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Cover Story

In this arid landscape of the United Arab Emirates (UAE), the Date Palm (Phoenix dactylifera) symbolises life and fertility. Sheikh Zayed bin Sultan Al Nahyan, the UAE's Founding Father, once remarked, "For us, the date palm is, and always has been, truly the tree of life. We have grown up with this remarkable species and its many products and find it impossible to imagine life without it. When we admire a date palm, we are looking at the foundations of our civilisation and the sustaining force for countless generations." Today, the UAE is among the top six date-producing countries, alongside Egypt, Iran, Algeria, Saudi Arabia, and Pakistan. Traditionally, dates were grown in surface-irrigated basins. In these arid regions, groundwater primarily irrigates date palms. Since ancient times, date palm trees are irrigated using a system called "aflaj" (singular: falaj, meaning "split into parts"), which channels water to each plot to irrigate the palms, inter alia. This system, dating back to AD 500, has archaeological evidence suggesting its existence as early as 2500 BC. Hydrologically, the aflaj collects water from various sources, such as groundwater, natural spring water or surface water, and distributes it through channels for domestic and agricultural purposes. These systems are categorised into three types based on their water sources: Aini, Daoudi and Ghaili. The aflaj systems channel groundwater from higher ground using gravity through man-made tunnels, effectively delivering it to the surface. Due to the declining underground water levels, the aflaj system is nearly exhausted, but it remains an exceptionally well-preserved form of land use.

(Pau Loke Show, Professor of Khalifa University, Abu Dhabi, United Arab Emirates)

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About the Journal

Agricultural & Rural Studies (**A&R**, **ISSN 2959-9784**) is an exclusively digital, open-access journal dedicated to advancing interdisciplinary scholarship at the critical nexus of agricultural sustainability, rural revitalization, and farmer well-being. Published quarterly, **A&R** features a range of content types—including original research, reviews, perspectives, and commentaries—serving as a professional and innovative platform for rigorous academic dialogue and global knowledge dissemination.

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Agricultural & Rural Studies

Article

The Power of Forests: A Study on the Spatio-Temporal Patterns of China's Forestry Carbon Sinks from the Perspective of GIS-LCA Technology

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Abstract: Forest carbon sinks are a crucial component in achieving China's "dual carbon" goals. This study integrates GIS-LCA technology to systematically examine the spatiotemporal evolution of China's forest carbon sinks and quantitatively assess afforestation carbon sequestration efficiency and carbon sink influencing mechanisms. The research findings indicate: (1) From 2003 to 2022, China's total forest carbon sink increased from 11.78 billion tons to 19.76 billion tons, with an average annual growth rate of 2.9%. This overall upward trend corroborates the research findings of other domestic scholars. The center of forest carbon sinks is mainly located in Shaanxi Province, showing a clear southeastward migration trend. (2) Forest carbon sink capacity exhibits significant regional differentiation: cold spot areas in the northeast gradually weakened, while hot spot areas in the west peaked in 2015 and subsequently declined. This shift reflects the complex interplay between climate change and human activities on carbon sink capacity. (3) Provincial-level analysis of afforestation carbon sequestration efficiency based on GIS-LCA technology reveals notable spatial disparities, with a national average of 579 t CO_2/km². Eastern provinces performed the best, averaging 749.6 t CO_2/km², while central and western provinces showed similar efficiencies at 471.5 t CO_2/km² and 494.4 t CO_2/km², respectively. This study provides theoretical support for advancing the high-quality development of China's forest carbon sinks and achieving carbon neutrality goals.

Keywords: forestry carbon sinks; dual carbon goals; high-quality development; GIS-LCA; spatiotemporal pattern

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1. Introduction

Global climate change has emerged as one of the most severe challenges facing humanity in the 21st century. In response, countries worldwide have proposed carbon neutrality goals (Tian et al., 2025; Yao et al., 2025). Based on data from the United Nations Framework Convention on Climate Change (UNFCCC), as of 2023, a total of 130 countries had pledged to attain carbon neutrality, accounting for two-thirds of global carbon emissions (Gao et al., 2025; Hu et al., 2021). As the world's largest carbon emitter, China announced its "dual carbon" goals in 2020, aiming to "peak carbon emissions before 2030 and achieve carbon neutrality before 2060." This commitment not only underscores China's sense of responsibility in global climate governance but also adds new momentum into global efforts to combat climate change. Achieving these "dual carbon" goals requires a multi-pronged approach, among which forestry carbon sinks play an irreplaceable role as a critical carbon sequestration pathway. Forests, as the dominant component of terrestrial ecosystems, possess strong carbon sequestration capacity (T. Wang et al., 2024). Through photosynthesis, forests absorb carbon dioxide from the atmosphere and store it in vegetation and soil, thereby reducing greenhouse gas concentrations and mitigating climate change. Studies indicate that global forests annually absorb approximately 2 billion tons of carbon dioxide, equivalent to one-third of emissions from fossil fuel combustion (Pan et al., 2024). Thus, strengthening forestry carbon sinks

is of great significance for realizing China's "dual carbon" objectives. Currently, the major global forestry carbon sink projects, as shown in Table 1, provide valuable references for China (Zhang & Yao, 2024). In recent years, China has placed a high priority on forestry carbon sink development, implementing a series of policy measures to promote the development and trading of forestry carbon sink projects. In 2021, the State Council of China (2021) issued the "Guidelines on Accelerating the Establishment of a Green, Low-Carbon, and Circular Economic Development System," explicitly calling for "strengthening forestry carbon sink capacity building and promoting the development and trading of forestry carbon sink projects." Additionally, the National Forestry and Grassland Administration (2021) released the "Guidelines for validation and verification of forestry carbon projects," offering technical support and policy guidance for project development. By 2022, China had launched a nationwide network of forestry carbon sink pilot projects, aiming to enhance ecological carbon sequestration capacity through diversified afforestation and forest management initiatives.

Table 1. Major Global Forestry Carbon Sink Project.

Project Name	Start Time	Initiator	Main Purpose	Implementation Scope	Implementation Category	Land Eligibility Certificate Requirements	Average Issuance Duration
CDM (Millock & Ollivier, 2025)	2001	United Nations Framework Convention on Climate Change	Help developed countries achieve mandatory emission reduction targets set in the Kyoto Protocol	Global	Afforestation, Reforestation	Afforestation: Forestless land for over 50 years; Reforestation projects require forestless land before the end of 1989	Approximately 5 years
VCS (Yang & Park, 2025)	2006	Verified Carbon Standard (by Climate Group International, International Emission Trading Association, etc.)	Reduce costs for applicants and improve the quality and sustainability of emission reduction projects	Global	Afforestation, Reforestation, Vegetation Restoration, Improved Forest Management, Reduced Deforestation, and Forest Degradation	Afforestation, Reforestation, and Vegetation Restoration: Forestless land for at least 10 years before project initiation; Reduced Deforestation and Forest Degradation: Eligible as forest for at least 10 years before initiation	2–5 years
GS (Yang & Park, 2025)	2003	World Wide Fund for Nature (WWF) and other international non-governmental organizations	Improve the quality of emission reduction projects and enhance their sustainability	Global	Afforestation, Reforestation	Afforestation and Reforestation projects require forestless land for at least 10 years before project initiation	2–5 years

However, compared with developed countries, the development of forestry carbon sinks in China is still in its early stages and faces numerous challenges, such as an imperfect policy system, inadequate scientific and technological innovation capabilities, and an underdeveloped market-oriented mechanism (Hubbart et al., 2025; J. Zhang et al., 2025). Specifically, in terms of the policy system, although China has introduced a series of policies to support forestry carbon sink development, deficiencies remain in implementation details and supporting measures, resulting in limited policy effectiveness. Regarding scientific and technological innovation capabilities, China lags behind international advanced levels in forestry carbon sink monitoring, measurement, and verification technologies, which constrains the high-quality development of forestry carbon sink projects. In terms of market-oriented mechanisms, despite the formal relaunch of the CCER (Chinese Certified Emission Reduction) market in January 2024 (with the forestry carbon sink trading process illustrated in Figure 1), the listing of the first batch of CCERs in September, and the registration of the first CCER project in December, China's forestry carbon sink trading market remains immature (Nian et al., 2025; Xu, 2024). The pricing mechanism and trading rules for carbon sink projects require further refinement, which affects the enthusiasm of social capital to participate in forestry carbon sink projects.

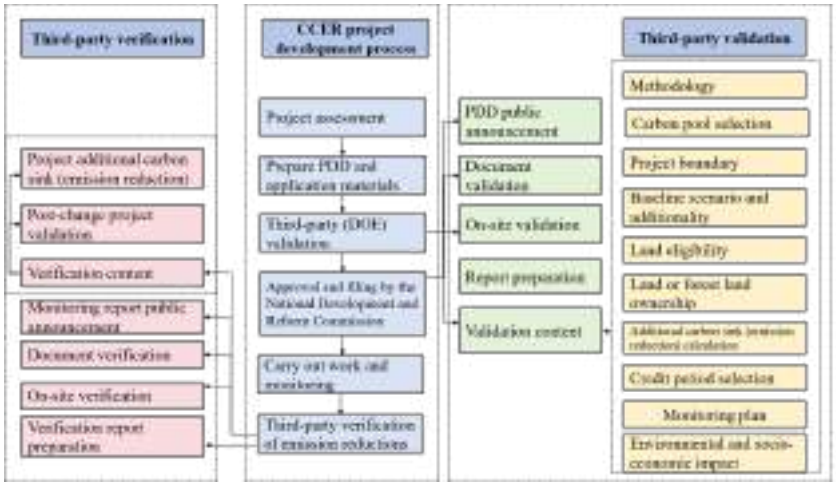


Figure 1. Flowchart for the Development of CCER Forestry Carbon Sink Projects.

To enhance the global reference value of this study, this section systematically compares the similarities and differences between mainstream international carbon sink projects, such as the Clean Development Mechanism (CDM) and Verified Carbon Standard (VCS), and China's Certified Emission Reductions (CCER) in terms of methodologies, verification costs, trading liquidity, and localization pathways:

(1) In terms of methodologies, CDM/VCS has developed a modular and dynamically updatable system that covers diverse forest types and incorporates risk buffers. In contrast, CCER suffers from outdated updates and insufficient support for complex systems like mixed forests. China can draw on the modular approach of CDM/VCS to develop refined, region-specific, and dynamically adjustable methodologies tailored to its context.

(2) Regarding verification costs and accessibility, while international projects entail high third-party fees and cumbersome processes, digital monitoring and "simplified procedures" have emerged to lower the barriers for small-scale projects. CCER still needs to shorten verification cycles and enhance transparency. It is recommended to promote simplified procedures integrating remote sensing, the Internet of Things, and smallholder farmer engagement to improve inclusivity.

(3) Concerning trading liquidity, VCS benefits from global carbon finance, offering a rich array of derivatives and mature price discovery mechanisms. In contrast, the revived CCER market remains small in scale, lacking market makers and financial instruments. To address this, China should accelerate the development of a national-level platform, introduce market makers and futures/options, and increase the offset ratio of allowances to stabilize demand.

(4) The localization challenges stem from the incompatibility of international additionality benchmarks and private capital models with China's collective forest tenure and government-led ecological projects. A "absorb-transform-innovate" strategy is needed: absorbing scientific methodologies and transparent mechanisms, transforming them to align with China's institutional framework, and innovating to form a forestry carbon sink governance system that combines international standards with Chinese characteristics. This approach will enable refined methodologies, intelligent verification, and market-oriented trading without blindly replicating international models, significantly enhancing the influence of China's CCER in global climate governance.

Scholars both domestically and internationally have conducted extensive research on forestry carbon sinks. In terms of strategy selection, based on real-world forestry carbon sink financing mechanisms, scholars have constructed three financing model frameworks: bank carbon sink expected earnings pledge, industrial investment funds, and BOT (Build-Operate-Transfer; He & Ren, 2023; J. Yang et al., 2025; Zhou et al., 2025). They have also considered moral hazards during project development and the supervisory intensity of regulatory authorities, establishing a stochastic differential game model between project development enterprises and forest farmers. Regarding carbon trading, based on the "dual carbon" goals, scholars have studied the impact of incorporating forestry carbon sinks into the carbon trading framework on China's regional carbon reduction costs (X. Li et al., 2022). They have found that numerous constraints exist in the forestry carbon sink pledge loan financing process, including limited pledged underlying assets, the absence of a unified accounting and evaluation system for pledged assets, an imperfect credit risk compensation mechanism, a lack of relevant institutional guarantees, and the absence of a comprehensive financial

service system (Begemann et al., 2025; Mohan, 2025; von Lüpke et al., 2025). In terms of optimization strategies, scholars have explored the comparison, constraints, and optimization strategies of forestry carbon sink insurance models, as well as the practical patterns and desirable approaches to determining the ownership of certified emission reductions from forestry carbon sinks. These studies provide theoretical support and practical guidance for improving the development of forestry carbon sinks in China. However, further theoretical research and refined practical pathways are still needed to better address the challenges.

Against this backdrop, the role of GIS-LCA carbon footprint assessment software is particularly critical. As an integration of Geographic Information System (GIS) and Life Cycle Assessment (LCA) technologies, this software provides robust technical support for the development and management of forestry carbon sink projects (García-Pérez et al., 2018; Guillén-Lambea et al., 2023). By integrating spatial data analysis, carbon sink measurement models, and life cycle assessment methods, the GIS-LCA software can accurately calculate the carbon sequestration capacity of forest ecosystems, evaluate the carbon reduction potential of forestry projects, and offer a scientific basis for carbon sink trading. Specifically, it plays a significant role in precise monitoring and measurement, carbon footprint assessment, policy support, and decision optimization, as well as the establishment of market-oriented mechanisms. For instance, by integrating remote sensing data, ground monitoring data, and climate models, the software enables dynamic monitoring and precise measurement of forest carbon sinks, identifies carbon sink hotspots, and optimizes project layouts. Meanwhile, its full life cycle carbon footprint assessment function covers stages such as afforestation, tending, harvesting, and reuse, enhancing project transparency and credibility while providing reliable data support for carbon sink trading. Additionally, the GIS-LCA software can simulate carbon sequestration potential under different policy scenarios, offering scientific evidence for policymakers to optimize carbon sink development goals and incentive mechanisms. By providing precise carbon sink data, it also promotes transparency and standardization in the carbon sink trading market, attracting social capital participation.

Building on this, this paper, grounded in the realities of China's forestry carbon sink development and utilizing GIS-LCA carbon footprint assessment software, aims to systematically evaluate the carbon reduction potential and full life cycle carbon footprint of forestry carbon sink projects. The application of the GIS-LCA platform is intended to identify and connect a full life cycle pathway, thereby enabling an integrated analysis of the carbon footprint across each stage of forestry carbon sink projects. It explores effective pathways for optimizing the layout of forestry carbon sink projects, improving carbon sink measurement accuracy, and facilitating market-oriented transactions, thereby providing scientific evidence and policy recommendations to drive high-quality development of China's forestry carbon sinks. The innovative aspects of this paper are primarily reflected in the following two dimensions: First, by integrating GIS spatial analysis techniques with LCA life cycle assessment methods, it constructs a carbon footprint assessment framework tailored to China's forestry carbon sink projects, addressing deficiencies in spatial precision and systemicity inherent in traditional approaches. Second, based on multi-source data integration and scenario simulation, it proposes innovative pathways for optimizing the layout of forestry carbon sink projects and designing market-oriented mechanisms, offering new theoretical support and practical references for relevant policy formulation and implementation.

2. Materials and Methods

2.1. Research Data

This study focuses on data related to forest stock volume, with the specific numerical unit of forest stock volume being 10,000 cubic meters. These data are primarily collected from the China Statistical Yearbook and the China Forestry and Grassland Yearbook. Compiled by relevant national departments, these two yearbooks offer a high degree of assurance in terms of data accuracy and authority, providing solid data support for the research. In terms of time span, the study selects data spanning two decades from 2003 to 2022. This period covers multiple important stages in China's forestry development, encompassing both the initial exploration and adjustment phase of forestry policies and the subsequent rapid development phase of forestry ecological construction. Through a systematic analysis of the data from these two decades, we can gain a more comprehensive and in-depth understanding of the dynamic trends in China's forest stock volume, explore the influencing factors behind these trends, and provide robust data evidence and decision-making references for formulating scientific and rational forestry development policies and promoting sustainable forestry development. Additionally, the data related to the GIS-LCA software primarily originates from various data documents collected by the platform, which have not been disclosed in publicly available information.

2.2. Evaluation of Forestry Carbon Sink Potential

In terms of carbon sink accounting, various methods already exist, such as the biomass method, carbon turnover model method, remote sensing technology method, and micrometeorological method. However, these methods still have certain limitations, including high technical requirements, difficulties in data acquisition, or reliance on research findings from other fields, which make them challenging to implement. In contrast, the volume method is considered a relatively straightforward approach, as it accounts for ecological factors such as stand growth and litterfall and features a more mature calculation system. Therefore, this paper selects the volume method to calculate carbon sinks across different regions. The volume method specifically comprises two components: First, based on forest stock volume, it calculates the biomass carbon sink primarily attributed to trees using parameters such as the stock volume expansion factor, bulk density, and carbon content rate (Ji et al., 2025). Second, on this basis, it further calculates the carbon sinks of understory vegetation and forest land by utilizing proportional relationships and conversion coefficients. The calculation model is presented as follows:

$$\begin{aligned} C_f &= C_b + C_v + C_s \\ &= V \times \delta \times \rho \times \gamma + \alpha(V \times \delta \times \rho \times \gamma) + \beta(V \times \delta \times \rho \times \gamma) \end{aligned} \tag{1}$$

Equation (2) illustrates the calculation method for the total forestry carbon sink. Here, Cf represents the total forestry carbon sink, C_b denotes the carbon sink of trees, Cv signifies the carbon sink of understory vegetation, and Cs indicates the carbon sink of forest land. The calculations of these carbon sinks are all based on the forest stock volume V, biomass expansion factor δ, bulk density ρ, and carbon content rate γ. In the equation, α and β represent the carbon sink conversion coefficients for understory vegetation and forest land, respectively. Their values are referenced from the study by Xue et al. (2017), with α = 0.195 and β = 1.244. Additionally, the equation provides the values of the carbon content rate γ = 0.500, biomass expansion factor δ = 1.900, and bulk density ρ = 0.500. By utilizing these parameters and the equation, we can calculate the total forestry carbon sink of forests, which holds significant importance for assessing forests' carbon storage capacity and formulating relevant carbon sink policies.

