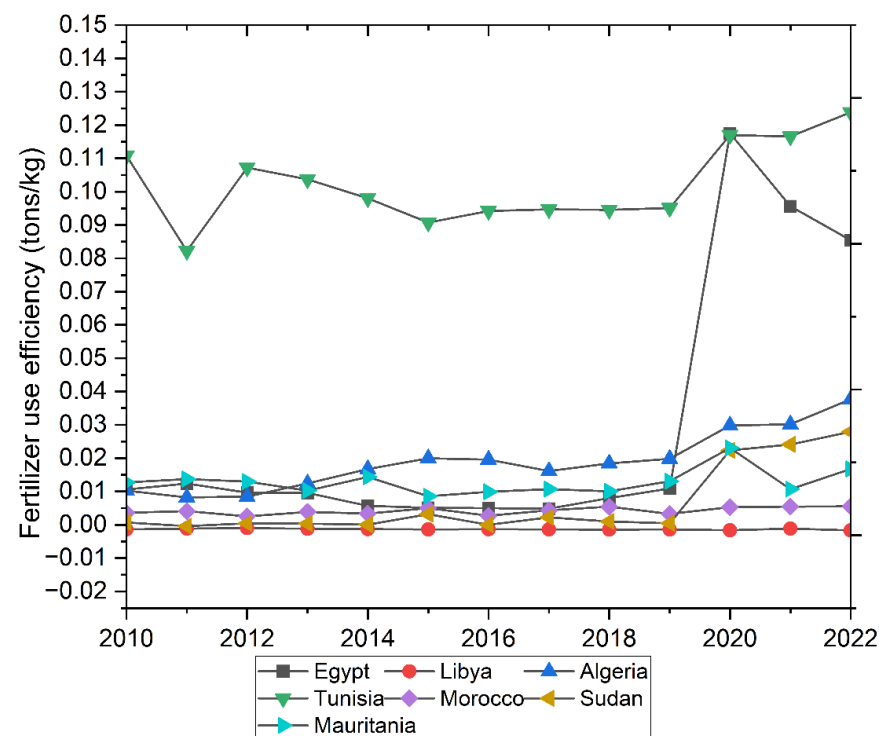


Figure 12. Fertilizer use efficiency (tons/kg) of North Africa from 2010 to 2022 The World Bank, 2024 [80].

3.3.2. Ecosystem Health

Ecosystem health in this study was examined via the SOC percentage and biodiversity index.

As illustrated in Figure 13, Egypt's SOC steadily rises from 1.8% in 2010 to 2.4% in 2022, reflecting improved land management and soil conservation practices. In contrast, Libya's SOC declines from 0.9% to 0.5% over the same period, signaling potential soil degradation exacerbated by conflict-related disruptions. Algeria and Tunisia both record moderate gains. Algeria increases from 1.2% to 1.8%, and Tunisia from 1.4% to 2.0%, indicating shifts toward more sustainable farming methods. Morocco experiences a steady rise from 1.6% to 2.2%, while Sudan's SOC falls from 0.7% to 0.4%, underscoring ongoing challenges in curbing land degradation. Mauritania's SOC also decreases, from 0.5% to 0.2%, highlighting the difficulty of maintaining soil fertility under arid conditions.

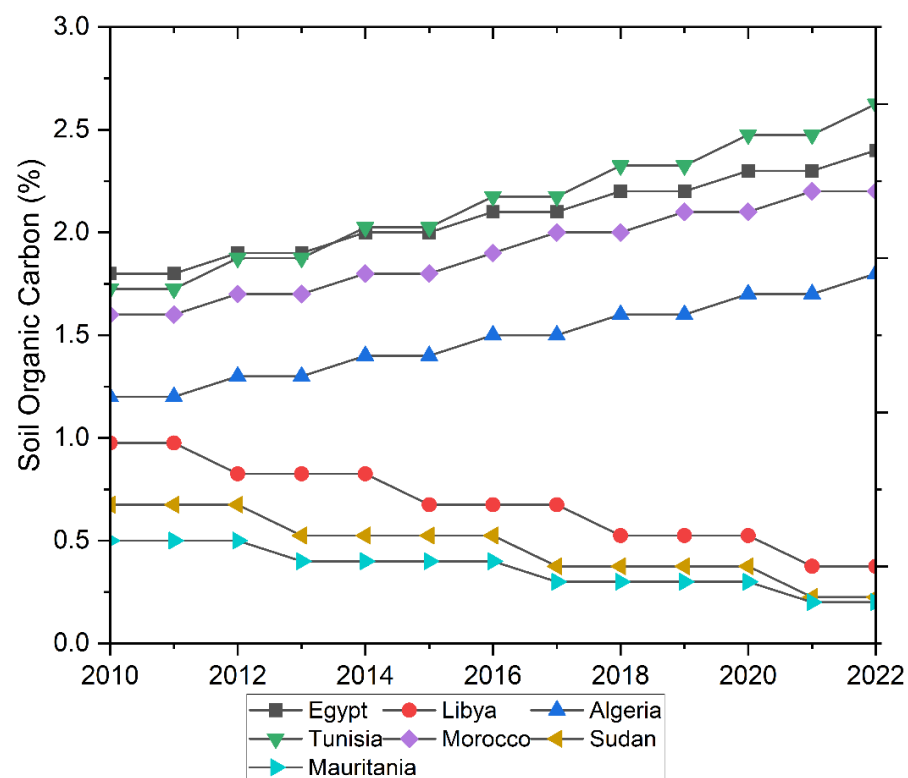


Figure 13. Soil organic carbon (%) in North Africa from 2010 to 2022 FAO, 2024 [81].

Figure 14 shows that Morocco leads the region in agrobiodiversity, with its index climbing from 0.45 in 2010 to 0.57 in 2022, suggesting successful conservation and habitat protection efforts. Tunisia's biodiversity index improves from 0.35 to 0.47, and Algeria's from 0.32 to 0.44, reflecting incremental gains in ecosystem management. Egypt records a rise from 0.28 to 0.40, indicating gradual improvements in habitat preservation. Conversely, Libya experiences a sharp decline from 0.18 to 0.06, and Sudan from 0.22 to 0.10, pointing to significant environmental pressures and governance gaps. Mauritania's index drops from 0.15 to 0.03, reflecting pronounced stress on its fragile ecosystems. These divergent trajectories underscore the need for tailored regional interventions to strengthen ecological resilience.

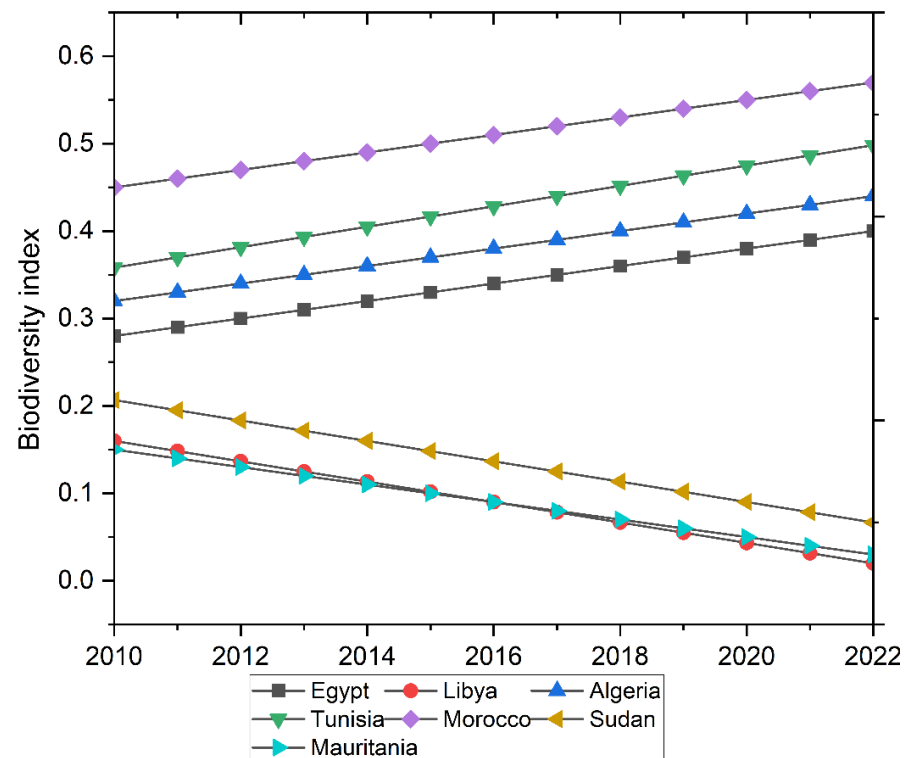


Figure 14. Biodiversity index values of North Africa from 2010 to 2022 GBIF, 2024 [82].