2.3. GIS-Based Spatial Distribution and Potential Assessment of Forestry Carbon Sinks

The concept of the "center of gravity" in physics, in brief, refers to the equilibrium point of an object's mass distribution. Its calculation involves first summing the products of the masses of individual particles and their respective positions, and then dividing by the total mass. This concept has been borrowed by geography and statistics to describe the concentrated areas of various elements (such as population density, intensity of economic activities, and resource allocation) within a specific geographical region, with a particular focus here on the concentrated areas of grain production. The gravity model plays a crucial role in this context, as it efficiently evaluates the match between various indicators of regional development and central point analysis, revealing the mobility and agglomeration characteristics of these elements in geographical space. The displacement of the center of gravity over time visually illustrates the transfer paths of regional development elements, making the model highly valuable for understanding the trajectories and trend changes of these elements (Chen et al., 2025; J. Wang et al., 2022). The specific calculation steps are as follows:

$$\bar{x} = \frac{\sum_{i=1}^{n} T_i X_i}{\sum_{i=1}^{n} T_i} \tag{2}$$

$$\bar{y} = \frac{\sum_{i=1}^{n} T_i Y_i}{\sum_{i=1}^{n} T_i} \tag{3}$$

In the formula: x and y represent the longitude and latitude values, respectively, of the centroid coordinates for a certain attribute within the study area; n denotes the number of sub-units; Xi and Yi are the geographic centroid coordinates of the i-th sub-unit; Ti indicates the value of a certain attribute in the region, which, in this paper, refers to the gross domestic product (GDP) and the area of urban construction land. From the centroid coordinates, the distance of spatial movement of the

centroid for a certain attribute within the study area can be calculated using the following formula (L. Li et al., 2023):

$$d = \rho\sqrt{(x_{i+t} - x_i)^2 + (y_{i+t} - y_i)^2} \tag{4}$$

In the formula: d represents the distance of centroid movement; (x_i, y_i) and (x_i+t, y_{i+t}) are the centroid coordinates of a certain attribute in the i-th and (i+t)-th years, respectively; ρ is the conversion rate between planar coordinates and geographic coordinates, typically taken as a constant value of 111.11 km.

2.4. Hotspot Analysis

The hotspot analysis employs the Getis-Ord Gi* index, proposed by British mathematicians Getis and Ord in 1992, for its analytical framework. Initially developed as a new analytical theory to address the spatial independence issues that global Moran's I statistics failed to properly reveal, this method can reflect the clustering effects of high and low values within spatial data over a certain range. By calculating each feature in the dataset, it identifies locations where high or low values spatially cluster (Iamtrakul et al., 2025). Statistically, a feature with a high value does not automatically signify a significant hotspot; it only qualifies as such when surrounded by other features with similarly high values (Kato, 2025).

$$\begin{aligned} G_i^* &= \frac{\sum_{j=1}^{n} W_{ij} - \bar{X}\sum_{j=1}^{n} W_{ij}}{S\sqrt{\frac{n\sum_{j=1}^{n} W_{i,j} - \left(\sum_{j=1}^{n} W_{i,j}\right)^2}{n-1}}}; \\ \bar{X} &= \frac{\sum_{j=1}^{n} X_j}{n}; \\ S &= \sqrt{\frac{\sum_{j=1}^{n} X^2}{n} - \bar{X}^2} \end{aligned} \tag{5}$$

In the formula: X_j is the attribute value of spatial feature j; $W_{i,j}$ is the spatial weight between features i and j, defined as 1 if they are adjacent and 0 otherwise; n is the total number of spatial features; $\bar{X}$ is the mean of the spatial features' attribute values; S is the standard deviation of the spatial features' attribute values; Gi* statistic is represented as a z-score. A higher z-score indicates tighter clustering of high values among spatial features, while a lower z-score indicates tighter clustering of low values. Through GIS maps, the spatial locations of these attribute values can be visualized, allowing for an analysis of whether they exhibit clustering effects. From the map, the Getis-Ord z-value for the selected attribute of a geographic object can be observed. A higher z-value, represented by a color trending towards red, indicates that the attribute is a spatial hotspot; conversely, a lower z-value, represented by a color trending towards blue, indicates that the attribute is a spatial cold spot.

2.5. GIS-LCA Carbon Footprint Assessment

The "GIS-LCA Carbon Footprint Assessment Software" (https://lca.qibebt.ac.cn/#/index), originally developed by the team led by Academician Xie Kechang and Director Tian Yajun from the Pan-Energy Big Data and Strategic Research Center of the Chinese Academy of Sciences (hereinafter referred to as the "Center"), represents the first in-depth integration of Geographic Information System (GIS) and Life Cycle Assessment (LCA) technologies. This innovation enables precise carbon footprint accounting and spatial traceability. The tool is capable of tracking the entire life cycle of a product, from raw material acquisition, production and processing, usage, to final disposal, conducting quantitative analysis of greenhouse gas emissions at each stage, and scientifically evaluating their potential impacts on climate change. This study systematically analyzed the carbon sequestration efficiency of afforestation across various provinces in China based on GIS-LCA carbon footprint assessment technology.

3. Analysis of the Current Development Status of Forestry Carbon Sinks in China

3.1. Assessment of Forestry Carbon Sink Potential

Through a temporal analysis of China's total forestry carbon sink (Cf, in units of 100 million tons) and its constituent elements—carbon sink of trees (Cb), carbon sink of understory vegetation (Cv), and carbon sink of forest land (Cs)—from 2003 to 2022, the study reveals that China's forestry carbon sink system exhibits significant phased growth characteristics (Figure 2). During the research period, Cf steadily increased from 11.78 billion tons in 2003 to 19.76 billion tons in 2022, with an average annual growth rate of 2.9%. Specifically, the growth process of Cf can be divided into three distinct phases: a rapid growth period (2003–2006), during which Cf increased from 11.78 billion tons to 14.02 billion tons; a plateau period (2006–2009), when the total carbon sink remained relatively stable; and a sustained growth period (after 2009), reaching two interim peaks of 17.12 billion tons in 2013 and 19.76 billion tons in 2018. In terms of carbon sink composition, forest land carbon sink (Cs) consistently dominated, contributing 10.08 billion tons in 2022, accounting for 51.0% of the total; tree carbon sink (Cb) followed with 8.1 billion tons (41.0%); although understory vegetation carbon sink (Cv) had the smallest share (1.58 billion tons, 8.0%), its growth trend remained synchronized with Cb and Cs, indicating its non-negligible role in the carbon sink function of forest ecosystems. These findings corroborate the research results of scholars such as Wu Weiguang, Xue Longfei, and Zhang Xufang, further confirming the reliability of the study's conclusions (Wu et al., 2024; X. Zhang et al., 2016; Xue et al., 2017). The results demonstrate that China's forestry carbon sink system has achieved qualitative improvements over the past two decades, reflecting significant achievements in sustainable forest resource management and the continuous enhancement of ecosystem service functions. The improvement in China's forestry carbon sink capacity not only provides crucial support for the realization of domestic carbon neutrality goals but also makes a positive contribution to global climate governance and ecological sustainable development.

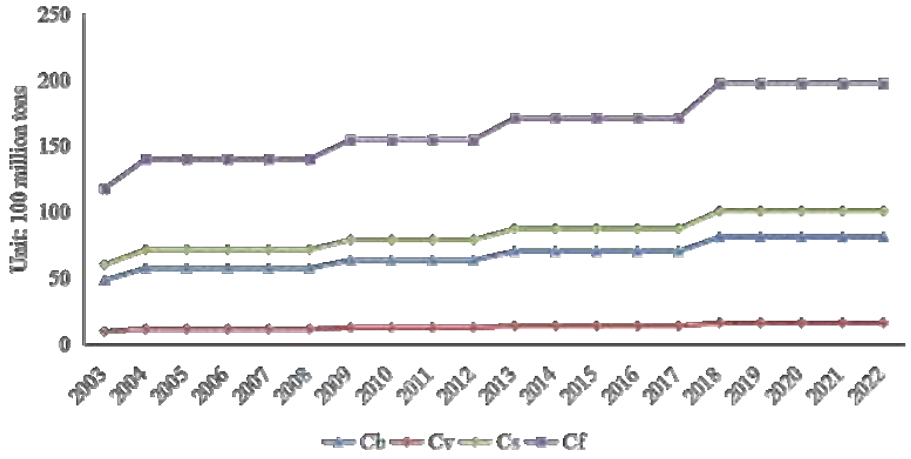


Figure 2. Trends in China's Forestry Carbon Sink from 2003 to 2022.

In recent years, China's forestry carbon sink has played an increasingly important role in addressing climate change and achieving carbon neutrality goals. Based on an analysis of spatial distribution maps of forestry carbon sinks at four time points—2003, 2009, 2015, and 2022—the dynamic trends and regional distribution characteristics of China's forestry carbon sink can be systematically assessed. In 2003, China's forestry carbon sink was primarily concentrated in the northeastern, southeastern, and southwestern regions, covering major forest areas such as the Northeast Forest Region and key forest areas in the south. By 2009, the spatial distribution of forestry carbon sinks exhibited significant changes, with an increase in carbon sinks in the southwestern region and a decline in some central areas. By 2015, carbon sinks in the southeastern region further increased, and the central region also showed recovery. The latest data from 2022 indicate that carbon sinks in the northeastern, southeastern, and southwestern regions remain at high levels, with an overall distribution tending towards equilibrium. These changes reflect significant temporal and spatial differences in China's forestry carbon sinks, with factors such as policy changes (e.g., the Natural Forest Protection Program and the Grain for Green Program), climate change, and shifts in land use patterns exerting important influences on carbon sink variations.

3.2. Current Status and Trends of Forest Resources

As shown in Figure 3, from 2003 to 2022, the centroid of China's forestry carbon sink remained primarily within Shaanxi Province, exhibiting a pronounced southeastward shift. This spatial trajectory not only reflects the dynamic redistribution of carbon sequestration capacity but also signals underlying shifts in ecological governance, land use transitions, and regional development strategies. Initially centered in central Shaanxi in 2003, the centroid's southeastward migration—particularly pronounced in 2009, 2015, and 2022—coincides temporally with key national ecological initiatives. These include the sloping land conversion program and the Natural Forest Protection Program, which were intensified in the Loess Plateau and its surrounding regions during the mid-2000s and 2010s. The 2015 peak and subsequent decline in western hotspot regions may reflect not only the maturation of early-planted forests but also the exhaustion of marginal lands suitable for afforestation, compounded by drought-induced mortality during extreme climate events. Additionally, the southeastward shift aligns with increasing human activity pressure in the northwest—such as expanded infrastructure development and agricultural intensification—which may have undermined local carbon sink stability. Mechanistically, these policy-climate-human interactions likely reconfigured the regional balance of carbon uptake, driving the observed centroid migration.

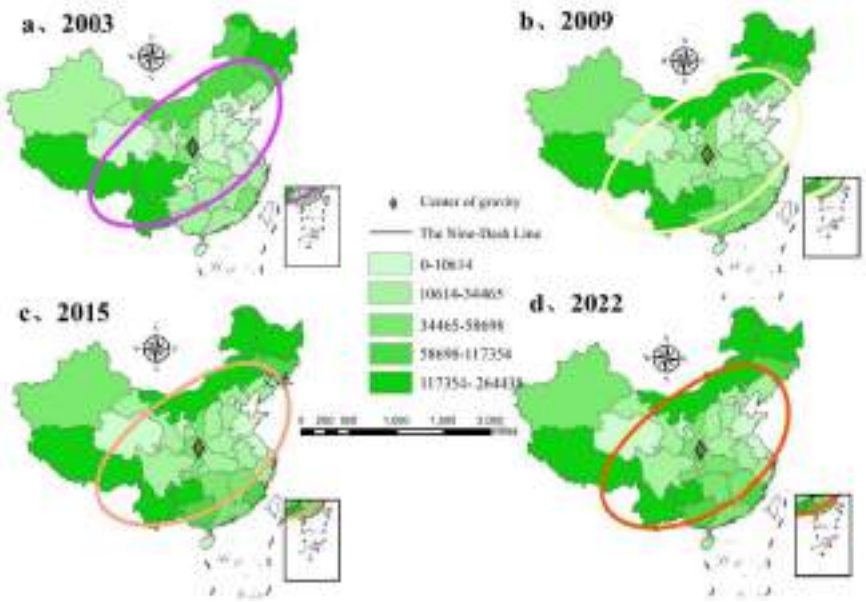


Figure 3. Spatial Evolution Trend of China's Forestry Carbon Sink from 2003 to 2022.

The standard deviational ellipse analysis further elucidates the directional asymmetry of this redistribution. The Y-axis dispersion (18.644) significantly exceeds that of the X-axis (9.556), indicating a north-south elongated pattern of carbon sink distribution. This anisotropy may reflect the orographic and bioclimatic gradient along the Loess Plateau-Qinling transition zone, where afforestation programs were disproportionately implemented along elevation and precipitation gradients. The rotation angle (64.46°) aligns closely with the northeast-southwest orientation of this topographic transition, suggesting that geo-ecological constraints—rather than administrative boundaries—have shaped the macro-scale configuration of carbon sinks. Thus, the spatial evolution of China's forestry carbon sink is not merely a descriptive pattern but a composite signature of policy intervention, climate variability, and anthropogenic land use dynamics, warranting region-specific attribution in future mechanism-focused studies.

3.3. Evolution Characteristics of Forest Resources

By analyzing hotspot and coldspot maps across different years, the dynamic changes in carbon sink capacity and their significance in various regions can be clearly observed. As illustrated in Figure 4, in 2003 (Figure 4a), northeastern China exhibited a prominent coldspot area (dark blue), indicating low forestry carbon sink capacity with a confidence level as high as 99%. The remaining regions were primarily classified as non-significant areas (yellow), suggesting that the carbon sink capacities in these areas were not statistically significant. By 2009 (Figure 4b), the extent of the coldspot in northeastern China had diminished, while a significant hotspot (dark orange) emerged in a western province, with a confidence level of 90%, indicating a notable increase in forestry carbon sink capacity in that region. The rest of the areas remained predominantly non-significant.

In 2015 (Figure 4c), the coldspot in northeastern China further weakened, and the hotspot area in the west expanded significantly, with the confidence level rising to 95% and reaching its peak at 99% that year, demonstrating a continuous enhancement in forestry carbon sink capacity in the western region. By 2022 (Figure 4d), the coldspot in northeastern China had nearly vanished, and while the hotspot area in the west persisted, its color lightened, and the confidence level decreased. Additionally, some new coldspot areas (grayish-blue) emerged, with a confidence level of 90%, indicating a reduction in carbon sink capacity and weakened statistical significance in these regions.

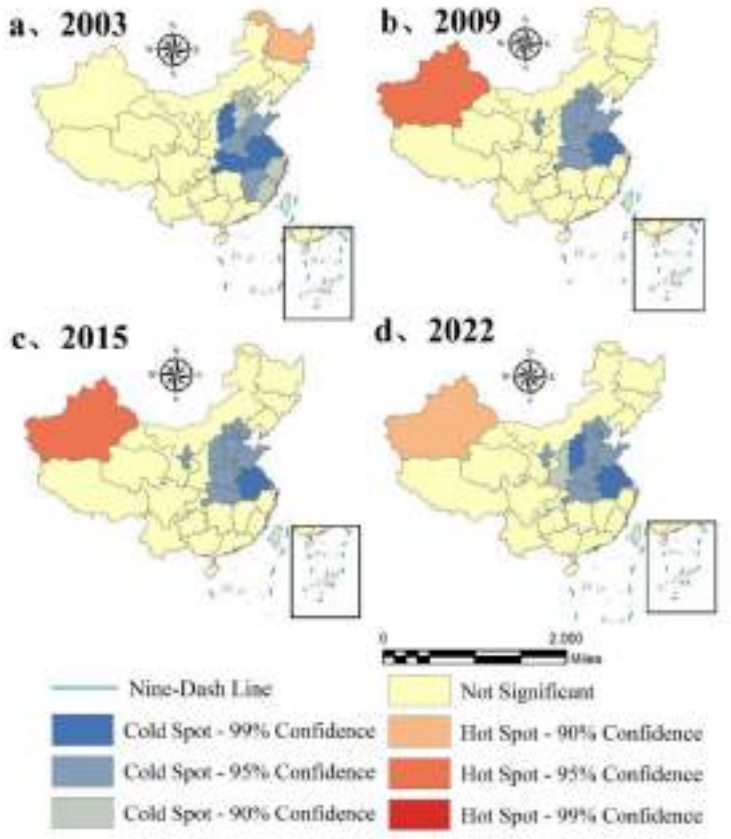


Figure 4. Spatial Distribution of Cold and Hot Spots in China's Forestry Carbon Sink from 2003 to 2022.