3.3.3. Climate Impact

The climate impact dimension is analyzed via two metrics: GHG emissions from agriculture (in kilotons) and the food loss/waste rate (%). Figure 15 shows that Egypt reported significant fluctuations in agricultural GHG emissions, ranging from approximately 7693.15 Kt in 2013 to 11,855.76 Kt in 2012, eventually settling near 7114.44 Kt in 2022. Libya's emissions remain below 1600 Kt except for a few minor peaks, with values stabilizing near 905.76 Kt in recent years, likely reflecting limited agricultural intensification amid ongoing unrest. Algeria exhibited a steady increase from approximately 966.39 Kt in 2010 to 2156.51 Kt by 2022, suggesting a more substantial expansion of agricultural activities or livestock rearing. Tunisia's emissions fluctuate between 1500 and 2000 Kt, ending at 1942.03 Kt in 2022, which is indicative of moderate intensification and changes in farming practices. Morocco experiences a generally increasing trend, hovering at approximately 4419.17 Kt in 2010 and reaching 5563.88 Kt in 2022, indicating a gradual increase in fossil fuel-based inputs or livestock operations. Sudan's emissions remain the highest in the region, climbing from approximately 23,690.10 Kt to 24,590.32 Kt over the period, reflecting large-scale agricultural expansion and livestock population growth. However, Mauritania's emissions also increase on a smaller absolute scale, from 1000.62 Kt to 1151.69 Kt, reflecting incremental intensification.

Figure 16 shows the food loss/waste rates reported by Morocco, Algeria, and Tunisia, which range from approximately 12 to 18%, with modest year-to-year changes. Egypt demonstrated significant volatility, increasing from 12.5% in 2010 to 35.5% in 2013 and then levelling near 24% by 2022. Libya shows a gradual decline in food waste, from 7.5% to 5.7%, possibly due to altered consumption patterns and reduced import volumes. Tunisia experiences a marked drop from 18.0% to 6.5% by 2022, underscoring improvements in supply chain management and consumer awareness. Algeria, while maintaining rates of approximately 13–14%, experienced minor fluctuations over the decade. Sudan and Mauritania both report relatively stable, low waste levels at approximately 2.95–2.97%, suggesting either limited surplus or persistent market constraints. Overall, these indicators

highlight distinct trajectories across North Africa, with some countries successfully mitigating food losses while others grapple with rising emissions and inefficiencies, underscoring the need for integrated strategies that reduce the environmental footprint of agriculture and strengthen food systems.

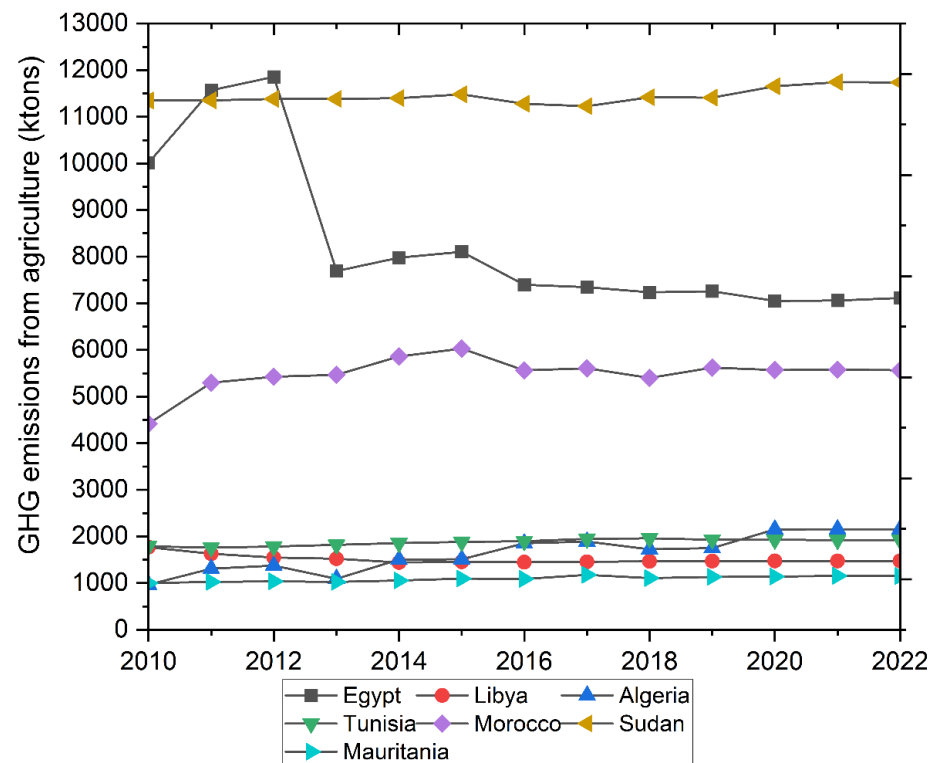


Figure 15. GHG emissions from agriculture (Ktons) in North Africa from 2010 to 2022 FAO, 2024 [83].

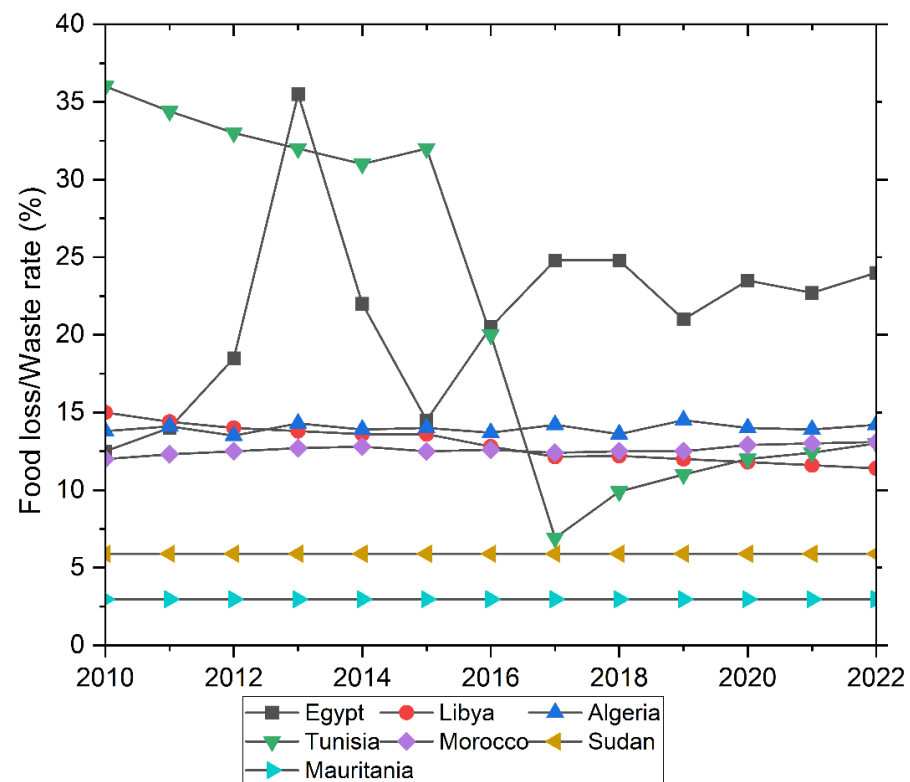


Figure 16. Food loss/waste rates (%) in North Africa from 2010 to 2022 FAO, 2024 [84].

3.3.4. Sustainable Practices

We assessed sustainable practices via two indicators: farmland under organic agriculture (as a percentage of total agricultural land) and the agroforestry adoption rate (%).

As depicted in Figure 17, Egypt begins with minimal organic farmland (approximately 0.001% in 2010), which experienced a dramatic increase of only 29.577% in 2018 before stabilizing at approximately 28–29% in subsequent years, suggesting that a mix of data outliers or experimental programs rapidly scaled and then adjusted. Libya remains virtually unchanged at 0.001% throughout, reflecting the limited uptake of organic methods amid ongoing instability. Algeria also hovered near 0.0019%, indicating marginal organic cultivation efforts. Tunisia shows a more pronounced rise, reaching 0.0284% by 2017 and then surging to approximately 28–30% in the late 2010s, indicating a possible policy-driven expansion of organic initiatives. Morocco remains below 0.07% until 2018, when it briefly spikes to 0.0683% before settling near 0.032–0.065%, reflecting pilot programs and market-driven demand. Sudan fluctuates between 0.001% and 0.0266% early on and then oscillates at approximately 0.06–0.08%, illustrating incremental but uneven progress in transitioning to organic systems. The abundance of Mauritania remains negligible, at or below 0.004% in most years, underscoring significant structural challenges in the adoption of organic standards.

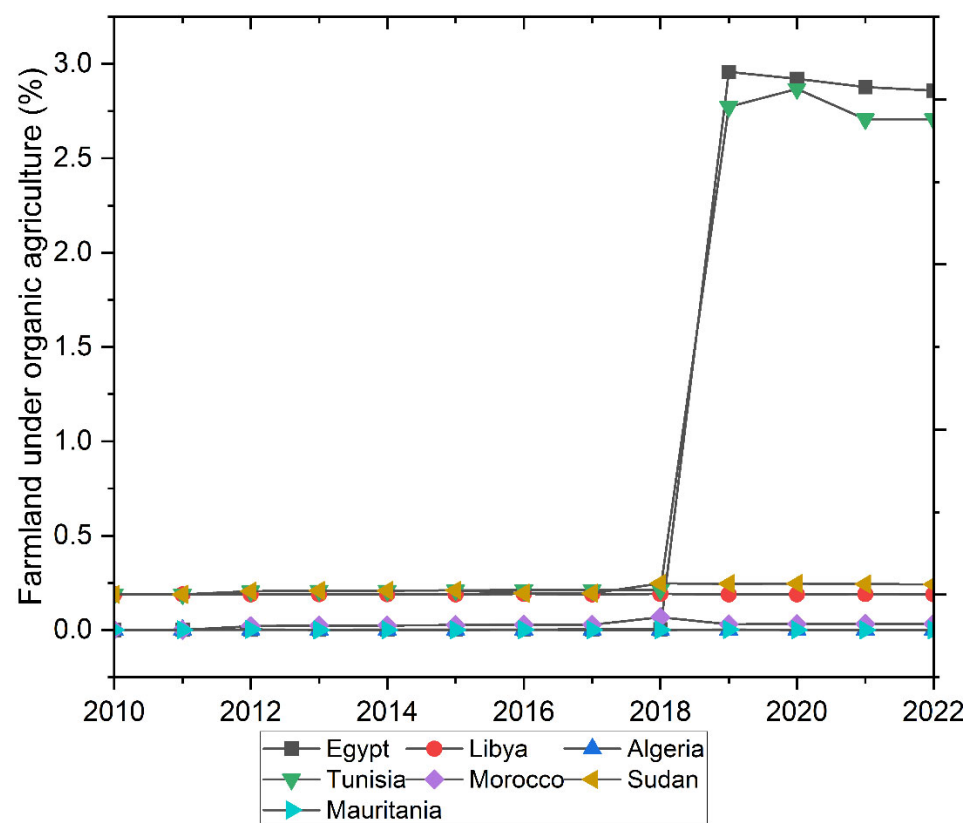


Figure 17. Farmland under organic agriculture (%) in North Africa from 2010 to 2022 Our World In Data, 2023 [85].

Moreover, agroforestry adoption is presented in Figure 18. Morocco has the highest rates, starting at approximately 127.147% in 2010 and increasing gradually to 129.137% by 2022, possibly reflecting a blend of traditional oasis systems and newly promoted agroforestry schemes. Tunisia's rates also remain substantial, hovering near 44–45% throughout the period, although they briefly dip to 4.474% in 2015, implying data anomalies or policy shifts. Algeria's adoption rate consistently remains between 0.80% and 0.82%, whereas

Libya's adoption rate remains fixed at 0.1233%, indicating minimal expansion of tree-based agricultural systems. Egypt shows a steady decline from 0.0659% to 0.0452%, suggesting that tree integration in croplands might be losing ground or facing reporting inconsistencies. Sudan fluctuates between approximately 100 and 105% early on and ends at 96.441% in 2022, indicating a partial contraction of tree-crop–livestock integration over time. Mauritania's rate decreases from 0.3563% in 2010 to 0.2929% by 2022, reflecting limited land suitability and ongoing resource constraints. Overall, these figures demonstrate a patchwork of sustainable practice adoption across North Africa, highlighting stark differences in policy support, market incentives, and agroecological conditions. These approaches underscore each nation's ongoing efforts to harmonize economic viability with environmental stewardship, although substantial opportunities remain for scaling up sustainable agriculture.

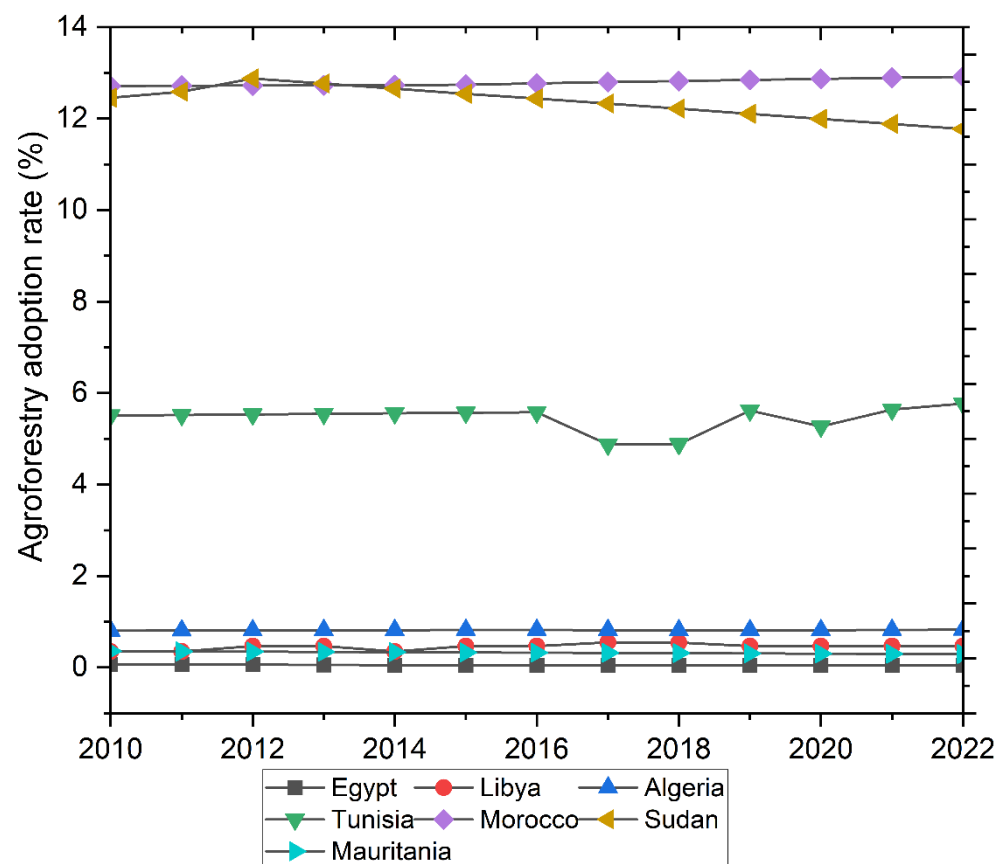


Figure 18. Agroforestry adoption rates (%) of North Africa from 2010 to 2022 Our World In Data, 2023 [86].