The observed peak and subsequent decline of the western hotspot after 2015 suggest that the enhancement of carbon sink capacity in this region may have encountered limiting factors. Potential mechanisms could include:

(1) Policy implementation cycles—if the region had undergone large-scale afforestation or ecological restoration projects prior to 2015, the maturation of these forests or reduced post-project maintenance could lead to growth saturation or degradation;

(2) Climate variability—periods of drought or extreme temperature events after 2015 could have suppressed vegetation growth and carbon uptake efficiency;

(3) Human activity interference—increased land use pressure or infrastructure development in the region may have fragmented forest landscapes, undermining their carbon sequestration function. In summary, from 2003 to 2022, China's forestry carbon sink capacity exhibited significant regional variations: the coldspot in northeastern China gradually weakened, while the hotspot in the west peaked in 2015 before experiencing a decline. These changes reflect the dynamic evolution of forestry management and carbon sink capacity across different regions, providing crucial scientific insights for formulating regional carbon sink policies and addressing climate change.

3.4. Analysis of the Differences in Carbon Sequestration Effects of Afforestation Among Chinese Provinces from the GIS-LCA Perspective

Against the backdrop of global climate change, forests, as the largest carbon reservoirs in terrestrial ecosystems, play a crucial role in achieving carbon neutrality goals due to their carbon sequestration capacity. This study developed a visualization model for the carbon sequestration

effects of provincial afforestation based on the GIS-LCA software platform (as shown in Figure 5). Through the GIS-LCA platform, a full life cycle pathway was identified, enabling the integration of all stages of afforestation into a coherent framework to analyze the carbon footprint across each stage. With "forest land use" as the core node, the afforestation processes of various provinces were linked to the same "forest land use" process. By utilizing this "forest land use" node, connections were established among the afforestation processes of 31 provinces in China, quantifying the differences in carbon sequestration efficiency per unit area (1 km²) during the afforestation process across provinces (higher values indicate greater carbon sequestration efficiency during afforestation).



Figure 5. Visualization Model of Provincial Afforestation Carbon Sequestration Efficiency Based on GIS-LCA.

From the perspective of the bar chart heights and colors in the afforestation carbon sequestration efficiency model, where higher values represent stronger efficiency, provinces with high efficiency include Shandong, Jiangsu, and Ningxia; those with relatively high efficiency are Shaanxi, Tianjin, and Shanghai, among others; provinces with moderate efficiency include Beijing, Inner Mongolia, and Hebei, among others; while provinces with relatively low efficiency include Qinghai and Sichuan, among others. This phenomenon may be related to the climatic suitability of each region. Shandong is located in the warm temperate sub-humid climatic region, and Jiangsu is situated in the northern subtropical humid climatic region. The suitable temperatures and soil moisture levels in these areas are likely reasons for their high carbon sequestration efficiency. Similarly, Shaanxi and Tianjin, like Shandong, are located in the warm temperate sub-humid climatic region, demonstrating relatively high afforestation carbon sequestration efficiency on a national scale. In contrast, Qinghai is located in the plateau subfrigid sub-arid climatic region, where the low temperatures in the frigid zone and arid climate have a certain impact on tree growth, thereby affecting the carbon sequestration efficiency of afforestation.

As shown in Table 2, the model results indicate that the afforestation carbon sequestration efficiency of various provinces exhibits significant regional differentiation characteristics. Again, larger numerical values correspond to higher carbon sequestration efficiency. The average afforestation carbon sequestration efficiency across the 31 provinces in China is 579 t CO_2/km². From the perspective of the three major regions—eastern, central, and western China—the eastern provinces demonstrate the most outstanding performance in afforestation carbon sequestration efficiency, with an average of 749.6 t CO_2/km². Among them, Shandong ranks first nationwide with a carbon sequestration efficiency of 1,925 t CO_2/km², followed by Jiangsu with 1,543 t CO_2/km². The afforestation carbon sequestration efficiencies of the central and western provinces are relatively close, at 471.5 t CO_2/km² and 494.4 t CO_2/km², respectively. In the central region, Shanxi, Henan, and Anhui exhibit relatively high carbon sequestration efficiencies, while in the western region, Ningxia, Shaanxi, and Gansu perform relatively well. In contrast, Sichuan's carbon sequestration efficiency is only 83 t CO_2/km², less than half of that of Shandong, making it one of the provinces with the lowest carbon sequestration efficiency nationwide. This regional differentiation characteristic may be closely related to factors such as climatic conditions, soil types, and afforestation policies, providing a scientific basis for further optimizing regional afforestation strategies.

Table 2. Results of Carbon Sequestration Efficiency of Provincial Afforestation Based on GIS-LCA.

Eastern Region	kg CO_2/km^2	Central Region	kg CO_2/km^2	Western Region	kg CO_2/km^2
Shandong	1,925,000	Shanxi	751,000	Ningxia	1,173,000
Jiangsu	1,543,000	Henan	719,000	Shaanxi	890,000
Tianjin	882,000	Anhui	606,000	Gansu	776,000
Shanghai	802,000	Heilongjiang	444,000	Chongqing	686,000
Fujian	758,000	Hubei	390,000	Inner Mongolia	552,000
Beijing	552,000	Jilin	343,000	Xinjiang	511,000
Hebei	515,000	Jiangxi	327,000	Guangxi	454,000
Zhejiang	487,000	Hunan	192,000	Guizhou	421,000
Guangdong	396,000			Yunnan	331,000
Liaoning	233,000			Qinghai	120,000
Hainan	153,000			Sichuan	83,000
				Xizang	64,000

4. Conclusions and Prospects

4.1. Research Conclusions

Through multi-dimensional analysis, this study draws the following key conclusions:

(1) China's total forestry carbon sink has experienced significant growth, with its spatial distribution pattern demonstrating dynamic evolution characteristics. From 2003 to 2022, China's total forestry carbon sink increased from 11.78 billion tons to 19.76 billion tons, with an average annual growth rate of 2.9%, indicating a steady improvement in China's forestry carbon sink capacity. In terms of spatial distribution, the centroid of forestry carbon sinks is primarily concentrated within Shaanxi Province, exhibiting a notable southeastward migration trend. In 2003, the centroid was located in central Shaanxi Province and subsequently shifted southeastward gradually, with particularly pronounced migration characteristics observed in 2009, 2015, and 2022. This evolutionary pattern reveals the combined influence of multiple driving factors, including regional development disparities, policy guidance, and natural conditions.

(2) The forestry carbon sink capacity exhibits significant regional differentiation characteristics. During the study period, the spatial heterogeneity of China's forestry carbon sink capacity was prominent. Cold spot areas in Northeast China demonstrated a gradual weakening trend, indicating an improvement in the region's carbon sink capacity. In contrast, hot spot areas in western China peaked in 2015 before experiencing a certain degree of decline, potentially related to the impacts of climate change and human activities. These changes in spatial distribution characteristics provide an important basis for a deeper understanding of the spatiotemporal evolution patterns of China's forestry carbon sink.

(3) Analysis of provincial afforestation carbon sequestration efficiency based on the GIS-LCA software platform. Against the backdrop of global climate change, forests, as the largest carbon reservoirs in terrestrial ecosystems, play a crucial role in achieving carbon neutrality goals due to their carbon sequestration capacity. This study constructed a visualization model for the carbon sequestration effects of provincial afforestation based on the GIS-LCA platform, with "forest land use" as the core node, and quantified the differences in carbon sequestration efficiency per unit area (1 km^2) during the afforestation process across 31 provinces in China. The results showed significant regional differentiation in afforestation carbon sequestration efficiency among provinces, with a national average of 579 t CO_2/km^2. Eastern provinces performed the best, with an average of 749.6 t CO_2/km^2, with Shandong (1,925 t CO_2/km^2) and Jiangsu (1,543 t CO_2/km^2) demonstrating the highest efficiency. Central and western provinces had similar efficiencies, at 471.5 t CO_2/km^2 and 494.4 t CO_2/km^2, respectively, with provinces such as Shanxi, Henan, Ningxia, and Shaanxi performing relatively well, while Sichuan (83 t CO_2/km^2) had lower efficiency. Climatic conditions are a crucial factor influencing carbon sequestration efficiency, with warm temperate and subtropical humid climate zones, such as those in Shandong and Jiangsu, being suitable for tree growth, while arid climate zones in plateau subfrigid regions, such as Qinghai, exhibit lower efficiency.

4.2. Prospects

Combining the deficiencies identified during this research process, future research can further explore the following key aspects to promote the continuous development of this field in depth.

4.2.1. Deepening Research on the GIS-LCA Model

Although the GIS-LCA model was applied in this study, there is still room for in-depth exploration in terms of model details. Future research should focus on refining the technical framework of the GIS-LCA model, detailing and elaborating its technical framework diagram to clearly illustrate the entire process from data collection and processing to final carbon sink measurement. Particularly, it is essential to delve into the specific setting basis and interrelationships of various parameters within the model. For instance, in the construction method of Life Cycle Inventory (LCI), clarify the dynamic variation patterns of parameters under different forest types and management measures to enhance the model's applicability across diverse geographical regions and forest management scenarios. Simultaneously, conducting extensive model validation work is crucial. By comparing and analyzing with field monitoring data and results from other authoritative models, the accuracy and reliability of the GIS-LCA model can be assessed. In-depth cause analysis should be carried out for the model's performance discrepancies in different regions and forest ecosystems, followed by targeted model optimization to improve its universality and scientific rigor.

4.2.2. Strengthening Data Management and Quality Assessment

Data serves as the foundation for forestry carbon sink research. While this study has elaborated on data sources and quality assessment to some extent, further strengthening is needed. In the future, a more comprehensive data management system should be established, integrating multi-source data, including national forest resource inventory data, satellite remote sensing data, and ground survey data, to achieve real-time data updates and sharing. By constructing a unified data platform, data acquisition efficiency and utilization value can be enhanced, providing more comprehensive and accurate data support for forestry carbon sink research. In terms of data quality assessment, stricter and more detailed standards should be formulated. Not only should data accuracy be evaluated, but also data completeness, consistency, and timeliness. Advanced data analysis techniques, such as data mining and machine learning, should be employed to identify and correct anomalies and errors in the data. Simultaneously, uncertainty analysis of data quality should be conducted to quantify the impact of different data sources and measurement methods on research results, providing stronger guarantees for the reliability of research conclusions.

4.2.3. Comprehensively Analyzing Factors Influencing Carbon Sink Efficiency

This study has preliminarily explored differences in carbon sink efficiency at the provincial level. However, the analysis of numerous factors influencing carbon sink efficiency is not yet comprehensive and in-depth enough. Future research needs to systematically identify and quantify the contributions of different factors to carbon sink efficiency, constructing a comprehensive influencing factor model. From the perspective of natural factors, in-depth research should be conducted on the impact mechanisms of soil type, texture, and nutrient content on forest growth and carbon sink capacity, analyzing differences in carbon cycling processes within forest ecosystems under different soil conditions. Simultaneously, consider topographic and geomorphic factors such as altitude, slope, and aspect on the spatial distribution of forest carbon sinks, revealing the intrinsic connections between geographical environments and carbon sink efficiency. In terms of human factors, detailed assessments should be made on the long-term impacts of forest management and operation measures on carbon sink efficiency, including different afforestation methods, thinning intensities, and forest pest and disease control measures on the dynamic changes in forest biomass growth and carbon storage. Furthermore, in-depth research should be conducted on the guiding role of policy incentives in the development of forestry carbon sinks, analyzing the impacts of various ecological compensation policies and carbon trading policies on the enthusiasm and behavioral choices of forest farmers and enterprises participating in forestry carbon sink projects, providing theoretical bases for formulating more scientifically effective policies.

4.2.4. In-Depth Exploration of the Formation Mechanisms of Carbon Sink Hotspot Regions

This study has identified hotspot and coldspot regions for carbon sinks, but in-depth analysis of the formation mechanisms of hotspot regions still needs strengthening. Future research should combine socioeconomic, policy implementation, and natural environmental factors in the regions to conduct in-depth mechanistic studies. For carbon sink hotspot regions, analyze the specific implementation effects and pathways of regional policies. For example, study the differences in implementation intensities, funding inputs, and management models of major ecological projects such as the "Grain for Green Program" and the "Natural Forest Protection Program" in different regions, and how these differences affect forest carbon sink growth. Simultaneously, consider the impacts and recovery mechanisms of extreme climate events on the carbon sink capacity of hotspot regions,

assessing the stability and sustainability of carbon sinks in hotspot regions under a climate change background. Additionally, attention should be paid to the impacts of human activity intensity on carbon sink hotspot regions. Research the changes in forest ecosystem structures and functions caused by human activities such as urbanization, agricultural expansion, and infrastructure construction, and how these changes feed back into the carbon sink process. By establishing a coupled model of human activities-forest ecosystems-carbon sink capacity, the complex mechanisms underlying the formation of carbon sink hotspot regions can be deeply revealed, providing targeted strategies for regional ecological protection and carbon sink enhancement.

5. Development Suggestions

As illustrated in Figure 6, under the backdrop of the "dual carbon" goals, promoting high-quality development of China's forestry carbon sink requires collaborative efforts across four key dimensions: mechanism refinement, technological innovation, scientific planning and innovative management, and deepening international cooperation.

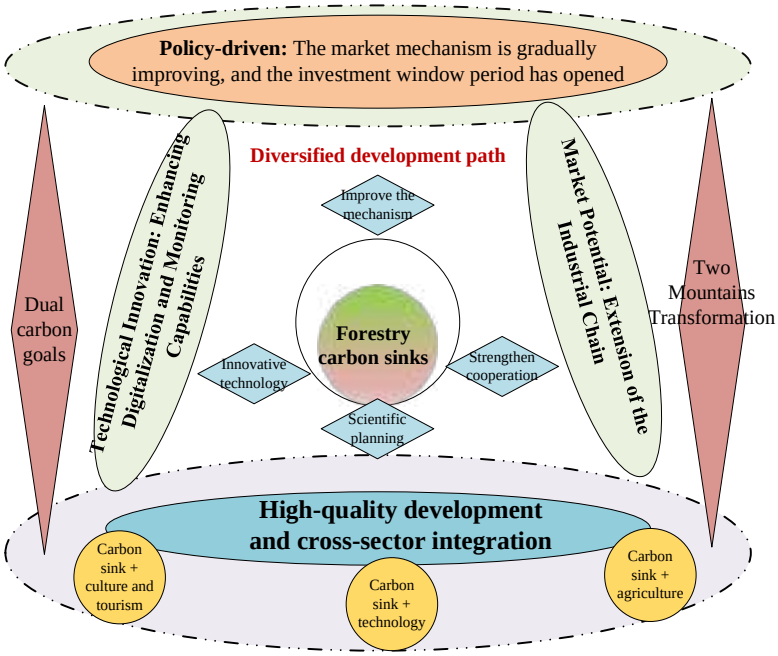


Figure 6. Schematic Diagram of the Development Pathway for China's Forestry Carbon Sinks.

5.1. Mechanism Refinement: The Fundamental Guarantee for the Implementation of Forestry Carbon Sink Projects

Establishing a policy framework and innovating market mechanisms are crucial for promoting the sustainable development of forestry carbon sinks. First, a legal and regulatory system centered on a Forestry Carbon Sink Law should be established to clarify the legal status and rights and responsibilities of various stakeholders in the development, trading, and supervision of carbon sink projects (He et al., 2025; Liu et al., 2023). This system should integrate international measurement methodologies with local conditions to refine technical standards for carbon sink monitoring and accounting, ensuring scientific rigor and transparency. Furthermore, policies should be regionally differentiated and tailored to local ecological conditions. In high-efficiency eastern provinces (e.g., Shandong, Jiangsu), afforestation efforts should be scientifically expanded in non-agricultural areas, promoting integrated models such as "urban forests + carbon sinks" to enhance synergistic benefits between carbon sequestration and ecosystem services. In ecologically fragile yet potentially high-yield regions of central and western China (e.g., Shanxi, Ningxia), enhanced policy support should be provided to promote adaptive afforestation based on water resource availability, advancing ecological protection and restoration in tandem. In ecologically sensitive or low-efficiency areas such as Sichuan and Qinghai, conservation should take precedence, with pilot adaptive afforestation projects carefully implemented based on local climatic and ecological conditions, and carbon sink initiatives advanced prudently. Second, market mechanisms must be innovated by establishing a unified national forestry carbon sink trading platform, leveraging blockchain technology to enhance transaction transparency and credibility, and developing financial instruments such as carbon sink futures, options, and pledge financing to invigorate the market. Additionally, a carbon sink price stabilization fund should be established, regional trading alliances promoted, cross-

border trading mechanisms explored, and China's pricing power in the global carbon market strengthened.

5.2. Technological Innovation: The Core Driving Force for High-Quality Development of Forestry Carbon Sinks

Technological innovation serves as the core driving force for the high-quality development of forestry carbon sinks, permeating all aspects from basic research and technological application to talent cultivation (Wise & Parker, 2025). In the field of basic research, it is crucial to establish national major science and technology projects focused on forestry carbon sinks, break through key technological bottlenecks, and construct national key laboratories to promote deep interdisciplinary integration and build a big data platform for forestry carbon sinks. Simultaneously, introduce blockchain technology to ensure data credibility and transparency, develop an intelligent carbon sink management platform based on GIS-LCA for dynamic optimization and precise management of carbon sink projects, and accelerate the application and commercialization of new technologies. In talent cultivation, establish interdisciplinary forestry carbon sink programs to train compound talents, set up talent training bases, implement the "Forestry Carbon Sink Young Talent Program," and attract high-level overseas talents.