3.4. Overall FSESI Score

After normalizing, weighting, and aggregating all the indicators into their respective subindices, we computed the FSESI for each country from 2010 to 2022, as presented in Figure 19. There was notable variation across North Africa. In 2010, Morocco recorded the highest FSESI value (0.78), reflecting strong performance in both the food security and environmental dimensions, whereas the values for Algeria and Libya each reached 0.48, indicating relatively modest outcomes. Over time, some countries experienced substantial fluctuations: Egypt climbed from 0.55 in 2010 to 0.88 in 2021 before slightly receding to 0.83 in 2022, suggesting episodes of rapid improvement interspersed with moderate setbacks. Tunisia peaked at 0.80 in 2014, dipped in subsequent years, and then rebounded to 0.81 by 2022, underscoring the interplay of agricultural, economic, and ecological factors.

Libya showed a steady upward trajectory, peaking at 0.81 in 2022, reflecting a gradual recovery in certain sectors despite ongoing challenges. Algeria rose from 0.48 to a peak of 0.85 in 2018 and then stabilized near 0.77 by 2022, suggesting that incremental gains were tempered by persistent resource constraints. Sudan fluctuated widely, from 0.62 in 2010 to a high value of 0.83 in 2014, followed by dips and partial recoveries, reaching 0.53 in 2022. Mauritania ranged between 0.45 and 0.84, ending at 0.55, a sign of intermittent progress yet enduring vulnerabilities. Overall, these final FSESI scores confirm that while certain countries, such as Morocco, Tunisia, and Egypt, have demonstrated a stronger balance between food security and environmental stewardship, others continue to face structural impediments. The observed volatility underscores the importance of sustained policy support, robust data collection, and context-specific strategies to reinforce both pillars of the index.

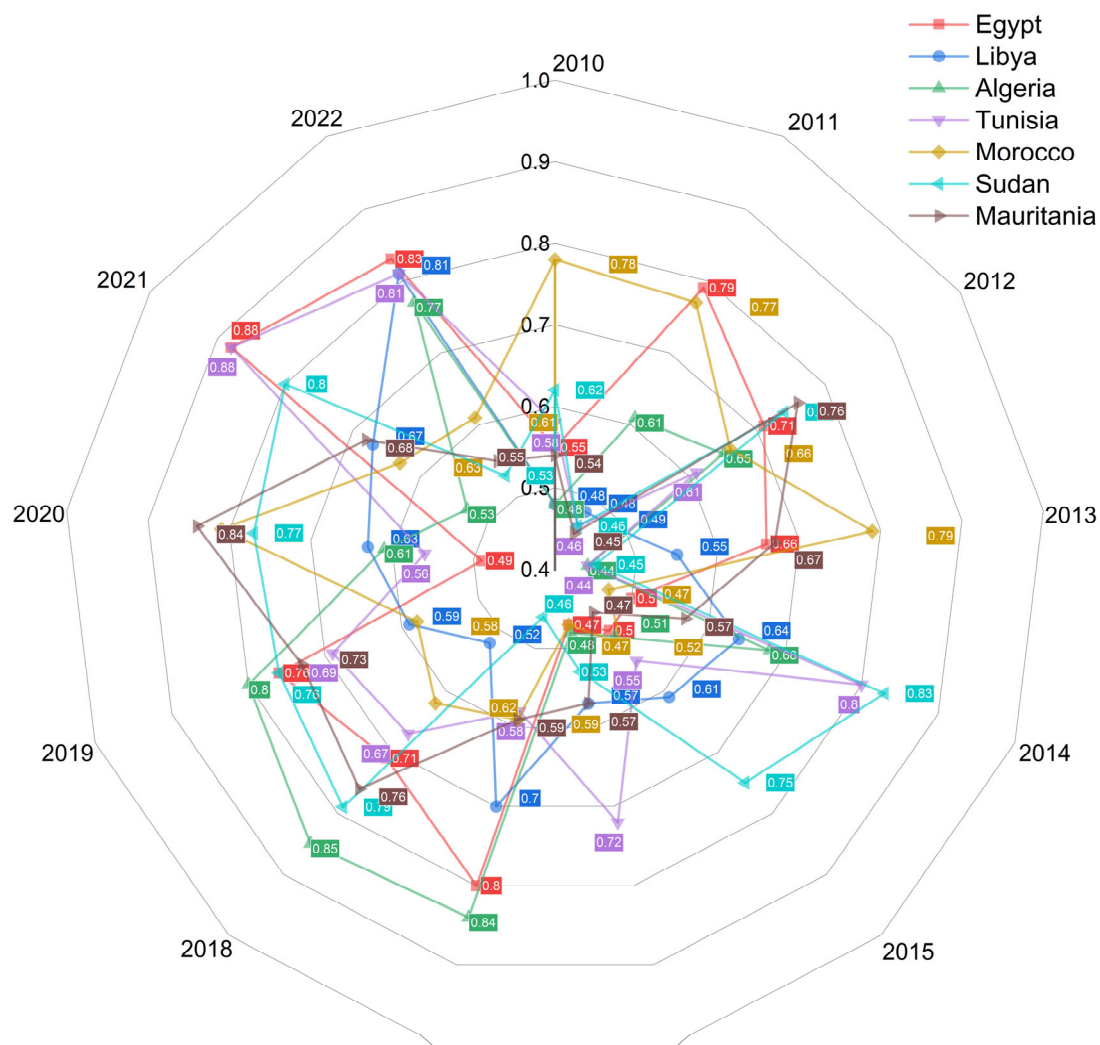


Figure 19. FSESI overall scores of North Africa from 2010 to 2022 (author's own drawing).

These results highlight the trade-offs between food security and environmental factors. For example, Sudan's heavy reliance on traditional biomass gives it a sustainability edge (low fossil CO₂), but its food insecurity undermines the overall index. Conversely, Algeria's oil-fueled economy hurts sustainability metrics despite good food security, keeping its FSESI moderate. Countries that balanced both dimensions (Tunisia, Morocco) achieved the highest composite scores.

The composite FSESI results reveal notable differences among North African countries and meaningful trends over the 13-year study period. Figure 18 illustrates the FSESI scores of North African countries from 2010 to 2022 (DEA-based index, normalized from 0 to 1). In 2010, Morocco had a moderate FSESI score (~ 0.60 on the 0–1 scale), leading slightly among the five countries, followed closely by Tunisia (~ 0.58). Algeria and Egypt trailed with scores in the 0.45–0.55 range, and Libya was lowest (~ 0.40), reflecting the initial impacts of its instability on food and environment systems. By 2022, Morocco’s FSESI had improved to about 0.75, remaining the highest in the group, and Tunisia’s score also rose to ~ 0.70 . These improvements can be attributed to concerted efforts in those countries to enhance agricultural productivity e.g., Morocco’s Green Morocco Plan, and manage resources better, alongside relatively stable economic conditions. Egypt showed a mild upward trend in FSESI (from ~ 0.50 to ~ 0.60), thanks to gains in food production and large-scale projects to expand agricultural land, though its progress was dampened by very high water stress and population growth diluting per capita food gains. Algeria’s FSESI remained roughly stagnant around 0.50–0.55 for much of the period, indicating that improvements in some indicators (like diet affordability due to subsidies) were offset by declines in others (such as water availability per capita and land degradation issues). Libya’s FSESI, after dropping sharply in the early 2010s due to conflict (reaching a low near 0.35), recovered somewhat to ~ 0.50 by 2022, but its trajectory was erratic, mirroring its political turmoil and subsequent partial recovery in agricultural capacity.

3.5. Sensitivity Analysis

To evaluate the robustness of the composite index, we conducted a sensitivity analysis by varying the control parameter λ from 0.1 to 0.9 (in increments of 0.1). The sensitivity was evaluated by systematically recalculating the composite index through an iterative process of omitting each subindicator one at a time and observing the stability of the resulting scores and rankings. Additionally, we assessed variations by uniformly adjusting the weights assigned to subindicators to evaluate the index’s resilience against potential weighting biases. The results indicated that the FSESI scores and rankings remained stable, demonstrating robustness across varying subindicator combinations and weighting schemes. This comprehensive sensitivity analysis confirms the reliability and validity of the FSESI as a balanced measure of food security and environmental sustainability.

Recall that $\lambda = 1$ weights the food security subindex exclusively, whereas $\lambda = 0$ emphasizes the environmental sustainability subindex. Table 3 shows how the overall index responds to these shifts in emphasis for each year. For example, in 2010, the FSESI values ranged from 0.60 (at $\lambda = 0.1$) to 0.62 (at $\lambda = 0.2$ and $\lambda = 0.8$) and then decreased to 0.56 (at $\lambda = 0.9$), indicating that although there were slight variations, the overall ranking for that year remained largely consistent (see Figure 20). Similarly, 2018 demonstrated a moderate swing between 0.66 and 0.75 but did not drastically alter the position of countries relative to one another. Tunisia, Morocco, Algeria, and Egypt consistently remain the top four countries regardless of λ . For instance, at $\lambda = 0.1$ (more pessimistic), the rank order (best to worst) is Tunisia > Morocco > Algeria > Egypt > Libya > Mauritania > Sudan. At $\lambda = 0.5$ (the baseline case), the ordering is the same except that Mauritania slightly edges out Sudan. At $\lambda = 0.9$ (more optimistic), the top four are unchanged, but we observe a subtle swap in the bottom ranks: Tunisia > Morocco > Algeria > Egypt > Mauritania > Sudan > Libya. In other words, under a very high λ , Mauritania (which struggles in many areas but has a relative strength in some environments) improves its composite score enough to overtake Sudan and even Libya, whereas Libya falls to the last rank when less weight is placed on its strong points. These outcomes underscore that no single indicator or subindex dominates the final FSESI score under reasonable weight adjustments, validating

the balance between the FS and ENV dimensions. The geometric mean aggregation further constrains compensability: a country performing poorly in one dimension cannot fully offset that weakness by excelling in another. The stability of the FSESI values across different λ values corroborates the even-handed weighting approach, reinforcing that both food security and environmental sustainability are indispensable for robust overall performance. Overall, the stability of rankings under different λ values strengthens confidence in the FSESI results and justifies the use of $\lambda = 0.5$ for reporting purposes.

Table 3. Sensitivity results of the FSESI.

Year	$\lambda = 0.1$	$\lambda = 0.2$	$\lambda = 0.3$	$\lambda = 0.4$	$\lambda = 0.5$	$\lambda = 0.6$	$\lambda = 0.7$	$\lambda = 0.8$	$\lambda = 0.9$
2010	0.6	0.62	0.54	0.57	0.56	0.59	0.58	0.62	0.56
2011	0.6	0.55	0.61	0.55	0.55	0.6	0.59	0.61	0.6
2012	0.67	0.65	0.66	0.62	0.61	0.63	0.61	0.64	0.7
2013	0.6	0.6	0.6	0.56	0.58	0.59	0.57	0.59	0.61
2014	0.64	0.61	0.68	0.69	0.64	0.63	0.61	0.67	0.67
2015	0.56	0.52	0.54	0.54	0.51	0.57	0.57	0.56	0.57
2016	0.54	0.52	0.51	0.55	0.52	0.56	0.51	0.55	0.5
2017	0.6	0.62	0.62	0.67	0.69	0.66	0.67	0.63	0.62
2018	0.66	0.75	0.7	0.69	0.68	0.66	0.69	0.66	0.74
2019	0.65	0.73	0.73	0.75	0.67	0.73	0.75	0.74	0.71
2020	0.69	0.69	0.71	0.72	0.67	0.65	0.64	0.71	0.62
2021	0.71	0.76	0.67	0.7	0.77	0.69	0.71	0.74	0.68
2022	0.7	0.73	0.7	0.7	0.68	0.66	0.66	0.69	0.72

As an important credibility check, we examined how the FSESI correlates with independent indicators of hunger and resource stress. We find that the FSESI is strongly negatively correlated with the prevalence of undernourishment (Pearson correlation $r \approx -0.82$, $p < 0.01$, across all country–year pairs). In simpler terms, countries and years with higher FSESI values tend to have lower proportions of undernourished people. For instance, Morocco and Tunisia, which consistently scored highest on FSESI, also report the lowest undernourishment rates, often under 5% in recent years. In contrast, years where Libya’s FSESI dipped correspond to spikes in undernourishment amid conflict. This alignment was expected and confirms that our composite index’s food security component is meaningful. We did not include undernourishment directly as an input indicator to avoid circular reasoning in validation, yet the index tracks it well—indicating that other included indicators food supply, diet affordability, etc., serve as effective proxies or contributors to actual food security outcomes.

Moreover, we looked at water stress, freshwater withdrawal as a percentage of renewable water, which is a critical sustainability metric. Ideally, a higher sustainability score in our index should mean a country is managing water more prudently, hence a lower withdrawal ratio. Indeed, we find a negative correlation between FSESI and water stress ($r \approx -0.60$, moderate strength, $p < 0.05$). The correlation is not as high as that for undernourishment, which is understandable because water stress is just one facet of sustainability and, moreover, tends to be structurally high for all these countries, with limited variation. Still, the signal is clear: in years when countries slightly reduced their water stress or maintained it instead of worsening, their FSESI tended to be higher. For example, Tunisia implemented water-saving measures in the late 2010s that kept its water withdrawal around 60–70% of resources instead of climbing—that period coincides with a rise in its FSESI. In contrast, Algeria’s increasing water stress, approaching 50% to 70% over the decade, weighed down its FSESI gains. We note that all countries have water stress well above the low threshold of 25% Our World in Data, 2024 [87], and several are in

the critical >100% zone, e.g., Egypt, relying on Nile inflows exceeding internal renewable supply. Our index reflects these nuances: Egypt's high overall FSESI relative to some neighbors is tempered by the lowest environmental subscore due to water overuse.