5.3. Scientific Planning and Management: The Key Pathway for the Implementation of Forestry Carbon Sink Projects

Establish a comprehensive carbon sink potential assessment system in China, prioritizing project deployment in ecologically fragile areas and regions with high carbon sink potential to achieve efficient resource allocation and maximize ecological benefits. Simultaneously, adopt a "multi-plan integration" approach to align carbon sink project planning with national land use, ecological protection, and other relevant plans, avoiding conflicts and resource waste. Introduce participatory planning to incorporate the opinions of local communities and stakeholders, enhancing project sustainability and social acceptance. Additionally, refine the environmental impact assessment system to scientifically evaluate ecological impacts, ensuring a balance between ecological and economic benefits and minimizing negative environmental impacts. Innovating management models is central to the efficient implementation of projects. It is essential to implement full lifecycle management, establishing a comprehensive regulatory mechanism from project initiation to operation to ensure orderliness across all stages. Introduce third-party certification bodies to objectively assess implementation effects, enhancing transparency and credibility. Establish a performance evaluation system to regularly conduct effect assessments, providing data support for subsequent project optimization. Develop an intelligent management platform that integrates big data and artificial intelligence technologies to achieve precise management and dynamic optimization, improving management efficiency. The monitoring system is a crucial safeguard for the smooth implementation of projects. Construct a national-provincial-municipal three-tier monitoring network to achieve comprehensive monitoring, ensuring data accuracy and completeness. Develop an intelligent monitoring platform that combines remote sensing, Internet of Things, and artificial intelligence technologies to enable real-time monitoring and dynamic assessment of carbon sinks. Additionally, establish a data-sharing mechanism to promote data openness and sharing, improving utilization efficiency. Further enhance monitoring capabilities through technical training and equipment upgrades to ensure scientific and reliable results, providing a solid data foundation for the sustainable development of projects.

5.4. Deepening International Cooperation: A Strategic Pathway to Enhance the International Competitiveness of Forestry Carbon Sinks

By actively participating in the formulation of carbon sink rules under the UNFCCC framework, promote the establishment of unified carbon sink measurement and trading standards, enhancing the normativity and transparency of the international carbon sink market (Nasiritousi et al., 2025; Yang & Park, 2025). Simultaneously, deepen cooperation with countries along the Belt and Road Initiative to explore international markets and optimize regional carbon sink resource allocation. Actively engage in shaping international carbon sink standards to strengthen China's voice and influence in the global carbon market. Expand international collaboration by forging in-depth partnerships with developed nations in carbon sink technology, management, and policy, leveraging their best practices, while enhancing support for developing countries through technical assistance and financial aid to foster mutual benefits and win-win outcomes—reinforcing China's leadership in global climate governance. Establishing robust international exchange platforms is equally critical. Host global forestry carbon sink forums to facilitate knowledge sharing and technological collaboration, establish international carbon sink technology transfer centers to accelerate the dissemination of innovations, and participate in mutual recognition mechanisms for carbon sink

certification to promote the seamless circulation of carbon credits. Together, these efforts will significantly enhance the international competitiveness, market reach, and global influence of China's forestry carbon sink initiatives.

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Abbreviations

The following abbreviations are used in this manuscript:

GIS-LCA	Geographic Information System-based Life Cycle Assessment
UNFCCC	United Nations Framework Convention on Climate Change
CCER	China Certified Emission Reduction
GIS	Geographic Information System
CDM	Clean Development Mechanism
VCS	Verified Carbon Standard
GS	Gold Standard
BOT	Build-Operate-Transfer

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Article

Exploring the Impact of the Digital Economy on Rural Mexico

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Abstract: This study explores the potential of the digital economy to strengthen rural resilience and promote territorial permanence in Mexico. Traditionally perceived as incompatible, the digital and rural spheres are increasingly converging, creating hybrid spaces that challenge simplistic dichotomies between modernization and tradition. By adopting a qualitative, exploratory, and descriptive design, the research analyzes the experiences of Oaxaca and Chiapas, two emblematic rural regions with high cultural diversity and socioeconomic marginalization. The findings reveal that digital technologies—including e-commerce, blockchain, and telemedicine—have enabled new economic opportunities, enhanced access to essential services, and fostered cultural preservation. Nevertheless, the results also underscore persistent challenges such as digital infrastructure gaps, new forms of dependency on external platforms, and tensions between innovation and cultural identity. The emerging role of women in leading digital adoption highlights promising paths for greater inclusivity. Overall, the study concludes that digital transformation in rural Mexico is not merely a matter of technological adoption but a complex process of social, economic, and cultural reconfiguration. For digitalization to truly support rural development and territorial permanence, it must be approached through holistic, community-driven, and culturally sensitive strategies that empower local actors and respect diverse knowledge systems.

Keywords: rurality; emerging technologies; Mexico; digital; rural sociology

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1. Introduction

The global transition to the digital age is reshaping economic, social, and cultural dynamics, challenging traditional notions of development and progress (Leviäkangas et al., 2025). In academic and policy debates, rural areas are often viewed as technologically backward or passive recipients of modernization (de Grammont, 2004; Bocean, 2025). This artificial dichotomy between "digital" and "rural" has reinforced extractive development models, overlooking the potential of rural communities to actively shape and adapt technology (Jamanbalayeva et al., 2025; Zhang et al., 2023).

In Mexico, this tension is particularly significant. It is a multiethnic country with rich knowledge systems and strong communal traditions, while experiencing rapid digital transformation in both urban and rural regions (Valdez-Juárez et al., 2024). During the COVID-19 pandemic, rural communities creatively adapted digital tools for education and cultural transmission, revealing a hybrid and dynamic relationship with technology (Barrios Vázquez, 2021; MacKenzie, 2023). However, digital infrastructure expansion often prioritizes external extractive connections rather than strengthening local networks, deepening inequalities and encouraging youth migration (Lynn et al., 2022; Iveson & Melo Zurita, 2025).

These dynamics reflect a broader global trend: despite the digital economy's rapid growth rural regions in Latin America remain severely underserved, with only 23% of households connected versus 77% in urban areas (Ziegler et al., 2019). In Mexico, nearly half the rural population lives in multidimensional poverty and faces persistent educational and infrastructural barriers (Consejo Nacional de Evaluación de la Política de Desarrollo Social [CONEVAL], 2025). Nevertheless, there are signs of agency and innovation, such as rural women increasingly leading mobile phone adoption and communities experimenting with digital tools to strengthen local economies (Martínez Domínguez, 2024).

This research seeks to answer the following question: How is the digital economy transforming the socioeconomic dynamics of rural Mexican communities, and to what extent does it contribute to reducing structural inequalities while fostering local sustainability and cultural resilience? Addressing this question aims to understand not only the economic dimension of digital integration but also its social, cultural, and territorial implications. Consequently, the main objective of this study is to examine the impact of the digital economy on rural Mexican communities, assessing its

capacity to close historical development gaps, strengthen local economic resilience, and preserve cultural identity within a framework of sustainable and inclusive growth. By reviewing current research and highlighting both promising practices and ongoing controversies, it underscores the need for approaches that move beyond simple connectivity to embrace community agency and technological co-creation.

2. Background

The tension between digital transformation and the preservation of rural ways of life remains one of the most persistent dilemmas in contemporary debates on development, technology, and society. Traditionally, the "digital" has been portrayed as synonymous with progress, innovation, and speed (Bocean, 2025), while the "rural" has been associated with tradition, slowness, and backwardness (de Grammont, 2004). This dichotomy, deeply rooted in technocratic and extractive frameworks, has often depicted the countryside as a blank canvas onto which modernity should be imposed (Jamanbalayeva et al., 2025). However, recent research challenges this binary vision, proposing instead a dynamic conjunction between the digital and the rural—a space of dialogue and mutual transformation that resists homogenizing narratives (Zhang et al., 2023).

In Mexico, this tension acquires particular relevance due to its rich biocultural diversity and the presence of 68 indigenous peoples who maintain millennia-old knowledge systems and communal structures (International Work Group for Indigenous Affairs, 2025). According to a recent report by ECLAC/IFAD, the rural population of Mexico exceeds 50 million people and covers 40% of the national territory (Gaudin & Padilla, 2023). Simultaneously, the country is experiencing rapid digitalization that is reshaping social and economic dynamics in both urban and rural areas (Valdez-Juárez et al., 2024). During the COVID-19 pandemic, for instance, rural students climbed hills to access internet signals for their studies, while elders shared traditional knowledge through digital platforms, revealing a hybrid reality that transcends conventional dichotomies (Barrios Vázquez, 2021; MacKenzie, 2023). There are successful experiences demonstrating the capacity for adaptation and technological appropriation in rural areas. In Chiapas, coffee cooperatives use mobile applications to improve bean quality and connect directly with international markets, bypassing exploitative intermediaries (Simple Blockchain Applications [SIMBA], 2025). In Oaxaca, Zapotec weavers document and market ancestral techniques via social media, strengthening cultural preservation and economic resilience (O'Connell, 2021; Nava Morales, 2023). However, digital infrastructure in rural Mexico often prioritises connections to urban and global markets over strengthening local communications, reproducing extractive logics and deepening historical inequalities (Lynn et al., 2022; Iveson & Melo Zurita, 2025). This contributes to youth displacement, turning technology into a factor that incentivizes migration rather than supporting territorial permanence (Martínez Domínguez, 2024; CONEVAL, 2025).

Far from being spaces resistant to innovation, rural Mexican communities possess a long history of technological transformation, from the domestication of maize (MacNeish, 1967) to the contemporary use of mobile phones for coordinating collective work (Manjarrez, 2023). Numerous community telecommunications initiatives demonstrate that it is possible to design digital infrastructures grounded in collective principles, prioritizing accessibility, cultural relevance, and self-governance (Ajani et al., 2024; Nava Morales, 2023). This perspective demands public policies that move beyond mono-technological visions and embrace diverse knowledge systems and local governance models (Trejo-Quintana, 2020; Valencia et al., 2025). Nevertheless, significant structural challenges persist. The accelerated pace of technological innovation may conflict with the time required for community decision-making, and digital platforms can introduce new forms of surveillance that threaten local autonomies (Gutierrez de Jesus, 2021; Shim et al., 2024).

Globally, the digital economy is projected to become a central transformative driver, valued at USD 16.5 trillion by 2028, equivalent to 17% of global GDP (Chakravorti et al., 2025). However, stark disparities remain: only 23% of rural households in Latin America have internet access compared to 77% in urban areas, perpetuating historical inequalities (Ziegler et al., 2019). In Mexico, over 48% of the rural population lives in multidimensional poverty, facing educational, health, and infrastructural deficiencies that hinder digital inclusion (CONEVAL, 2025; Martínez Domínguez, 2024).

Despite these limitations, there are encouraging signs of emerging digital agency, particularly among rural women, who are increasingly leading mobile phone adoption and reshaping local social and economic networks (SIMBA, 2025; Martínez Domínguez, 2024). The integration of technologies such as blockchain, artificial intelligence, and IoT within communal and ejido structures suggests potential for building decentralised, culturally rooted digital ecosystems (Obasun, 2025; Valdez-Juárez et al., 2024).

From a forward-looking perspective, Mexico stands at a historic crossroads to rethink its role in the global digital ecosystem and become a reference point for inclusive and sustainable technological transitions (Rosa, 2022). The convergence between the rural and the digital is not merely a

challenge but a vital necessity for shaping future socioeconomic models that reconcile technological advancement with ecological and cultural continuity (Contreras-Medina et al., 2020; Sandoval Cabrera, 2019; Stern, 1973).

3. Materials and Methods

In order to address the research question and objective, the study adopted a qualitative, exploratory, and descriptive methodological design, seeking to gain a comprehensive and contextualised understanding of the impact of the digital economy on rural Mexican communities. This methodological approach was chosen in response to the complex and multidimensional nature of the phenomenon under study, which requires an in-depth understanding of sociocultural dynamics, technological adaptation processes, and transformations in traditional productive structures (Lim, 2025). This qualitative approach enables the interpretation of meanings, perceptions, and experiences of those involved, facilitating an understanding of how digital transformation interacts with indigenous worldviews, ancestral practices, and community organizational systems (Makateng & Mokala, 2025). This approach prioritises descriptive richness and analytical depth over statistical generalisation, recognising that rural digitisation processes manifest in different ways in specific geographical, cultural, and socioeconomic contexts.

3.1. Research Design

The qualitative component of the research was structured through a systematic literature review covering specialized sources on the rural digital economy (Lim et al., 2022). A bibliographic search strategy was implemented using internationally recognized academic databases, including MDPI, SpringerLink, SAGE, Elsevier, and Redalyc. Search terms in Spanish and English, such as "rural digital economy," "digital economy rural communities," "digital transformation agriculture," and "digital divide rural Mexico", were used, combined with boolean operators "AND" and "OR" to optimize the retrieval of relevant information. Inclusion criteria prioritized scientific articles published in indexed journals and chapters from academic books specializing in rural development and technology. Official reports from public and private organizations were also included, dating from 1967 to 2025. Document selection emphasized empirical studies, systematic reviews, and theoretical frameworks that contributed to understanding technology adoption processes, the socioeconomic impacts of rural digitalization, and experiences of implementing public policies for digital inclusion. Official reports were analyzed using thematic content analysis techniques to identify recurring patterns in policy objectives, implementation strategies, performance indicators, and reported obstacles (Braun & Clarke, 2022). This approach enabled institutional perspectives to be contrasted with the empirical evidence collected, identifying convergences and divergences between political intentions and implementation realities in the territory. It also allowed the coherence between official discourse and documented experiences in rural communities to be evaluated.

In addition, two case studies were analyzed: the states of Oaxaca and Chiapas, which were selected for representing paradigmatic contexts of rural Mexico, characterized by their socioeconomic, cultural, and technological features. Case studies are a qualitative research method that has been widely used to gain an in-depth understanding of social phenomena (Yin, 1989). Oaxaca is a notable case study due to its ethnic diversity, socioeconomic marginalization, and advances in community e-commerce, such as the "Producto Oaxaca" store on Mercado Libre, as well as its telemedicine and satellite connectivity projects via CFETEit. In contrast, Chiapas stands out as a coffee producer with traceability initiatives using blockchain technology and direct trade platforms, such as "Café Orgánico," which connect producers with global markets.

3.2. Data Processing and Analysis

The data analysis strategy was carried out systematically. Qualitative information derived from a literature review, document analysis, and case studies was processed using thematic coding techniques with the help of NVivo 12 software. Open, axial, and selective coding were employed to identify emerging patterns, conceptual categories, and theoretical relationships (Mortelmans, 2025). Thematic analysis was complemented by content analysis techniques for government documents and case studies. This analytical process culminated in the construction of a convergence/divergence matrix that systematised concordances and discrepancies between different types of qualitative evidence, thus facilitating the formulation of conclusions. Different versions of the NVivo software, including version 12, can be downloaded free of charge via the following link: https://techcenter.qsrinternational.com/Content/nv12/nv12_standard_installation.htm

The methodological strategy was supported by NVivo 12 software, which analyzed the data through thematic coding. This tool facilitated the management, organization, and analysis of a diverse and complex body of work consisting of three main sources: a systematic literature review; an analysis of official reports; and case studies. Triangulating these sources enabled different scales

of evidence—macro, meso, and micro—to be integrated, providing a comprehensive view of the socioeconomic dynamics associated with implementing the digital economy in rural contexts. The analysis began with the creation of a project in NVivo 12, into which PDF and Word files were imported, including institutional reports and specialized academic publications. The documents were then classified into thematic folders to allow efficient traceability of the analyzed material. The analytical strategy was structured around an iterative coding process based on the Grounded Theory principles proposed by Strauss and Corbin (1998) and adapted for use in a digitally assisted qualitative analysis environment. This process was carried out in three complementary stages: i) Open coding, which aimed to identify emerging concepts; ii) Axial coding, which focused on grouping and relating categories; and iii) Selective coding, which aimed to integrate the central categories that underpinned the overall interpretation of the findings.

3.3. Process of Constructing the Analysis Assisted with NVivo 12

The first phase of the analysis involved open coding to identify emerging concepts directly from the text. Key fragments were given initial labels such as “structural digital divide,” “symbolic connectivity,” and “absent infrastructure.” These codes did not respond to a prior hypothesis; rather, they emerged from patterns or discursive emphases detected in the documents' content. This coding enabled the predominant approaches of official digital policy and the tensions highlighted by the literature to be thematically approximated. In the second phase, axial coding was used to group the open codes into broader, more analytically coherent categories. For instance, codes relating to service costs, signal quality, and limited access were integrated into the category “Material barriers to digital inclusion.” Similarly, references to the role of the state, private investment, and regulatory frameworks were grouped under “Institutional architecture of digitalization.” Subsequently, selective coding was applied to identify the central categories that summarize the observed phenomenon. This stage highlighted integrative concepts, such as “asymmetry in technological appropriation,” which articulated the material, cultural, and political aspects of unequal access to the digital environment.

To systematize the points of convergence and contradiction between the different sources, a comparative matrix was constructed in NVivo. This matrix covered categories such as “connectivity,” “effective access,” “productive use,” and “community values,” relating them to the type of source analyzed (academic literature, an official report, or a case study). Cross-referencing revealed that, for example, whilst official documentation emphasizes the extent of connected communities, case studies show that this connectivity is often intermittent or unequal. Similarly, critical literature highlights how the discourse of digital modernization often renders the dynamics of exclusion or cultural resistance to the intensive use of digital platforms invisible (Table A1).

4. Case Studies: Oaxaca and Chiapas

4.1. Oaxaca

Oaxaca is emblematic of rural Mexico. According to the 2022 Agricultural Census, the state comprises 9.2 million hectares of rural land, 1.9 million of which are used for productive activities such as agriculture and livestock farming (Martínez Domínguez, 2025). The state is characterized by its high indigenous diversity, high levels of marginalization, and low urban density. However, it has recently shown growing interest in the digital economy (Jiménez García, & Pérez Soto, 2020). In 2024, only 69.2% of Oaxacan households had internet access, which was one of the lowest percentages in the country (National Institute of Statistics and Geography, 2024). In order to reduce this disparity, the local government has introduced various initiatives. A notable example is the collaboration with Mercado Libre to establish the official “Producto Oaxaca” shop on the e-commerce platform. Under this agreement, the state provides training in e-commerce to Oaxaca’s rural entrepreneurs and artisans and gives them access to an online marketplace, thus increasing their potential clientele (see https://www.oaxaca.gob.mx/comunicacion/gobierno-de-oaxaca-y-mercado-libre-suman-esfuerzos-para-impulsar-la-digitalizacion-de-las-pequenas-y-medianas-empresas/).

In addition, a telemedicine programme has been implemented in remote regions of Oaxaca. The programme aims to create a state telemedicine network and provide marginalized populations with quality services using satellite technology. This will avoid unnecessary travel costs and provide free short-term specialized care, as well as training for medical staff. Recent reports indicate that remote medical consultation systems have enabled people in rural areas to consult specialists and receive diagnoses without travelling long distances (Martínez López, 2019). Supported by improvements in school and community connectivity, these digital health initiatives illustrate how digital infrastructure can enhance quality of life in remote locations (Llinás-Delgado et al., 2023).

As part of its digital inclusion policies, the federal government has implemented comprehensive strategies to reduce the technological divide in rural Oaxaca, making systematic efforts to provide satellite internet connectivity to historically disconnected areas of the state. The CFETEit project, also known as "Internet for All," was developed through a strategic public-private partnership between the Mexican government and the US company Viasat. This flagship initiative has succeeded in establishing reliable, high-speed connectivity in 1,169 rural communities across 16 Mexican states (https://es.paperblog.com/viasat-en-el-marco-del-proyecto-de-cfeteit-impulsa-el-desarrollo-de-1169-comunidades-rurales-en-mexico-8028953), and Oaxaca is one of the main beneficiaries of this digital transformation. This technological implementation involved the strategic installation of high-speed access points in key community infrastructure, such as primary and secondary schools, rural health clinics, and public squares. These spaces traditionally lacked any telecommunications services, but now function as central connectivity nodes for their respective communities. The convergence of these concrete examples, which include community e-commerce development, rural telemedicine service implementation, and state-of-the-art satellite infrastructure deployment, demonstrates a growing and sustained trend towards the adoption of digital technologies in this rural Mexican region. This aligns with the findings of Chen et al. (2023). They argue that wireless networks play a key role in reducing the smart infrastructure gap in rural communities, where inequalities in ICT infrastructure, access to software, and individual capabilities pose significant barriers to smart society development. The structural causes of this digital transformation lie in the consolidation of effective public–private strategic alliances and the development of comprehensive, well-articulated government initiatives that prioritize and promote digital inclusion as a tool for socioeconomic development and reducing territorial inequalities. This contributes to closing the "smart divide," as defined by Chen et al. (2023), through the implementation of ICT infrastructures that allow equitable access to modern information and communication technologies

4.2. Chiapas

Chiapas is the poorest state in Mexico, but this is offset by its important coffee production, which is significant both nationally and internationally (Calvillo-Arriola & Sotelo-Navarro, 2024). For decades, coffee-growing communities in Chiapas have faced structural challenges, including price volatility, exploitative intermediaries, and limited access to international markets (Rice, 1997). However, the digital economy has recently emerged as a catalyst for change, redefining the region's productive and commercial dynamics (Contreras-Medina et al., 2020). A significant advance has been the adoption of digital platforms that connect producers directly with global consumers. Initiatives such as Café Orgánico (*see* www.rutamayacoffee.com) and Equipoise Coffee (*see* www.equipoisecoffee.com/mexico-chiapas-coffee/) have demonstrated the potential of e-commerce by enabling the sale of certified organic coffee in premium markets in Europe, Asia, Oceania, and the United States. This has increased local income by up to 40% by eliminating intermediaries (Folch & Planas, 2019). At the same time, emerging technologies have improved the production process and supply chain by adding value through certification of product quality and ethical origin (Contreras-Medina et al., 2020). Furthermore, blockchain technology has the potential to improve transparency, fairness, and sustainability in the supply chain, which could benefit small coffee farmers (Samoggia et al., 2025). Blockchain initiatives are being implemented in Mexico. One such initiative is Toks, which is improving the lives of small-scale producers by using SIMBA Chain technology (*see* https://simbachain.com/). Toks is a Mexican chain of casual fast food restaurants owned by Grupo Gigante. It opened its first restaurant in Mexico City in 1971, near the Basilica of Our Lady of Guadalupe. It currently operates more than 200 locations nationwide and plans to expand further. In response to the growing popularity of sustainable brands among consumers, some companies have resorted to 'greenwashing', such as mixing low-quality coffee beans with organic beans and marketing them as high-quality organic coffee. This practice can occur at different stages of the supply chain. Recognizing this issue, Toks has implemented a transparent system to verify the authenticity of its coffee beans, tracing them from farm to restaurant. This level of transparency validates the product segmentation and eliminates the possibility of greenwashing or mixing beans of different qualities (Feghali et al., 2025). These measures have enabled Toks to reduce the number of intermediaries in its supply chain and increase the average farmer's income by 700% (SIMBA, 2025). SIMBA Chain's cloud platform allows academic, industrial, and government institutions to swiftly and effectively develop and deploy distributed Web 3.0 applications (dApps) across various blockchain protocols. Established in 2017 with funding from a DARPA grant awarded to the University of Notre Dame and ITAMCO, SIMBA Chain has received TechPoint's 2019 Mira Award for New Product of the Year and 1st Source Bank's 2019 Commercialization Award. The platform is compatible with various blockchain protocols, including Avalanche, Ethereum, Consensys Quorum, Binance Smart Chain, Stellar, and Hyperledger (SIMBA, 2025).

However, this transition faces barriers. Lack of connectivity remains a major obstacle: although programmes such as Internet for All have made progress, 46% of rural municipalities in Chiapas and Oaxaca still lack adequate coverage (Centro México Digital [CMD], 2022). This digital divide limits access to essential tools, ranging from sales platforms to agricultural management systems. Added to this is the lack of training in basic digital skills, which hinders full participation in the digital economy (Barbara Mungaray Moctezuma & Guadalupe González López, 2025).

The cultural dimension adds complexity to the process. Some communities view technology as a threat to their traditional practices, which creates resistance to its adoption (Ortíz Ricaurte, 2004). The conflict between innovation and tradition requires a sensitive approach that balances modernization with the preservation of identity, avoiding homogenizing solutions (Castillo-González & Gabarrot Arenas, 2021). To assess the impact of this transformation, contrasting indicators must be considered. Among the advances are increased income, access to global markets, and the promotion of sustainable agriculture. However, challenges remain, including insufficient infrastructure, dependence on new digital intermediaries, and educational barriers. Transparency in the value chain and the loss of traditional practices are ambivalent effects that require contextualization analysis.

Multisectoral initiatives are driving progress. While the Mexico Conectado programme has had a positive impact in rural areas, efforts remain insufficient (Martínez Hernández et al., 2023). Meanwhile, partnerships with private sector actors, such as the Toks restaurant chain, have facilitated investments in digitalization (SIMBA, 2025). The case of Chiapas illustrates the potential of the digital economy to reduce inequalities in marginalized regions, but it also highlights risks that require tailored public policies. The key lies in hybrid models that integrate technology while keeping communities connected to their roots, ensuring digitization is an inclusive tool (Rosa, 2022). The future of Chiapas coffee depends on how these tensions between innovation and tradition are managed.

4.3. Synthesis and Interpretation of Case Studies

An analysis of digitization processes in Oaxaca and Chiapas reveals a paradox that challenges traditional ideas about the digital economy in Mexico. The states experiencing the highest levels of socioeconomic marginalization are undergoing digital transformations that contradict conventional predictions about technology adoption. This apparent contradiction suggests that the digital divide is not simply a matter of economics, but a complex phenomenon involving factors such as political will, strategic public-private partnerships, and the specific needs of each territory. Oaxaca's experience with the CFETEit project and its telemedicine initiatives, as well as Chiapas's e-commerce revolution in the coffee industry, demonstrate that economic marginalization is not necessarily an insurmountable barrier to technological innovation when favorable institutional conditions exist. One of the aspects of this transformation is the reconfiguration of traditional value chains. The Chiapas coffee sector illustrates how digital technologies, particularly blockchain and e-commerce platforms, are dismantling intermediation systems that had remained stable for decades. The Toks chain's 700% increase in producer income demonstrates these technologies' disruptive potential to redistribute value throughout the production chain. However, this apparent economic democratization simultaneously generates new forms of dependence and digital intermediation. Technology platforms, connectivity providers, and e-commerce services are becoming new links in the power chain, which can reproduce traditional asymmetries in different ways. Replacing physical intermediaries with digital ones does not automatically guarantee greater equity; specific regulatory frameworks are required to ensure the fair distribution of value.

Digital infrastructure is emerging as a new territorial factor that is changing the prospects for regional development in rural Mexico. The implementation of satellite connectivity in 1,169 rural communities through the CFETEit project is comparable in historical importance to the construction of roads or rural electrification in past decades. This infrastructure facilitates access to global markets and specialized services, such as telemedicine, while also reconfiguring space-time relationships in historically isolated territories. However, the fact that 46% of rural municipalities in both states still lack adequate coverage reveals that this transformation is creating new exclusionary geographies. The tensions between technological modernization and cultural identity are perhaps the most complex and least resolved aspect of these processes. The community resistance documented in both states should not be viewed as merely irrational obstacles to progress, but rather as a legitimate expression of concern for preserving ancestral cultural practices and traditional forms of social organization. This dichotomy poses a fundamental dilemma for development policies: can technological modernization occur without cultural homogenization? The analyzed experience suggests that successful digitization requires hybrid approaches that integrate technological innovation with respect for local knowledge systems and community organizational forms. The challenge lies in avoiding both technological determinism, which imposes homogeneous solutions, and cultural relativism, which rejects any form of modernization.

The sustainability of these rural digital transformation processes depends critically on three interrelated factors. Firstly, local capacities must be consolidated to reduce external technological dependence and enable community ownership of digital tools. Secondly, economic models must be developed that guarantee the long-term financial viability of digital initiatives, avoiding excessive reliance on government subsidies or short-term private investment. Thirdly, institutional frameworks must be constructed that balance the promotion of innovation with cultural preservation, ensuring that digitalization functions as a tool for social inclusion rather than exclusion. The experiences of Oaxaca and Chiapas demonstrate that rural digital transformation involves more than simply adopting technological tools; it is a complex process of social, economic, and cultural reconfiguration that presents extraordinary opportunities and significant risks for the future of rural development in Mexico.

5. Results

The analysis reveals that the digital economy is actively reshaping socioeconomic dynamics in rural Mexican communities, though in uneven and paradoxical ways. Drawing on a rich background of studies and historical perspectives, rural Mexico has long been perceived as technologically static and resistant to innovation. However, recent empirical evidence contradicts this view, showing that rural areas can become dynamic sites of technological appropriation when adequate institutional support and community involvement converge.

The qualitative, exploratory, and descriptive approach adopted in this research, which included systematic literature review, document analysis, and case studies in Oaxaca and Chiapas, allowed for an in-depth exploration of this transformation. In Oaxaca, the combination of community-led e-commerce initiatives (e.g., Producto Oaxaca on Mercado Libre), telemedicine programmes, and the deployment of satellite-based connectivity via the CFETEit project illustrates a multidimensional integration of digital technologies. These efforts have not only enhanced market access and healthcare delivery but have also strengthened local economic resilience and contributed to cultural preservation through the promotion of local knowledge. Similarly, in Chiapas, digital platforms such as Café Orgánico and the adoption of blockchain technologies in coffee production have reconfigured traditional value chains, enabling producers to bypass intermediaries and achieve income increases of up to 700%. This case underscores how technological tools can disrupt entrenched exploitative structures, allowing for more equitable redistribution of value within rural economies. Nevertheless, the emergence of new digital intermediaries, such as e-commerce platforms and connectivity providers, signals a shift rather than a complete elimination of dependency dynamics, highlighting the need for regulatory frameworks to safeguard fair value distribution.

A major finding is the duality of digitalization as both an enabler and a potential risk. While digital infrastructure, exemplified by satellite connectivity in 1,169 rural communities, has been likened to transformative projects such as rural electrification, the persistence of coverage gaps (46% in some areas) indicates the creation of new spatial inequalities. The study also documents strong community resistance in both states, driven by concerns over the erosion of ancestral practices and local governance systems. Rather than dismissing this resistance as irrational, it should be understood as a legitimate defence of cultural identity.

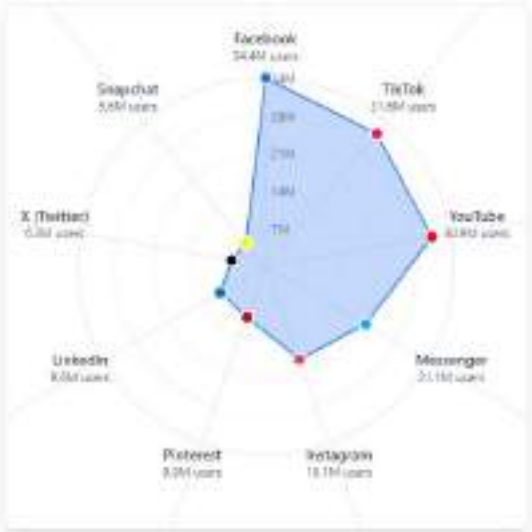
Moreover, the research highlights the critical role of rural women as emerging leaders in technological adoption. Their increased involvement in mobile technology and e-commerce initiatives points to the potential for digital economies to reshape local power dynamics and foster more inclusive socioeconomic structures. However, the lack of training and infrastructural support remains a significant barrier to fully realizing this potential. Overall, these results suggest that rural digital transformation in Mexico is not a monolithic process but rather a complex reconfiguration shaped by historical inequalities, institutional frameworks, and community agency. The interplay between tradition and innovation underscores the importance of hybrid approaches that respect local knowledge systems while fostering technological advancement. In this context, digital economy initiatives must be designed as inclusive tools for development, prioritizing cultural preservation and community empowerment to ensure they contribute meaningfully to reducing structural inequalities and supporting sustainable territorial resilience.

6. Discussion

This study set out to explore how the digital economy is transforming rural Mexican communities, asking to what extent digitalization can become a tool for strengthening rural resilience and territorial permanence, rather than exacerbating historical inequalities. The findings confirm that, far from being passive recipients of external technological impositions, rural communities in Mexico are actively negotiating, adapting, and repurposing digital tools to fit local needs and values. This aligns with recent scholarship arguing for a dynamic conjunction rather than a dichotomy between rural and digital realms (Zhang et al., 2023).

The integration of digital platforms and blockchain technology in Chiapas's coffee sector illustrates a disruptive capacity to dismantle traditional value chains, providing direct access to global markets and significantly increasing producer incomes (SIMBA, 2025; Samoggia et al., 2025). However, these successes simultaneously generate new dependencies on technological intermediaries and global consumer markets, echoing concerns in the literature about the replication of extractive logics within digital infrastructures (Lynn et al., 2022; Iveson & Melo Zurita, 2025). While the elimination of physical intermediaries can democratize economic benefits (Contreras-Medina et al., 2020), it does not automatically ensure equitable power redistribution without robust regulatory frameworks. Similarly, the case of Oaxaca demonstrates that digitalization can transcend mere economic modernization to improve health and cultural outcomes, as seen in telemedicine initiatives and the promotion of local knowledge through e-commerce (Jiménez García, & Pérez Soto, 2020; Martínez López, 2019). Yet, this integration remains uneven: while satellite connectivity projects like CFETEit represent historic milestones comparable to rural electrification (Chen et al., 2023), coverage gaps persist, leaving 46% of rural municipalities without adequate access (CMD, 2022). This reflects broader Latin American trends where only 23% of rural households have internet access compared to 77% in urban areas (Ziegler et al., 2019).

A critical contradiction emerges regarding the perception of rural communities as technologically resistant. Contrary to views depicting rural Mexico as backward or inert (de Grammont, 2004), this research and supporting evidence (MacNeish, 1967; Manjarrez, 2023) show that rural communities have a longstanding history of technological innovation, from maize domestication to contemporary mobile-based collective coordination. This echoes global arguments for community-based, culturally embedded digital infrastructures (Ajani et al., 2024; Nava Morales, 2023). Moreover, the emergence of rural women as digital leaders challenges entrenched gender dynamics, suggesting the digital economy's potential to foster new social configurations and empowerment pathways (Martínez Domínguez, 2024; SIMBA, 2025; Figure 1). However, as Gutierrez de Jesus (2021) and Shim et al. (2024) warn, digital tools can introduce new surveillance mechanisms and exacerbate local vulnerabilities, highlighting the dual nature of technological integration.