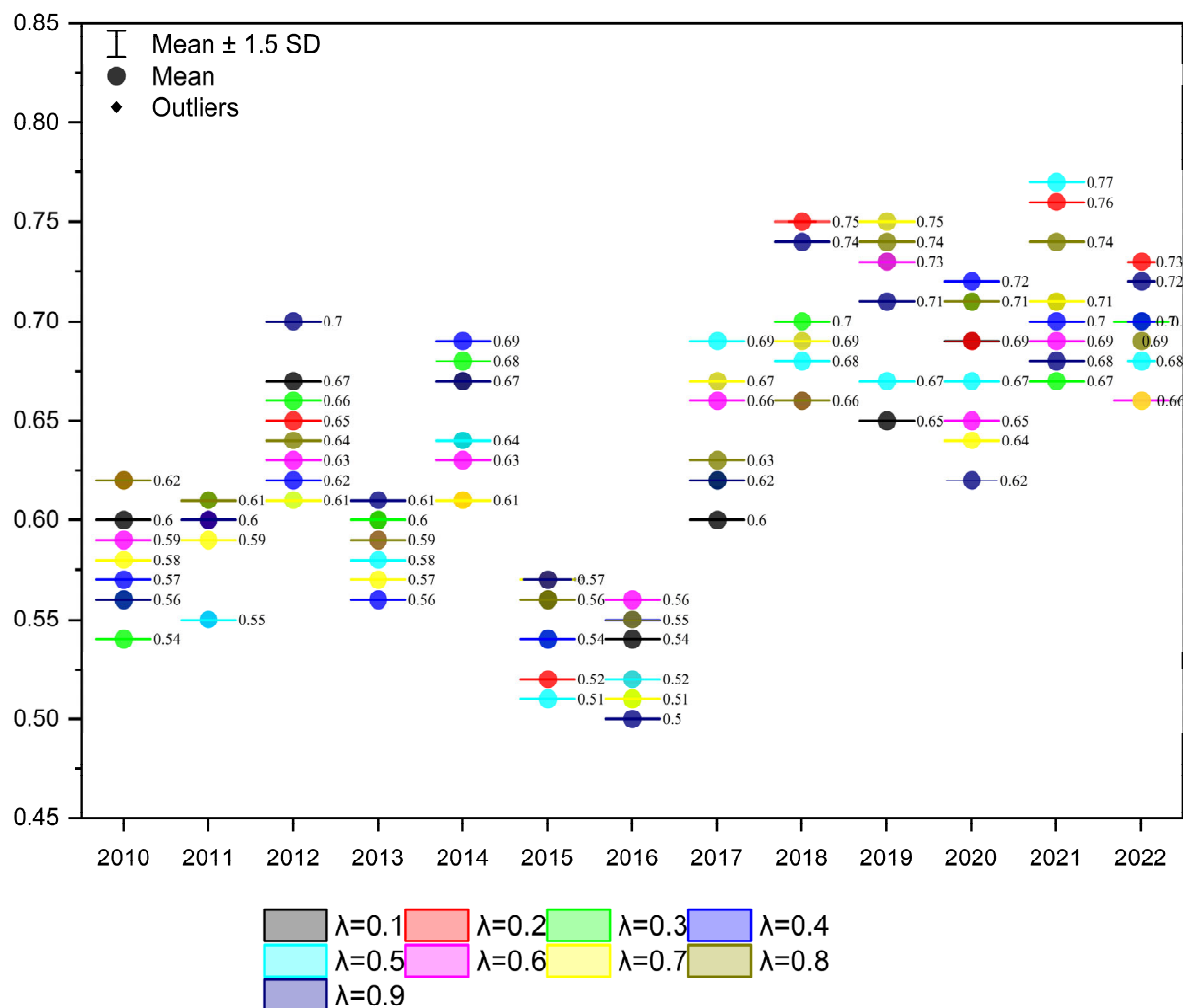


Figure 20. Sensitivity analysis variations of FSESI for North Africa (author's own drawing).

4. Discussion

This study provides an integrated evaluation of food security and environmental sustainability for North African countries, yielding important insights into their relative performance and trajectory. The composite FSESI scores offer a holistic view of how each nation balances the dual challenges of feeding its population and managing environmental resources. Our analysis revealed that Morocco achieved the highest FSESI score in the region. These findings suggest that Morocco has made progress in ensuring food security while maintaining relatively sustainable resource use. Several factors likely contribute to Morocco's leading position. Morocco has invested in agricultural development programs such as the Plan Maroc Vert during 2008–2020, aimed at improving farm productivity and rural incomes. These efforts have translated into better food availability and lower rural poverty. At the same time, Morocco pioneered renewable energy projects (such as large solar farms) and reforestation campaigns, which reinforce environmental sustainability indicators. However, Morocco's performance is not without concern because the country remains highly vulnerable to drought, and its heavy import dependence for staple cereals means that external shocks could still disrupt its food security. Tunisia ranks second in

the FSESI and presents a relatively stable score over the 2010–2022 period. Tunisia's low prevalence of undernourishment (approximately 3%) and strong social programs have kept food insecurity at bay, which aligns with its high food security subindex. Tunisia also benefits from a smaller population and more effective water management in the agricultural sector (e.g., widespread use of drip irrigation for high-value crops), contributing to a moderate environmental footprint. Nonetheless, Tunisia faced economic and political turbulence after 2011, which stagnated some improvements. Its FSESI trend was largely flat, indicating that early gains in areas such as hunger reduction plateaued in the last decade, and issues such as water stress and land degradation remain unresolved.

Egypt showed a substantial improvement in its FSESI performance over the study period, placing it third. As the most populous country in North Africa, Egypt's food security is critical to the region. The index captures Egypt's efforts to increase domestic food production through land reclamation in the desert to expand agricultural areas and improvements in cereal yields. Egypt has managed to keep undernourishment at approximately 57%, even during periods of political upheaval. From 2010 to 2022, Egypt's food security improved due to investments in infrastructure (such as grain storage to reduce postharvest losses) and targeted subsidy reforms that maintained a social safety net for the poor. These policies likely drove the upward FSESI trend. However, Egypt's environmental sustainability scores lag behind its food security gains. The country faces severe water scarcity because of its dependence on the Nile River and little increase in renewable water resources or efficiency; per capita water availability continues to decline amid population growth. Additionally, Egypt's contribution to regional CO₂ emissions is significant, reflecting an oil- and gas-based energy mix and increasing industrialization. Thus, while Egypt made strides in food availability and economic access (raising its index ranking), its long-term sustainability is challenged by environmental constraints.

Algeria is ranked fourth in the FSESI and has experienced a modest downward trend in its score in recent years. Initially, Algeria's extensive social welfare system and oil-funded food imports maintained high food security indicators, increasing one of Africa's lowest undernourishment rates. Over time, however, Algeria's vulnerabilities have become more apparent in the index. A decline in global oil prices after 2014 strained government budgets, leading to a reduction in food subsidy coverage and greater difficulty in financing food imports, which may have affected food access for certain groups. The decrease in FSESI for Algeria also mirrors a lack of progress on the environmental front. Algeria has done relatively little to diversify its energy or water resources; it remains heavily reliant on fossil fuel revenues and has made limited investments in renewable energy or large-scale water conservation for agriculture. Consequently, environmental indicators such as carbon emissions per capita and water stress remained high or worsened, decreasing the sustainability score. Algeria's case highlights the risk of complacency that strong food security outcomes funded by resource wealth can mask underlying environmental and economic unsustainability. Without proactive reforms, the slight decline in Algeria's FSESI could accelerate, especially under external shocks.

Libya consistently obtained the lowest FSESI score among North African countries, underscoring the profound impact of conflict and instability on both food systems and environmental management. Libya's FSESI trajectory deteriorated sharply after 2011, when civil war broke out, and it remained at depressed levels through 2022. The collapse of centralized governance and infrastructure in Libya led to frequent food shortages and price spikes, as well as the disruption of agricultural activities. Humanitarian assessments and regional analyses have noted that conflict-hit states such as Libya and Yemen suffer the highest rates of child malnutrition and stunting in the Arab region. Our findings are consistent with these observations: Libya's poor food security subscore is driven by

an increased prevalence of undernourishment and widespread livelihood losses during conflict years. The environmental sustainability in Libya also suffered. The country's ability to manage its scarce water was severely hampered; maintenance of critical systems such as the Great Man-Made River (an aquifer-based water supply) was disrupted, leading to water outages for agriculture and households. Moreover, unregulated exploitation of oil, along with conflict-related damage (oil spills, neglect of conservation), likely worsened environmental degradation. The net result is an extremely low FSESI, identifying Libya as the most food- and environment-insecure country in North Africa. This aligns with the broader literature noting that countries in protracted crises show heightened vulnerability across all sustainable development metrics. Notably, even as Libya's conflict ebbed and flowed, its FSESI did not recover meaningfully by 2022, indicating long-lasting scars on its institutional capacity for food and environmental governance.

Comparing these FSESI results with those of external benchmarks and studies provides additional validation and context. The ranking of countries by the FSESI corresponds closely with their standing on independent measures. For example, global hunger statistics consistently rank Algeria and Tunisia as having "low" hunger levels, whereas Libya's food situation is categorized as concerning due to conflict. These parallels provide confidence that the FSESI's food security component accurately reflects ground realities. Furthermore, the index's trends capture known events: Egypt's improvement aligns with its post-2016 economic stabilization and agricultural initiatives, and Libya's decline mirrors its instability. The stagnation observed in Tunisia's and Algeria's scores is also echoed in studies highlighting how those countries struggled to improve water management or agricultural productivity in the 2010s.