Detailed estimation for rural areas

Social Network	National (M)	Rural Estimated (M)	% of Total Rural
Facebook	93	54.4	14%
TikTok	85.4	31.6	13%
YouTube	83.6	30.9	12%
Messenger	57	21.1	8%
Instagram	48.8	18.1	7%
Pinterest	26.7	9.9	4%
LinkedIn	24	8.8	3%
X (Twitter)	16.9	6.3	2%
Snapchat	15.1	5.6	2%

Figure 1. Estimated social media usage in rural Mexico, 2025.

Source: Own elaboration with data from Mejia (2025). Methodological note: The estimation applies a 37% adjustment factor considering that rural areas have limited broadband internet access, lower smartphone penetration, and different digital usage patterns. Facebook maintains its leadership due to its lower data consumption and higher adoption in communities with limited connectivity.

The results underscore the necessity of hybrid approaches that respect local knowledge and governance structures while promoting innovation. The tension between cultural preservation and economic modernization remains a central dilemma (Castillo-González & Gabarrot Arenas, 2021; Contreras-Medina et al., 2020). While some communities perceive digital tools as threats to identity, these same tools can also serve as instruments for cultural survival and market diversification, as illustrated by the Zapotec weavers' social media strategies (O'Connell, 2021; Nava Morales, 2023). Institutional frameworks and public policies thus emerge as decisive factors. Oaxaca's successful e-commerce and telemedicine programmes, supported by strategic public-private partnerships (e.g., with Mercado Libre and Viasat), contrast with infrastructural deficits that continue to impede full participation in Chiapas (Martínez Hernández et al., 2023; CMD, 2022). This supports the argument that political will, community agency, and tailored policy design can mitigate the structural barriers typically attributed to poverty or remoteness (Trejo-Quintana, 2020; Valencia et al., 2025).

Globally, the digital economy is projected to reach 17% of GDP by 2028 (Chakravorti et al., 2025), yet its uneven integration in Mexico reflects the coexistence of advanced technological experimentation alongside severe multidimensional poverty affecting over 48% of rural residents (CONEVAL, 2025; Martínez Domínguez, 2024). This paradox suggests that digitalization alone cannot resolve structural inequalities without simultaneous investments in education, health, and local governance capacity. While Mexico stands at a critical crossroads, possessing both cultural richness and decentralized demographic structures that could support culturally grounded digital ecosystems (Obasun, 2025; Valdez-Juárez et al., 2024), the risk of reproducing extractive and homogenizing models persists (Jamanbalayeva et al., 2025; Rosa, 2022). Therefore, achieving the research objective—to understand how digitalization can support resilience and territorial permanence—depends on policies that transcend technological determinism, instead fostering inclusive, community-led digital transitions. This study corroborates that rural digital transformation in Mexico is a profoundly socio-cultural process rather than a purely technological one. It presents extraordinary opportunities for economic diversification, empowerment, and cultural revitalization, while simultaneously posing significant risks of exclusion, dependency, and cultural erosion. The challenge, therefore, is not merely to implement digital infrastructures, but to co-create them with rural communities, ensuring they become instruments of collective agency and long-term territorial sustainability (Figure 2).

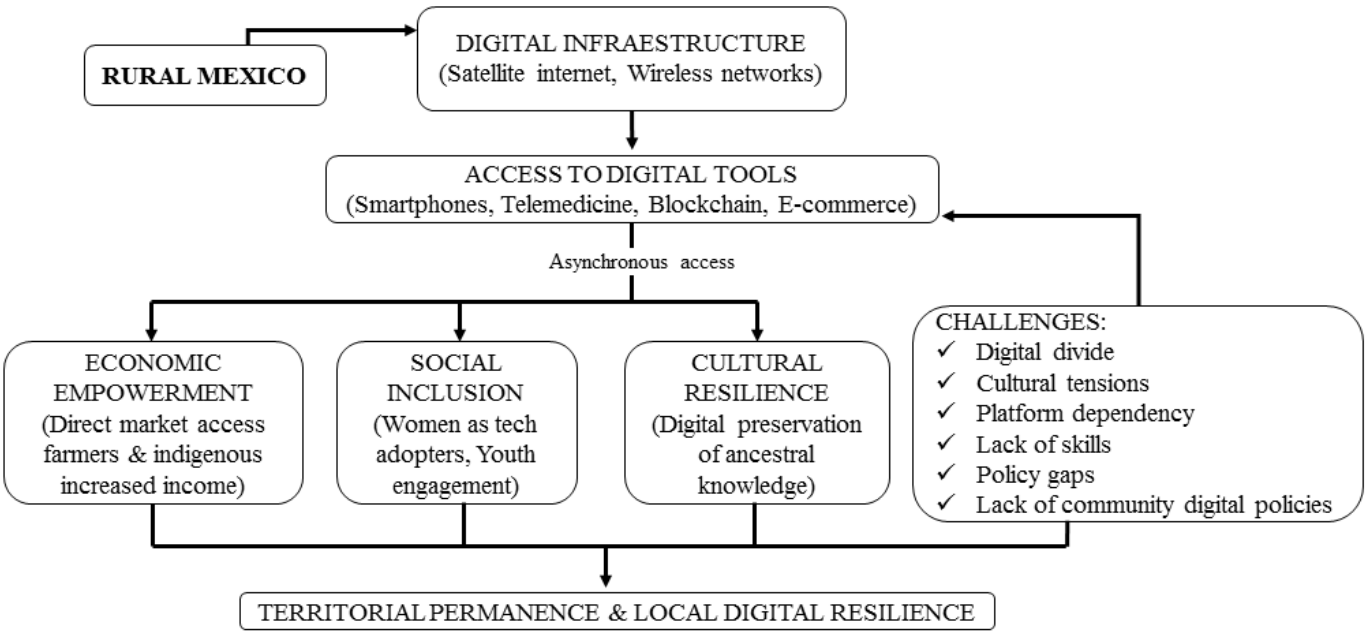


Figure 2. Asynchronous expression of the digital economy in rural Mexico.

7. Conclusions and Strategic Recommendations

7.1. Conclusions

This study set out to examine how the digital economy can support rural resilience and territorial permanence in Mexico, rather than exacerbate existing inequalities. The analysis demonstrates that rural communities are not merely passive recipients of technological innovations; rather, they actively engage in shaping and appropriating digital tools to fit their collective needs and cultural contexts. The case studies of Oaxaca and Chiapas illustrate that digital technologies -from e-commerce and blockchain traceability systems to telemedicine networks- can generate new economic opportunities, improve access to health services, and contribute to cultural revitalization. These experiences challenge the simplistic notion of a strict opposition between digital progress and rural tradition. However, the findings also highlight important contradictions. While digitalization has enabled the dismantling of exploitative value chains and increased local incomes, it has simultaneously introduced new dependencies on external digital platforms and infrastructures. In many rural areas, significant gaps in connectivity and digital literacy persist, limiting the potential for inclusive development. Cultural resistance towards certain technological changes reflects a legitimate concern for safeguarding local identities and ways of life. This tension underscores the need for hybrid approaches that integrate technological innovation with respect for community values and traditional knowledge systems.

Moreover, the emerging leadership of rural women in adopting and managing digital technologies signals important shifts in local social and economic dynamics, opening up opportunities for greater inclusivity and empowerment. Yet, without comprehensive policy support and sustained investment in local capacities, these advances risk reinforcing existing inequalities instead of alleviating them. Rural digital transformation in Mexico is a complex and multifaceted process of social, economic, and cultural reconfiguration. For digitalization to effectively strengthen rural resilience and foster territorial permanence, future strategies must be holistic, community-led, and culturally sensitive. Rather than viewing technology as a tool for imposing uniform models of progress, it should be understood as a means to support diverse, locally defined pathways towards sustainable and inclusive development.

7.2. Strategic Recommendations

It is recommended that future strategies for rural digital transformation in Mexico prioritize the co-creation of technology with local communities, ensuring that innovation strengthens–rather than supplants–territorial knowledge systems. Public policies should promote robust digital infrastructures focused on accessibility and affordability, particularly in the most marginalized areas. Furthermore, it is crucial to develop educational programmes that integrate digital skills with cultural identity, empowering rural youth and women as key agents of transformation. Strengthening transparent regulatory frameworks will also be essential to prevent new forms of digital dependency and guarantee equitable value distribution along local production chains. Finally, fostering multisector partnerships among government, academia, the private sector, and community organizations will enable holistic, context-sensitive solutions that embed technological progress within sustainable and culturally respectful rural development models.

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Abbreviations

The following abbreviations are used in this manuscript:

ECLAC	Economic Commission for Latin America and the Caribbean
IFAD	International Fund for Agricultural Development
ENDUTIH	National Survey on the Availability and Use of Information Technology in Homes

CFETEit	The Federal Electricity Commission's cellular telephone and wireless internet service
CMD	Centro México Digital
CONEVAL	National Council for the Evaluation of Social Development Policy

Appendix A

Table A1. A qualitative analysis process, assisted by NVivo 12.

N°	Stage	Description of the procedure	Results
1	Documentary corpus preparation	The process began with the creation of a project in NVivo. Fifty-seven scientific articles, six institutional reports and two case studies were then imported into the project in compatible formats (PDF and Word).	The corpus was organised by source type and theme to facilitate traceability.
2	Initial thematic classification	The corpus was organised into hierarchically structured folders based on analytical areas, and classified thematically. These folders were labelled: "Public Policies," "Critical Literature," and "Sectoral Studies." This categorisation made it easier to navigate the documents and optimised the identification of patterns according to the level of analysis (macro, meso or micro). Although this phase presented some challenges, such as the possibility of category overlap or the necessity of making early interpretive decisions, implementing it was essential for structuring subsequent analysis.	The initial segmentation of the corpus according to relevant analytical axes.
3	Open coding	Emerging themes were identified directly from the data, without the application of predefined conceptual frameworks. This phase captured the semantic richness of the documents. While this approach resulted in a wide dispersion of categories, it also revealed unanticipated dimensions not identified in the initial theoretical review, thereby broadening the analytical scope of the study.	Generation of initial codes and open nodes.
4	Axial coding	At this stage, an interpretive process was employed to identify the causal conditions, contexts, strategies and consequences associated with each coded phenomenon. Conceptual groupings then emerged, including "structural barriers to digitalisation", "transformation of rural work through ICT", and "technologies as a bridge or cultural rupture". These relationships revealed connections between public policies and the different social effects observed in various regions, among different gender groups, and at different educational levels. This enabled progress towards a relational understanding of the phenomenon.	Consolidation into interrelated thematic categories.
5	Selective coding	This stage involved refining the core categories that explain the phenomenon under study. Based on previous groupings, two main analytical axes were identified: i) digitalisation as a strategy for economic resilience in marginalised communities; and ii) the sociocultural tensions between technological modernity and traditional identities. This synthesis incorporated structural (e.g. connectivity and infrastructure), institutional (e.g., programmes and policies) and symbolic (e.g., local perceptions and values) dimensions, resulting in a theoretical narrative that addressed the research question.	Identification of core categories and construction of the analytical argument.
6	Content and narrative analysis	Alongside thematic analysis, content analysis was applied to official reports, while narrative analysis was applied to case study experiences. This triangulation enabled a comparison to be made between the official and private reports, and the experiences drawn from the case studies. For example, while the reports paint a positive picture of digital coverage, the case studies reveal ongoing issues regarding access, quality and cultural adaptability.	The documentary and experiential evidence was contextualised and interpreted in depth.

Table A1. *Cont.*

7	Convergence/divergence matrix	Coincidences and discrepancies among the sources (literature, reports and case studies) were organised using a comparative analysis matrix. This integrative systematisation strengthened the interpretative validity of the study and enabled conclusions to be formulated.	The results were cross-validated and integrated conclusions and policy recommendations were formulated

Source: Authors' elaboration based on NVivo.

Stage 1: The analytical environment in NVivo 12 was created, efficiently centralizing a diverse corpus. However, it was time-consuming and required technical resources to standardize formats and metadata. For future projects, it will be necessary to curate documents digitally and establish protocols for their collection.

Stage 2: Organizing documents by thematic areas facilitated analytical navigation, but also introduced interpretative bias at an early stage.

Stage 3: enabled the capture of a wealth of emerging themes without prior assumptions, opening the field to diverse interpretations. Nevertheless, the proliferation of nodes led to analytical dispersion that was difficult to manage without prioritization criteria. The establishment of theoretical saturation thresholds is needed to reduce excessive fragmentation.

Stage 4: facilitated the grouping of nodes into categories with causal and contextual relationships, thereby improving interpretive depth. However, this stage relies heavily on the researcher's analytical judgement.

Stage 5: Allowed for the refinement of findings. Nevertheless, there is a high risk of oversimplifying the complexity of the phenomenon by creating overly broad categories. Future research would benefit from striking a balance between theoretical synthesis and contextual specificity.

Stage 6: Key relationships were revealed between institutional sources, literature and cases, generating robust evidence. The main limitation was the difficulty of comparing dissimilar formats (narratives versus technical data).

Stage 7: The analytical process culminated in conclusions being drawn. To enhance the scalability of the findings, it would be useful to combine qualitative analysis with geo-referenced quantitative mapping in future agendas.

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Article

Effects of Production and Distribution Factors on Improved Seed Systems in Nigeria: Implications for Scaling Climate Resilient Production and Food Systems

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Abstract: This study examines the effects of production and distribution factors on improved seed systems in Nigeria and their implications for scaling climate resilient production and food systems, because production and distribution factors of improved seed and planting materials are major determinants of food and livelihood security. In this study, the interactions among these factors were examined using secondary data from the National Seed Council of Nigeria over 12 years. The variables covered are the number of seed companies, agro-dealers, quantity of foundation, certified breeder, and price of hybrid and open-pollinated seeds of maize, rice, sorghum, millet, wheat, cowpea, soybean, and groundnut. Principal component analysis extracted six components underlying seed production and distribution as Factor 1 (non-hybrid), Factor 2 (certification), Factor 3 (foundation), Factor 4 (prices), and Factor 5 (distribution), which accounted for a cumulative 89.51% variance. The correlation matrix shows that the quantity of certified open-pollinated maize seed is the most highly correlated variable, followed by certified lowland rice seed varieties, price of open-pollinated maize seed, and price of rice seeds. The findings on the production and distribution factors for improved seed imply that farmers will have low adaptive capacity in the use of climate resilient production and food systems.

Keywords: climate resilience; seeds; food security; distribution; availability

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1. Introduction

Agriculture in many African countries has been marked by prevailing scenarios of decreasing availability of food, land, water, and energy resources, as well as changes associated with climatic factors, dietary patterns, and technologies (Stringer et al., 2021). Miller et al. (2023) stated that the food production revolution in Africa can be achieved through seed security, which translates to food security by overcoming unstable seed supply, changing climate, and increasing threats of disease and pests, by enhancing farming households' access to adequate quantities of quality seeds and plant materials of adapted varieties at all times. A major response to these scenarios is the intervention to increase access to better quality inputs to close the yield gap between farmers' fields and the actual potential of planting materials (Fraser et al., 2016). Agricultural transformation has always hinged on the use of high-yielding varieties (HYV) and, more recently, climate-resilient planting materials; however low adoption has been reported (Martey et al., 2020; Vercillo et al., 2020).

Food security, nutrition, livelihoods, and environmental sustainability are ensured by the functional seed sector as the most crucial production input (Duncan, et al., 2021) The promotion of increased productivity, food and nutrition security, and resilience among smallholder farmers is dependent on the availability and access to improved seeds (Ruane et al., 2022). The favourableness of soil, climatic, biotic, and abiotic factors would amount to no effects if the quality of seeds and planting materials is low through poor access to improved seeds, fake and recycled seeds leading to low yields (Breen et al., 2024). Good quality seeds are essential for profitable farming in the food production systems, and the challenge of improved seed supply must be tackled to ensure availability, accessibility, affordability, and sustainability for smallholders (Ojiewo et al., 2020; Sperling et al., 2021). The lack of effective improved seeds and planting materials system has led to limited agricultural productivity (Martey et al., 2020), prevented structural transformation (Miller et al., 2023), stagnated yields, neglect of vegetative reproduced crops by the private

sector, complex seed multiplication and distribution requirements and low perceived commercial value (Tadesse et al., 2017). A responsive seed system enhances the diversification of production systems to cope with climate change, reduces the use of pesticides and fertilizers through complementarities, improves resilience with ecosystem services, and enhances income (Joshi et al., 2019). Seed, as the cornerstone of food security, contributes to food systems but is contingent on the seed system that influences the production and distribution (Breen et al., 2024). The improved seeds are produced through a dedicated production channel, with a specific package of practices, with desirable characteristics to local cultivars that give higher yields, are resistant to pest attacks, and require less water supply. Access to seeds and information on improved seeds leads to an increase in yields, production costs, net returns per hectare, and a reduction in poverty incidence (Manda et al., 2025).

The importance of an improved seed system can be attributed to the focus of development and humanitarian practitioners (Martey et al., 2020), increasing yields, yield stability, food security, profitability, and reducing poverty in smallholder farming by exponentially translating seed into food. The process of improved seed production consists of the selection of breeding lines, Identification of promising genotypes, Development of new strains, and evaluation of their performance, through value in cultivation and use to develop distinctness, uniformity, and stability characteristics, seed production, variety maintenance/maintenance breeding, seed quality (genetic purity, physical and physiological quality; Sendekie, 2020; Sundareswaran et al., 2023); Seed health, Seed Quality Assurance through regulation, maintenance, upgradation and enhancement, Genetic improvement, registration for multiplication, field inspection, seed sampling, testing and seed Certification (Kimani, 2025; Gatto et al., 2025). Muthamilarasan and Prasad (2021) noted that all areas of seed improvement require extensive coordination, ranging from genetic diversity, breeding, seed production, seed germinability and vigor, seed marketing, and delivery to the application of sound approaches by the farmers. Vegetative propagation enhances farmers' use of recycled planting materials, but enforcement of property rights is difficult and consequently low returns on investment in improved planting materials through quality control and certification (Wossen et al., 2024). According to Joshi et al. (2019), seed certification is an important step in seed production and marketing, which is usually carried out to maintain high-quality seed standards and make the same available to farmers for maintaining good and quality yields.

Globally, farmers' sources of seeds and planting materials are neighbors, relatives, friends, seed cooperatives/associations, national extension agencies, national seed companies, multinational seed companies, and international gene banks. These sources span the local to international level and are interconnected through multiple linkages and interdependencies (Westengen & Brysting, 2014). It must be, however, noted that there are several intermediaries and varied degrees of access among farmers for each of the sources. The access is also affected by cost, quality, timeliness, availability, and other preferences. Farmers, therefore, explore a combination of sources with different capital assets available to them (Sperling et al., 2021). Several interventions on seeds and planting materials have attempted to increase the capacity for seed multiplication at the personal and communal level; however, the technical limitations have restricted such interventions to open-pollinated varieties.

The seed systems are often fraughted with fake and counterfeit due to urgent and unplanned needs arising from shortages of quantity demanded. Community seed banks, as another mechanism of intervention, have been supported technically, organizationally, and financially by development agencies and complement individual farmers and groups that produce and sell seed following a quality assurance scheme outside the formal systems as intermediaries (Mulesa et al., 2021). Seed banks hold the key to food security and climate change mitigation to alter the trend of losing more than 600 plant species and the extinction of more than 93% of food seed varieties (Wossen et al., 2024).

The availability of improved quality seeds is important for attaining good yields with a significant impact on the farmers' production potential; however, the informal seed system constitutes and dominates about 75% of the seed market. The distribution of improved seeds has not been able to catch up with the pace of releases of improved varieties, over the last ten years, in Kenya, over two hundred maize varieties were released however varieties on farmers' fields were between 15 to 20 years (Ayiecho & Nyabundi, 2025; Obebo & Coyne, 2023); in Ethiopia, 25 common bean varieties were released with a mean varietal turnover of 19 years (Manda et al., 2025).

Even though improved seed is a crucial path for attaining increased yield potential (Obebo & Coyne, 2023), the dominance of the public sector of the upstream seed supply constraints the accessibility of early-generation seeds due to a lack of sufficient capacity within National Agricultural Research Systems (Mastenbroek et al., 2021). In the last two decades, an increase in the number of seed value-chain actors has led to greater seed production, delivery, and quality, albeit not at the level commensurate with the demand (Barriga & Fiala, 2020). The institutional framework to promote the use of improved seeds in Nigeria includes the National Agricultural Seeds Council (NASC), the ANCHOR borrowers' scheme, the Agricultural Transformation Agenda Special

Program, and the Seed Entrepreneurs Association of Nigeria (SEEDAN; Onyeneke, 2021; Iliyasu & Lawal, 2020). Smallholder farm households acquire their seeds through unofficial channels such as fellow farmers and local markets (Chiemela et al., 2021), while only 5 to 10 percent of cultivated land is planted with improved seeds and this has resulted in low yield whereas the use of improved seed varieties can boost crop yield by about 35% (Takeshima et al., 2022; Akanbi, et al. 2022).

HarvestPlus discovered, developed, and delivered biofortified seeds and planting materials to farmers and sequentially engaged farmers by scaling operations through marketing, and finally, anchored biofortification in local food systems for long-term sustainability (Foley et al., 2021). The seed systems are classified as farm-saved seed, community-based, public companies, commercial companies, and closed value chains. Alternative seed systems include seed that is produced by local farmers under financial and technical support from non-government organizations (NGOs) and breeding centers. The intermediary seed system combines attributes of both the formal and the informal seed systems. Smallholder farmers often demand small quantities of seed, exclude remote areas unreached by formal systems, have limited financial resources to purchase certified seed, and have diversified and unpredictable seed demand (McGuire & Sperling, 2016). Private sector participation in the seed sector has been enhanced by several regulations, time and cost investments, and the incentives of intellectual property rights (Miller et al., 2023); on which companies have leveraged economies of scale for vertical integration with other agro-inputs and closing the innovation gap of responding to seeds of crops, geography and market of interest (Deconinck, 2020).

Ojiewo et al. (2020) outlined the principles of mainstreaming improved seeds as a clear theory of change, robust policy environment, regional integration, institutional framework, availability of early generation seed (EGS) elimination of commercial seed class, institutional capacity building, promotion of crop utilization, linkages to market, income security, dietary diversification, resilience, women and youth empowerment, multi-stakeholder platforms and well-defined seed and adoption roadmaps. Several authors listed the seed marketing and distribution constraints to include lack of infrastructure, poor extension support systems, ineffective promotional campaigns, seed prices, market control, poor awareness of varieties and hybrids, monopolistic distribution, and unaffordability of complementary inputs.

Improved seeds have huge potential to enhance food and nutrition security; however, good quality seed availability is not always ensured, and distribution networks are often neglected in the rhetoric of market forces. Improved seed is one of the most important inputs for increasing agricultural production and plays a major role in the spread of improved technology essential for increasing agricultural productivity. Therefore, making high-quality seed available to Nigerian farmers is necessary for the transformation of the predominantly subsistence agricultural production system to achieve a meaningful increase in agricultural productivity in the country.

However, crop production output depends to a large extent on the quality of seed made available and planted by farmers. According to NASC and SEEDAN (2020), the major seed sector challenges are seed production systems and other dependent constraints such as service provision, seed market development, revenue generation and reinvestment, seed sector coordination, and seed sector regulation and management. These are manifested in multi-dimensional scenarios. NASC and SEEDAN (2020) reported that the seed gap in 2020 for Maize HV, Maize OPV, Cowpea, and Groundnut was 90%, −7%, 80%, and 94% respectively. The Maize OPV market is oversaturated, which explains the −7%, implying overproduction and increased availability that lead to reduced prices.

A major hindrance to improved agricultural practices has been the limited availability and accessibility of improved seed and planting materials to farmers, a problem often attributed to the general supply chain and the seed value chain, while overlooking the inherent challenges in seed production and distribution. A major gap addressed by this study is that several types of research on the adoption of improved seeds have focused on constraints at the farmers' level (Ainissyifa et al., 2018), socioeconomic and demographic issues (Atilaw et al., 2016; Ainissyifa et al., 2018; Kansanga et al., 2019), and agroecology and intensification complexities (Quarshie et al., 2021), with little or no attention on the production and distribution factors of improved seed systems.

This paper explores the underlying seed production and distribution factors in order to contribute to knowledge on the improvement of seed production and distribution for improved availability and access to end users. The main objective of this study, therefore, was to examine the examines the effects of production and distribution factors on improved seed systems in Nigeria and their implications for scaling climate resilient production and food systems.

2. Materials and Methods

The study was carried out in Nigeria with a wide range of agroecological zones and arable land, making agriculture account for 45% of the GDP and providing employment for at least 60% of the population, fully or partially. The great cultural diversity and agroecological diversity influence the farming system and dietary patterns, and practices across the country. Despite its

contribution to the economy, Nigeria's agricultural sector is limited by the unmet demand for improved seeds—particularly major staple food crops—high production costs, poor distribution of inputs, limited financing, high post-harvest losses, and poor access to markets. Secondary data was used in this study and was extracted and cleaned from the data collected by the National Seed Council of Nigeria for the 2023 survey /covering the six geo-political zones of Nigeria. The secondary data used for this study were based on the inclusion criteria of production and distributive factors within the last two agricultural seasons in Nigeria. The secondary data from the National Seed Council of Nigeria cover 12 years on the number of seed companies, agro-dealers, quantity of foundation, certified breeder, and price of hybrid and open-pollinated seeds of maize, rice, sorghum, millet, wheat, cowpea, soybean, and groundnut. The actual data of the volume recorded over the years under review were extracted from the data archive of the National Seed Council. Data were analyzed using Statistical Package for the Social Sciences (SPSS) Version 29 to analyze and compare the data collected. Descriptive statistics were computed for the variables (Table 1). Principal Components Analysis was conducted to extract the components underlying the data, and the correlation matrix was examined to assess the interrelationships among variables. The principal component analysis was applied to simplify complex, high-dimensional data sets in relation to production and distribution factors on improved seed systems. The analytical tools applied were based on the need to simplify complex datasets by reducing dimensionality while retaining important patterns and relationships. It does this by identifying the most important directions of variance (principal components) in the data, and then projecting the data onto these directions. This results in a smaller set of uncorrelated variables that capture the majority of the data's variation.

The Principal Components Analysis, as specified by Koutsoyiannis (1972), is presented as follows:

Given variables (*Xs*, the original variables of the composite production and distribution factors)

$X_1 \ldots X_p$: measured in "n" factors

$P_1 \ldots P_P$: the principal components, which are uncorrelated linear combinations of the original variable, $X_1 \ldots X_p$, given as:

$$\begin{aligned} P_1 &= \alpha_{11}X_1 + \alpha_{12}X_2 + \cdots + \alpha_{1p}X_p \\ P_2 &= \alpha_{21}X_1 + \alpha_{22}X_2 + \cdots + \\ P_p &= \alpha_{p1}X_1 + \alpha_{p2}X_2 + \cdots + \alpha_{1pp}X_{pz} \end{aligned} \quad (1)$$

The component loadings were chosen on the condition that the principal components were not related, and that the first component would account for the maximum possible proportion of the total variation in the original variables. The PCA helps to filter out principal components that have low variance and high noise, which can help reveal the underlying structure and patterns in the data.

Table 1. Description of independent and dependent variables.

Seed parameters C- certified, F- foundation, B- Breeder	Unit (MT)	N - years	Minimum	Maximum	Mean	Std. Deviation
Maize HybridC	Quantity	12	1,137.0	4,639.0	2,823.1	922.8
Maize OPVC	Quantity	12	1,781.0	71,145.0	25,450.3	24,576.1
Rice LowlandC	Quantity	12	965.0	90,439.0	32,522.3	31,551.8
Rice UplandC	Quantity	12	219.0	2,790.0	1,218.8	885.6
SorghumC	Quantity	12	199.0	2,845.0	1,164.6	888.6
MilletC	Quantity	12	98.0	1,002.0	401.7	321.2
WheatC	Quantity	12	0.0	250.0	73.3	84.7
CowpeaC	Quantity	12	50.0	1,448.0	354.3	444.5
SoybeanC	Quantity	12	151.0	3,278.0	1,122.4	950.6
GroundnutC	Quantity	12	15.0	586.0	235.4	194.3
MaizeF	Quantity	12	0.0	2,631.0	613.4	920.5
RiceF	Quantity	12	0.0	1,624.0	272.3	532.3
SorghumF	Quantity	12	0.0	157.0	23.5	48.2
MilletF	Quantity	12	0.0	16.0	2.0	5.0
WheatF	Quantity	12	0.0	37.0	6.8	13.3
CowpeaF	Quantity	12	0.0	63.0	10.2	19.6
SoybeanF	Quantity	12	0.0	157.0	32.8	58.4
GroundnutF	Quantity	12	0.0	105.0	11.9	30.0
MaizeB	Quantity	12	0.0	298,700.0	60,610.0	85,518.7
RiceB	Quantity	12	0.0	114,900.0	41,641.7	39,785.1
SorghumB	Quantity	12	0.0	28,300.0	5,609.6	9,372.2
MilletB	Quantity	12	0.0	6,000.0	987.5	1,752.7
WheatB	Quantity	12	0.0	7,000.0	1,733.3	2,786.1
CowpeaB	Quantity	12	0.0	9,600.0	3,133.3	3,618.6
SoybeanB	Quantity	12	0.0	12,100.0	4,725.0	4,646.0
GroundnutB	Quantity	12	0.0	37,240.0	7,445.8	11,265.2
Maize HybridP	Price	12	155.0	400.0	250.7	86.7
Maize OPVsP	Price	12	125.0	370.0	214.3	81.4
RiceP	Price	12	149.0	400.0	239.7	82.4
SorghumP	Price	12	116.0	350.0	198.8	67.4
MilletP	Price	12	77.0	400.0	206.7	100.3
CowpeaP	Price	12	150.0	600.0	295.0	139.8
SoybeanP	Price	12	132.0	850.0	279.8	196.3
GroundnutP	Price	12	238.0	700.0	398.7	155.7
No companies	Actual number	12	0.0	51.0	9.8	15.1
companies /state	Actual number	12	1.0	11.0	4.8	3.2
Agrodealers	Actual number	12	1.0	48.0	16.4	14.3

3. Results

The results of the Principal Component Analysis (PCA) of Effects of production and distribution factors on improved seed systems are in Table 2. Five factors were extracted due to the Kaiser criterion, which was used to select the underlying types and the number of components explaining the data. All variables in each of the extracted components that had Eigen values, which are a measure of explained variance, of less than one, while variables with factor loadings greater than or equal to ± 0.300 were considered in the depiction of the components. Similarly, a factor loading significantly contributes to the derived component of the study if it exceeds 0.30; thus, all the items explaining each derived component on the scale were expressed properly on the PCA.

Table 2. Principal Analysis Components estimates

Variables labels	Variable description	1	2	3	4	5	Communalities
M _OPVC	Maize OPVC	.679					.793
R_LC	Rice LowlandC	.749					.938
R_UC	Rice UplandC	.648					.865
S_C	SorghumC		.526				.786
M_C	MilletC		.522				.827
Gnut_C	GroundnutC		.657				.833
M_F	MaizeF		.551				.988
R_F	RiceF			−.713			.939
S_F	SorghumF			−.768			.948
M_F	MilletF			−.788			.999
W_F	WheatF			−.725			.954
Soy_F	SoybeanF			−.737			.800
Gnut_F	GroundnutF				−.833		.959
M_B	MaizeB				−.694		.963
M_OPVP	Maize OPVsP				.885		.987
R_P	RiceP				.857		.982
S_P	SorghumP				.882		.990
Mi_P	MilletP				.927		.951
Cow_P	CowpeaP				.829		.813
Soy_P	SoybeanP				.874		.886
Gnut_P	GroundnutP				.645		.758
Comp_N	No companies					.694	.852
Agro_D	Agrodealers					−.603	.775

According to Otitoju and Enete (2016) “only variables with factor loadings of ± 0.346 and above at 10% overlapping variance were used in naming the factors and significant at 1% level of probability; thus, variables that have factor loading of less than ± 0.346 were not used while variables that loaded in more than one constraint were also discarded”. The squared multiple correlations between each item and all other items that are commonalities show the relationship between each variable and all other variables; it also shows the association between variables. In this study, GroundnutP (0.758) is the least explained by the analysis. The extracted components for production and distribution factors on improved seed systems are described as Factor 1 (non-hybrid), Factor 2 (certification), Factor 3 (foundation), Factor 4 (prices) and Factor 5 (distribution), which accounted for 53.02%, 16.24%, 10.59%, 5.24%, 4.41 of the variances respectively; with a cumulative 89.51% variance.

The results of the correlation matrix of production and distribution factors on improved seed systems in Nigeria are presented in Table 3. Positive correlation signifies a direct relationship, and negative correlation reflects an inverse relationship.

Table 3. Correlation matrix of production and distribution factors on improved seed systems.