Our FSESI results indicate that Morocco leads the region in overall performance, followed by Tunisia and a steadily improving Egypt, whereas Algeria and especially Libya lag behind. This pattern is consistent with external assessments: for instance, The Economist's Global Food Security Index 2022 also ranks Morocco highest among North African nations in food security. Likewise, the 2024 Global Hunger Index categorizes Libya and Sudan as having significantly worse hunger levels (GHI scores of 19.2 and 28.8, respectively) compared to Morocco's low hunger score of 9.2 GHI, 2024 [88]. These independent metrics corroborate our composite index's indication that Morocco and Tunisia are ahead in addressing food security, while Libya and Sudan face acute challenges. However, our FSESI provides additional nuance by integrating environmental sustainability. For example, Egypt's GFSI ranking might be lower than Tunisia's in pure food terms, but our index shows Egypt catching up by 2022 due to improvements in areas like renewable energy in agriculture and reforestation efforts, which pure food indices would overlook. Izraelov & Silber, 2019 [89] assessed the Global Food Security Index. Their findings broadly agree on Morocco's relative strength. Our use of DEA weighting, however, further confirms this in an objective manner and incorporates environmental criteria, leading to a more sustainability-oriented ranking.

An important insight from the FSESI is that no country in North Africa is performing strongly on both food and environmental criteria simultaneously. Even the top-ranked countries have notable weaknesses: Morocco and Tunisia remain highly vulnerable to climate variability, and Egypt and Algeria rely on unsustainable practices (such as over-abstraction of water or fossil fuel use) to prop up their food systems. This finding is analogous to what Pandey & Asif, 2022 [90] observed in South Asia: countries could be energy secure yet environmentally unsustainable, or vice versa. In North Africa, we observe a similar disconnect at times. The implication is that achieving a high overall FSESI requires balanced progress; focusing on food production alone is not enough if it comes at the cost of depleting natural resources.

Morocco and Tunisia achieved the highest FSESI scores. This reflects their investments in both agriculture and environmental management. Morocco, for instance, has expanded its irrigated agriculture and simultaneously pursued renewable energy (e.g., solar farms) that benefits water pumping and climate mitigation in an integrated approach Kusi et al., 2022 [91].

The temporal analysis from 2010 to 2022 reveals both encouraging and cautionary trends. On the positive side, some countries (e.g., Egypt and Morocco) have managed to improve food security outcomes over the past decade, demonstrating that policy interventions can yield positive results. On the negative side, environmental indicators for the region have generally not improved and, in some cases, have worsened (e.g., per capita water availability has decreased, and forest cover has not increased substantially). This divergence suggests that gains in food security may not be sustainable without concurrent environmental action. For example, expanding irrigation helps increase yields, but if aquifers and rivers are overdrawn, those gains could be short-lived. The FSESI framework captures this by design: any boost in the food subindex could be offset by a decline in the environment subindex if it is achieved unsustainably. A key takeaway from the discussion, therefore, is the importance of integrated strategies. North African governments should emphasize that long-term food security is inseparable from environmental stewardship. Our index reinforces findings from MENA-wide analyses that emphasize the region's reliance on imports and vulnerability to climate change.

Libya and Sudan rank lowest on the FSESI, each exemplifying how conflict and resource mismanagement can collapse the food–environment nexus. Libya, ravaged by conflict during much of the last decade, shows a stark decline: its undernourishment worsened, and it has the highest water stress in the region (over 800%). Our index captures this compounded effect: despite Libya's relatively high GDP, its food security is undermined by instability, and its natural resource base is overexploited. Sudan, on the other hand, demonstrated some improvement in undernourishment (as reflected in a better food security score by 2022), but it remains very low on the index due to ongoing issues with political instability, climate shocks (droughts), and ecosystem degradation. In Sudan, hunger rates fell slightly, but progress is fragile and reversible given worsening climate events Verhoeven, 2011 [92]. Notably, our analysis found Sudan had the lowest CO₂ emissions per capita (a sustainability advantage due to low industrialization), but this is overshadowed by poor scores in food availability and stability. This resonates with the notion of hollow sustainability, low emissions born from underdevelopment rather than deliberate policy. Ultimately, neither Libya nor Sudan is on track to achieve sustainable food security without significant intervention.

This underlines calls in the literature for a nexus approach to address water, energy, and food security together Rasul & Sharma, 2016 [93], which is particularly relevant in North Africa's context of scarce water and increasing energy needs for desalination and irrigation. In conclusion, the FSESI not only benchmarks country performance but also highlights critical policy gaps: countries doing relatively well in the short term must fortify their environmental resilience, and those lagging must restore stability and invest in sustainable infrastructure to catch up. The next section outlines specific policy implications drawn from these findings.

While the DEA approach provides flexible weighting, it can also allow each country to be evaluated on its best aspects, potentially masking weaknesses; we note this is a known caveat of benefit-of-the-doubt weighting, where countries might achieve a high score by excelling in a few indicators and ignoring poor performance in others. We mention that to mitigate this, one could impose weight constraints, but in this study, we opted to reflect each country's strengths, which is both a feature and a limitation of the method. Moreover, our FSESI is tailored to North Africa and focuses on food security and environmental

sustainability; it does not directly include other dimensions like economic shocks, conflict, or political stability, which can also affect food security. We caution that this narrow focus is a limitation and that results should be interpreted in context.

The result drawn by FSESI is endorsed by other food security index studies, e.g., Global Food Security Index (GFSI) and the Global Hunger Index (GHI). The GFSI is a widely used measure that ranks Morocco as one of the most food-secure African countries. In fact, in GFSI 2022, Morocco was 57th globally with a score of 63.0, and Tunisia was 62nd with 60 Economist, 2022 [94]. Our FSESI findings are consistent with GFSI in terms of relative country performance on food security; for instance, we also find Morocco and Tunisia performing relatively well in the region—but we highlight important differences. Unlike the GFSI, which includes economic and quality/safety aspects, our FSESI explicitly incorporates environmental sustainability factors like water and land use. This leads to some delicate differences: e.g., a country like Egypt ranks higher in GFSI due to affordability and availability, but our FSESI might score it lower relative to its peers because of very high water stress or other environmental challenges. We mention that other global indices such as the Environmental Performance Index or composite Sustainable Development Goal (SDG) indices include environmental metrics but do not specifically merge them with food security as we do. Moreover, North African countries tend to have moderate hunger levels when measured by GHI scores due to low undernourishment and child mortality, but the GHI does not consider water or environmental aspects GHI, 2024 [95]. This comparison underscores the novelty of our index—FSESI fills a gap by linking food security with sustainability.

Comparison of FSESI with Undernourishment and Water Stress Indicators

To validate the food security dimension of the FSESI, we compared each country's composite score with its prevalence of undernourishment. Reassuringly, the FSESI aligns well with this conventional hunger metric. Countries that score high on the FSESI tend to exhibit very low undernourishment rates, whereas nations with poorer FSESI performance such as Libya and Sudan correspond to higher undernourishment levels. Tunisia and Algeria have maintained undernourishment below ~3% in recent years and rank among the top performers in our index, indicating that the FSESI's food security component captures these successes. Conversely, Libya's FSESI is the lowest in the region, consistent with its elevated undernourishment and food insecurity during the instability of the 2010s FAO, 2018 [96]. This close correspondence suggests that our composite index's food security subindex is reflecting ground realities similarly to the traditional FAO hunger measure. Notably, Algeria achieves one of the lowest undernourishment rates in Africa (around 2.5%), yet its overall FSESI ranking is mid-tier; our index takes into account Algeria's environmental sustainability shortcomings, e.g., high resource stress, which a hunger metric alone would overlook. Thus, while FSESI corroborates the prevalence of undernourishment in identifying food-secure countries, it also differentiates countries on additional facets, offering a more comprehensive view of food security quality and resilience than the undernourishment rate alone.

We similarly evaluated how the FSESI relates to each country's freshwater water stress level, SDG indicator 6.4.2, the ratio of water withdrawals to resources. We found an inverse relationship: countries with lower or more manageable water stress tend to score higher on the FSESI, reflecting more sustainable environmental management. For instance, Morocco's relatively moderate water stress, around a 50% withdrawal rate, pairs with its top-ranked FSESI score, and Mauritania's very low water stress aligns with a better environmental subindex, though Mauritania's overall FSESI is tempered by weaker food security outcomes. In contrast, Libya's extreme water stress, which regularly exceeds 800% of renewable

resources, is mirrored by its poor FSESI result. The composite index is not a mere proxy for water stress. Egypt faced critically high water stress of >140% in recent years Elkholy, 2021 [97], yet managed a substantially improved FSESI over the study period owing to strong gains in food availability and access that offset some environmental weaknesses. This indicates that our index can acknowledge significant food security improvements even when a country's water situation remains challenging. Likewise, Tunisia's FSESI is the second highest in the region despite high water stress of 90%, a reflection of efficient water management policies and good food security status balancing out the stress level. These comparisons show that the FSESI incorporates water stress as one crucial component alongside many others, dampening the influence of any single indicator. Countries that might be ranked similarly in terms of severe water stress can thus still be distinguished in the FSESI based on how well they mitigate resource pressures or compensate with food security measures.

Overall, this new comparative lens demonstrates that the FSESI is consistent with established metrics; countries identified as food-secure (low hunger) or environmentally secure (low water stress) by traditional measures also tend to score well on our index. This alignment builds confidence that the index accurately reflects real-world conditions; it effectively captures the signal of low hunger and sustainable resource use. At the same time, the FSESI provides added interpretive value by combining dimensions: it flags cases like Algeria, where outstanding hunger performance is counterbalanced by environmental risks, or Mauritania (where low water stress does not equate to high food security) that single-factor metrics would not adequately distinguish. By integrating multiple facets, the FSESI offers a more significant validation; it confirms expected patterns and highlights important outliers. This comparison was explicitly aligned to emphasize the robustness of the FSESI and to validate its usefulness against known benchmarks.

5. Conclusions and Policy Implications

This study developed a composite food security and environmental sustainability index (FSESI) to assess North African countries, providing a holistic view of their progress and challenges from 2010 to 2022. The FSESI approach proved valuable in illuminating how each nation balances the dual imperatives of feeding its population and safeguarding its environmental base. The main findings indicate that Morocco leads the region in overall performance, followed by Tunisia and an improving Egypt, whereas Algeria and especially Libya trail with vulnerabilities. Crucially, even the top performers face sustainability challenges, and the lowest performer (Libya) exemplifies how conflict can devastate both food security and environmental management. In summary, no North African country was completely food-secure and environmentally sustainable by 2022, but the FSESI highlights where improvements have occurred and where critical deficits remain.

These insights carry important policy implications for North African governments and regional bodies. Achieving durable food security in an environmentally constrained region will require coordinated and forward-looking strategies. On the basis of these findings, several actionable recommendations have emerged:

North African nations face critical challenges that require joint strategies to strengthen food security and environmental sustainability. These countries must address import dependency collaboratively and establish protection against global supply disruptions. Forming regional food reserves and facilitating intraregional trade agreements could enable the sharing of agricultural surpluses during crises. Additionally, cooperative management of shared water resources, such as the Nile basin and shared aquifers between Algeria and Tunisia, is crucial for sustainable water usage and agricultural production. Regional markets and collective early warning systems for droughts and food shortages would further increase overall resilience.

To sustain productivity without causing further environmental degradation, governments should prioritize agricultural practices that are both efficient and sustainable. Promoting climate-smart agriculture, including drought-resistant crops, enhanced rainwater harvesting, and conservation agriculture, can significantly preserve soil moisture and agricultural yields. The expansion of efficient irrigation methods such as drip and sprinkler systems can substantially reduce water waste. Investing in agricultural research, technology development, and extension services is essential to encourage farmer adoption of these innovations. These actions collectively enable sustained productivity while protecting valuable natural resources.

The findings from this study explicitly reinforce the advancement toward SDGs 2, 6, 13, and 15 by demonstrating how integrated approaches to food security and environmental management yield measurable improvements. Policymakers can leverage these insights to devise strategies that simultaneously reduce hunger, improve water resource management, mitigate climate risks, and protect terrestrial ecosystems, thus enhancing regional resilience.

Given severe water scarcity, sustainable water management policies are critical for North Africa. Effective water governance, repairing leaky infrastructure, and encouraging water reuse and recycling can maximize existing water resources. Countries should also explore nonconventional water sources, including renewable-powered desalination plants, wastewater treatment for irrigation, and aquifer recharge techniques. Allocating water efficiently between the agricultural, industrial, and domestic sectors, alongside stricter groundwater extraction regulations, is necessary to maintain long-term water security, which directly impacts food security.

Policymakers must diversify food production beyond cereals to increase dietary variety and reduce reliance on a limited number of staple crops. Encouraging the local cultivation of nutrient-rich food products, such as legumes, vegetables, and fruits, can bolster nutritional security and reduce import dependency. Strengthening social safety nets and nutritional assistance programs can address persistent malnutrition challenges. Initiatives such as food vouchers or conditional cash transfers can enable vulnerable households to maintain food access during economic shocks. Moreover, emphasizing nutritional education and food fortification programs can combat chronic issues such as child stunting and anemia, ensuring that food security encompasses both quantity and quality.

Long-term environmental sustainability requires incorporating ecological protection within development agendas. Reforestation and afforestation initiatives can restore degraded lands and strengthen watershed resilience, while conserving wetlands and oases helps sustain the ecological balance. Integrating climate change adaptation measures into policy frameworks, such as early warning systems for extreme weather and drought conditions, and introducing crop insurance programs can protect farmers from environmental shocks. Reducing greenhouse gas emissions through renewable energy transitions and energy efficiency improvements not only aligns with global climate mitigation goals but can also attract international climate financing for the region. Building resilience in food systems through climate-proof infrastructure and community-based adaptation initiatives is essential for enduring food security in the face of climate volatility.

Reducing food loss and waste presents a practical avenue for enhancing both food availability and environmental sustainability. Significant quantities of food are currently lost because of inadequate storage, transportation, and marketing infrastructure. Investing in improved postharvest facilities, including grain silos, cold storage, and better rural market connectivity, can substantially decrease these losses. On the consumer side, educational campaigns aimed at minimizing food waste, establishing food recovery systems, and promoting composting can further reduce waste and environmental impact. The implementation of such strategies can improve food availability and reduce the ecological footprint associated with food production and disposal.

To address food security comprehensively, North African governments must also strengthen socioeconomic measures. Updating and refining existing food subsidies and cash transfer programs can help protect the most vulnerable populations from food price fluctuations. Expanding employment and income-generating opportunities, especially in rural areas, through public work programs or the support of small-scale agribusinesses, will significantly increase food access. Nutrition-specific interventions, including micronutrient supplementation, fortified food programs, dietary diversity campaigns, and school feeding initiatives, will ensure improved nutritional outcomes.

Regional cooperation, the integration of water–energy–food policies, and the creation of interministerial frameworks for managing these interlinked sectors are critical. Collaborative research, region-wide drought-resistant agriculture techniques, and coordinated early warning systems for environmental threats can significantly enhance regional preparedness and response capabilities. Facilitating intraregional food trade and collectively negotiating climate financing can improve a region’s overall resilience. By adopting integrated strategies addressing agriculture, water management, nutrition, and ecological preservation, North Africa can ensure sustainable and secure food systems for future generations.

The FSESI provides a diagnostic tool: policymakers can use it to identify which pillars are weakest in their country and prioritize them accordingly. For example, if a country’s score is low in stability, it should invest in safety nets and diversification; if its score is low in resource efficiency, water-saving technology should be front and center. Over time, progress in these indicators can be tracked via the index to evaluate whether policies yield improvements (e.g., is undernourishment falling? Is water productivity rising?). The ultimate policy goal is to achieve a virtuous cycle: leveraging sustainability to enhance food security and achieving improved food security outcomes without degrading the environment.

North Africa stands at a critical juncture, with climate change intensifying and populations growing, and the decisions made now will determine whether the region can ensure food security for future generations in a sustainable way. The analysis above suggests that through smart, integrated policies focusing on water, soil, and people-centric interventions, North African countries can increase their FSESI scores. In practical terms, this means fewer hungry people, more resilient communities, and farming systems that thrive within environmental limits. The path is challenging but feasible, and the indicators we have discussed offer guidance for monitoring and achieving the two objectives of food security and environmental sustainability in the region.

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