	M _OPVC	R_LC	R_UC	S_C	M_C	Gnut_C	M_F	R_F	S_F	M_F	W_F	Soy_F	Gnut_F	M_B	M_OPVP	R_P	S_P	Mi_P	Cow_P	Soy_P	Gnut_P	Comp_N	Agro_D
M _OPVC	1																						
R_LC	**0.58***	1																					
R_UC	**0.62***	0.95**	1																				
S_C	0.16	0.18	0.10	1																			
M_C	0.35	**0.69***	**0.59***	0.30	1																		
Gnut_C	**0.72****	**0.77****	**0.71***	0.17	0.47	1																	
M_F	0.12	**0.60***	0.47	**0.58***	**0.79****	0.34	1																
R_F	**−0.69***	**−0.67***	**−0.65***	−0.36	−0.40	**−0.62***	−0.42	1															
S_F	**−0.66***	−0.51	−0.49	0.02	−0.17	−0.42	−0.07	0.43	1														
M_F	**−0.73****	−0.49	−0.48	−0.08	−0.33	−0.42	−0.18	0.44	**0.95****	1													
W_F	**−0.72****	−0.41	−0.40	−0.18	−0.46	−0.37	−0.26	0.39	**0.82****	**0.95****	1												
Soy_F	**−0.65***	−0.52	−0.52	−0.24	−0.33	−0.49	−0.25	**0.76****	**0.67***	**0.73****	**0.71***	1											
Gnut_F	**−0.74****	−0.57	−0.55	−0.14	−0.32	−0.50	−0.20	**0.63***	**0.92****	**0.95****	**0.88****	**0.91****	1										
M_B	**−0.66***	−0.40	−0.39	−0.09	−0.37	−0.34	−0.19	0.24	**0.88****	**0.95****	**0.94****	0.52	**0.81****	1									
M_OPVP	0.38	0.54	0.41	**0.71****	0.31	0.47	0.49	−0.56	−0.54	−0.51	−0.42	−0.47	−0.56	−0.44	1								
R_P	0.36	0.48	0.34	**0.70***	0.25	0.42	0.43	−0.52	−0.53	−0.50	−0.41	−0.45	−0.54	−0.43	**0.99****	1							
S_P	0.35	0.55	0.40	**0.73****	0.36	0.46	**0.58***	−0.52	−0.51	−0.49	−0.41	−0.45	−0.53	−0.43	**0.98****	**0.97****	1						
Mi_P	0.44	**0.65***	0.48	**0.58***	0.44	**0.61***	**0.59***	**−0.61***	**−0.60***	**−0.58***	−0.48	−0.54	**−0.63***	−0.49	**0.95****	**0.92****	**0.96****	1					
Cow_P	0.40	0.50	0.36	**0.60***	0.22	0.45	0.50	−0.45	**−0.59***	−0.55	−0.44	−0.44	−0.56	−0.48	**0.86****	**0.83****	**0.91****	**0.88****	1				
Soy_P	0.38	**0.67***	0.52	**0.62***	0.44	0.55	**0.73****	**−0.59***	−0.52	−0.51	−0.43	−0.51	−0.56	−0.42	**0.86****	**0.82****	**0.92****	**0.93****	**0.93****	1			
Gnut_P	0.25	0.28	0.21	**0.61***	0.13	0.21	0.18	−0.42	−0.38	−0.36	−0.30	−0.36	−0.41	−0.30	**0.83****	**0.87****	**0.74****	**0.67***	0.48	0.47	1		
Comp_N	0.13	0.26	0.08	0.45	0.15	0.28	0.22	−0.25	−0.51	−0.47	−0.3	−0.41	−0.50	−0.40	**0.83****	**0.87****	**0.80****	**0.80****	**0.66***	**0.62***	**0.80****	1	
Agro_D	0.17	0.05	0.18	−0.29	0.02	−0.02	0.10	−0.24	−0.15	−0.19	−0.21	−0.20	−0.20	−0.15	−0.26	−0.27	−0.30	−0.18	−0.27	−0.08	−0.22	−0.37	1

4. Discussion

These results affirm Bartlett's Test of Sphericity with a value of $X^2 = 2{,}990.14$, $p = 0.00$, and Kaiser-Meyer-Olkin Measure of Sampling Adequacy of 0.93. The influence of the variables that belong to the extracted components explaining production and distribution factors on improved seed systems was measured by the weights of their factor loadings. The prominent items under the non-hybrid factor are Maize OPVC (.679), Rice LowlandC (.749), and Rice UplandC (.648). Quarshie et al. (2021) stated that the commercialization and adoption of improved varieties are hindered by early Generation Seeds value chain constraints among smallholder farmers; lack of knowledge about the seeds, socio-economic, and institutional factors influenced the adoption of OPVs (Sigigaba et al., 2021). Ayenan et al. (2021) reported that available seed varieties are predominantly open-pollinated and that private sector-mediated seed systems offered the higher potential for seed quality and profitability, with the community-based seed system showing the highest potential for ensuring the greatest access to seeds.

4.1. Findings from Principal Component Analysis

For the certification Factor, the items are SorghumC (.526), MilletC (.522), GroundnutC (.657), MaizeF (.551). Ayenan et al. (2021) found that in Africa, Quality Declared Seed is an alternative seed quality assurance adapted to contexts where official seed regulatory bodies have limited resources to implement a complete certification scheme. Mamo et al. (2023) affirm that seeds from informal seed systems are less expensive because they do not go under the certification process, are distributed through Farmer-to-farmer exchange networks, and are thus readily available for farmers, however, Kuhlmann et al. (2023) stated that mandatory Value for Cultivation and Use (VCU) trials and state-controlled seed certification are the two examples of regulatory approaches that may work for cereals. Ayenan et al. (2021) reported that a lack of human and technical resources, understaffing in seed certification agencies, and weak collaboration between seed sector stakeholders are institutional factors hindering the production and delivery of high-quality seed to farmers. Kuhlmann et al. (2023) reported that a government-centered approach to seed quality control was adopted in many countries in sub-Saharan Africa without the requisite capacity for such. Similarly, a government-centred approach was applied to the neglected alternatives to certification, such as truth-in-labelling, self-certification, group quality assurance, quality-declared seed, and other approaches (Kuhlmann & Dey, 2021). Kuhlmann et al. (2023) found that in Nigeria, seed certification is mandatory for the formal seed sector, but not for registered vegetable varieties produced in the informal sector, which are only subject to minimum standards that have yet to be defined.

The foundation factor is composed of items such as RiceF (−.713), SorghumF (−.768), MilletF (−.788), WheatF (−.725), SoybeanF (−.737). Kimenye (2014) stated that foundation seeds are critical for the promotion of better access to high-quality seeds which can be through farmer-led seed production of contract model, research model, and quality declared seed model for the acquisition of skills for establishment and management of seed production and marketing; while Walsh et al. (2015) found that community seed production improves formal and farmer seed system links, sustains transition into commercial entities, and linkage with publicly funded programs. The production and delivery of breeder and foundation seed is a key bottleneck in the performance of seed value chains in sub-Saharan Africa (Integrated Seed System Development Africa, 2015). However, Chivasa et al. (2022) and Rutsaert et al. (2021) reported that the unavailability of early-generation seed, breeder, pre-basic, and basic seed is considered a major bottleneck in seeds and varietal replacement.

The prices factor included GroundnutF (−.833), MaizeB (−.694), which were inversely correlated. Langyintuo (2020) found that seed prices are a major impediment to farmers' access to improved seeds and inputs. Thomas (2020) found that cost limits the use of improved seeds and consequently limits the productivity level. However, other price factors positively correlated are Maize OPVsP (.885), RiceP (.857), SorghumP (.882), MilletP (.927), CowpeaP (.829), SoybeanP (.874), GroundnutP (.645). Branca et al. (2022) found that access to extension services, land, credit, and input and output markets impact the adoption of improved seeds; while Dunjana et al. (2022) reported that Availability and access to improved seeds determine household food and livelihood security.

The distribution factor is composed of two variables that includes number of companies (.694), Small and medium enterprises occupy space in Africa's agricultural input value chains, involving seed companies and input agro-dealers that facilitate the distribution of improved farm inputs, extension information and post-harvest handling services to smallholder farmer (Alliance for a Green Revolution in Africa, 2017; Das et al., 2019). Ncube et al. (2023) found that local seed systems contribute to household seed security through timely and effective distribution networks that offer several choices and alternatives. Kaliba et al. (2021) stated that agricultural projects that

enhance access to improved seeds generate a positive and sustainable effect on food security and poverty alleviation. The other variable in the distribution factors is agrodealers (−.603). Haug et al. (2023) reported that effective distribution of improved seeds enhances the multiple expectations of seed systems outcomes; while Doody (2023) stated that last mile delivery of stress-tolerant and nutritious seeds addresses the impacts of climate change, pests and diseases, shocks on food systems, by enhancing access to a diverse range of seeds means they can choose the best varieties to suit their needs and their local environment. The distribution factors is enhanced according to Bernard et al. (2023) that unless combined with interventions to maintain soil fertility, policies to promote modern seed varieties may come at the cost of important losses in biodiversity and Myeni and Moeletsi (2023) stated that the adoption of improved seed varieties was driven mostly by factors such as easy and stable access to seeds.

4.2. Findings of the Correlation Matrix

The matrix shows that certified open-pollinated maize seed is the most highly correlated variable, showing significant relationships with 10 other variables in the production and distribution factors of improved seed systems. These are R_LC, $r = 0.581$, $p < 0.05$; R_UC $r = 0.616$, $p < 0.05$, Gnut_C $r = 0.716$, $p < 0.05$. Thijssen et al. (2015) noted that integrated seed sector development as an inclusive approach through local seed business that recognizes and builds upon a diversity of seed systems and complements farmers' practices, for increased farmers' access to quality seeds of superior varieties; and Vernooy et al. (2019) stated that resilient seed systems are critical to sustainable food systems connected to diverse cultural and culinary traditions, and promote diet diversity and health, thus responsive to climate change food and nutrition security, and agricultural biodiversity enhancement. The other variables have inverse relationship and these are: R_F $r = -0.695$, $p < 0.05$; S_F $r = -0.668$, $p < 0.05$; M_F $r = -0.732$, $p < 0.05$; W_F $r = -0.727$, $p < 0.05$; Soy_F $r = -0.659$, $p < 0.05$; Gnut_F $r = -0.741$, $p < 0.05$ and M_B $r = -0.661$, $p < 0.05$. Westengen and Brysting (2014) found that the value and importance of location-specific information about crop variety use are crucial to seed systems perspectives. Cacho et al. (2020) found that the participation of communities in the breeding, delivery, and adoption of resilient seeds would be enhanced by the establishment and maintenance of a flexible national seed sector.

In the matrix, certified lowland rice seed is correlated with 8 other variables of the production and distribution factors of improved seed systems, which include M _OPVC $r = 0.581$, $p < 0.05$; R_UC $r = 0.959$, $p < 0.05$; M_C $r = 0.691$, $p < 0.05$; Gnut_C $r = 0.771$, $p < 0.05$. Choudhary and Kumar (2020) stated that improved seeds offer ample opportunities to adapt and respond to climate variabilities, while Kansiime et al. (2021) found that seed production by farmers contributed to the increased availability of quality seeds, and quality-declared seeds were constrained by a lack of access to foundation seeds, inspections, and seed testing services. The other variables correlated are M_F $r = 0.600$, $p < 0.05$; R_F $r = -0.670$, $p < 0.05$; Mi_P $r = 0.656$, $p < 0.05$; Soy_P $r = 0.670$, $p < 0.05$. The development of different seeds and varieties, and their delivery through a variety of models, recognize the existence of diverse demands and have implications for organizing and targeting the seed delivery system (Mausch et al., 2021).

Similarly, the quantity of sorghum foundation seeds is significantly correlated to 7 variables of the production and distribution factors of improved seed systems, M_F $r = 0.959$, $p < 0.05$; W_F $r = 0.827$, $p < 0.05$; Soy_F $r = 0.671$, $p < 0.05$. The educational level, credit access, household income, extension services, and seed quality significantly and positively influenced farmers' selection of a formal seed distribution system, while the distance to the nearest seed distribution area negatively influenced the selection of a formal seed distribution system in the study areas (Wosene Minwagaw & Gobie Ejigu, 2021).Others are Gnut_F $r = 0.916$, $p < 0.05$; M_B $r = 0.881$, $p < 0.05$; Mi_P $r = -0.604$, $p < 0.05$; Cow_P $r = -0.592$, $p < 0.05$. Ahmed et al. (2017) found complementarity of the adoption of improved seed and crop diversification. The utilization of improved seed was constrained by unaffordable prices of improved seed, limited financial capacity, untimely availability of improved seed, and lack of credit for seeds and fertilizer (Tarekegn & Mogiso, 2020).

In addition, the quantity of certified sorghum seeds is significantly correlated to M_F $r = 0.577$, $p < 0.05$; M_OPVP $r = 0.712$, $p < 0.05$; R_P $r = 0.702$, $p < 0.05$; S_P $r = 0.731$, $p < 0.05$; Mi_P $r = 0.578$, $p < 0.05$; Cow_P $r = 0.603$, $p < 0.05$; Soy_P $r = 0.624$, $p < 0.05$; Gnut_P $r = 0.611$, $p < 0.05$. The trend of the relationship in the correlation matrix can be attributed to the use of some crops for market-oriented production, as well as the crops used in the farming system practices for intercrop and crop rotation, particularly in the cereal-legume combinations. The demand for seeds is also influenced by the use of different cereals as alternatives in the intercrop and crop rotation cycles. In Ethiopia, the pluralistic seed system development strategy enhanced the elimination of dysfunctionalities associated with the seed system but not the time lags associated with the informal seed system (Mulesa et al., 2021).

5. Implications for Scaling Climate Resilient Production and Food Systems

The findings have established the nexus among seed availability, distribution, climate resilience, and food systems. In this study, seed availability is the ability to supply sufficient quantities of quality seed to meet the needs of farmers. The availability of early generational seeds influences the critical connection between breeding activities and the eventual production and distribution of varieties to farmers. The timeliness, quantity, and accessibility factors, such as price and ease of purchase, would have a combined effect on response to climate change and the food systems. The food systems of the majority of farmers in Nigeria depend on the crop production practices to guarantee household food security and income generation for other essentials for their livelihoods. Cramer (2019) stated that a great deal of previous development funding on breeding new varieties and farmers' adoption notwithstanding, early-generation seed (EGS) availability continues to be limited by bottlenecks in the supply chain, particularly for non-hybrid varieties and less-commercialized food crops developed by public-sector institutions. The provision of farmers with access to the latest, improved germplasm plays a major role in adapting agricultural systems to climate change, while the adoption of improved varieties with climate resilient traits stimulates private sector interest and investment in seed systems (Das et al., 2019). The seed system interventions promote the distribution of climate-resilient varieties, diffusion of nutrient-dense varieties, increased speed of delivering new varieties, reaching the last-mile areas and populations, and maintenance of performance in high-stress contexts.

6. Conclusions

The analysis of the trend of production and distribution of improved seeds over a 12-year period has explored the nexus of seed availability, distribution, climate resilience, and food systems. The production and distribution factors influence response to climate change and food security, because seed security is food security, while seed insecurity undermines subsequent production. The extracted components for production and distribution factors on improved seed systems are non-hybrid, certification, foundation, prices, and distribution. The matrix shows that certified open-pollinated maize seed is the most highly correlated variable, showing significant relationships with 10 other variables in the production and distribution factors of improved seed systems. The availability of seed in sufficient quantities and quality to meet the needs of farmers would promote the replacement of old varieties with varieties with climate-resilient traits that are crucial in responding to the incidences of climate change. The study concludes that the availability of foundation, breeder, and certified seeds, in addition to the number of seed companies, agro-dealers, influences improved seed availability. The concerted efforts of role players in the seed systems, such as breeders, seed producers, governmental and non-governmental extension workers, drive the development, release, and rapid adoption of improved seeds towards contributing to food and income security of farming households and mitigation of climate change effects. This study recommends actionable policy interventions covering strengthening farmer seed systems, improving seed quality and availability, promoting equitable access to improved varieties, and supporting the seed sector.

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Abbreviations

HYV	High-yielding varieties
NGO	Non Governmental Organisation
NASC	National Seed Council
SEEDAN	Seed Association of Nigeria
OPV	Open Pollinated Variety
HV	Hybrid Variety
EGS	Early-Generation Seed

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Article

Differentiated Adaptation Dynamics to Climate Change in the Cameroonian Sahel: Local Perceptions and Agricultural Resilience in a Context of Multidimensional Vulnerability

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Abstract: This study examines perceptions of climate change and the adaptation strategies adopted by small-scale producers in the sudano-sahelian region of Cameroon. The survey was conducted in five villages distributed along a North-South ecological gradient: Pintchoumba, Bamé, Bang (North Region), and Gadas and Douroum (Far North Region). A sample of 250 producers comprising 30 agro-pastoralists, 10 livestock farmers, and 10 crop farmers per village was interviewed using a structured questionnaire based on a three-level Likert scale. The data, processed using R and Excel, primarily represent individuals aged 36 to 45, with women accounting for 22% to 30% of respondents. Findings indicate that 60% of participants perceive climate change through rainfall variability, rising temperatures, vegetation loss, and increased incidence of crop diseases. Perceptions and vulnerability levels vary by geographic location, gender, and livelihood. The northernmost villages, particularly Douroum and Gadas, appear to be the most affected, especially among livestock farmers. Reported adaptation strategies include crop diversification, adoption of short-cycle seeds, transhumance, and food storage. The study recommends context-specific responses: promotion of organic farming in the South, irrigation and farmer innovation hubs in central zones, and microcredit schemes, pastoral corridors, and assisted natural regeneration in the arid North. Emphasis is placed on integrating local knowledge, empowering women, and fostering inclusive governance.

Keywords: perception; sahelian gradient; local knowledge; resilience; farming practices; agricultural challenges

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1. Introduction

Climate change is a global phenomenon whose effects are felt across nearly the entire surface of the Earth. It manifests through profound and lasting changes in climate systems, affecting the frequency, intensity, duration, and spatial extent of extreme events such as heatwaves, cyclones, prolonged droughts, sudden floods, as well as the emergence of agricultural diseases and pests (Bryan et al., 2013; Gaymard et al., 2015; Mbuli et al., 2021; Verma et al., 2025). These disturbances have significant ecological, social, and economic consequences, making adaptation essential, particularly in climate-sensitive sectors such as agriculture.

These climatic disturbances have directly impacted on agricultural productivity. Recent studies indicate that average cereal yields in northern Cameroon have declined by 15 to 30% over the past two decades, mainly due to decreased rainfall, shortened growing seasons, and the increased prevalence of diseases and agricultural pests (Fofiri Nzossie et al., 2016). Staple crops such as millet and sorghum critical for household food security are particularly affected. For example, sorghum yields dropped from 1.1 tonnes per hectare in 2000 to less than 0.8 tonnes per hectare in

some departments by 2022 (MINEPAT, 2022). This decline threatens the livelihoods of over 730,000 people, including many women and youth highly dependent on subsistence agriculture.

Globally, approximately 475 million smallholder farmers cultivate less than two hectares of land (Aguiar et al., 2020; Morton, 2007). These farmers, who contribute significantly to food security in developing countries, are especially vulnerable to climate change impacts. Their reliance on rain-fed agriculture, limited financial and technical resources, restricted access to climate information and technologies, as well as social and land tenure inequalities, increases their exposure to poverty and food insecurity (Njoya et al., 2022; Verma et al., 2025).

These climatic disturbances have had direct impacts on agricultural productivity. Recent studies indicate that average cereal yields in northern Cameroon have declined by 15 to 30% over the past two decades, mainly due to decreased rainfall, shortened growing seasons, and increased prevalence of diseases and agricultural pests (Fofiri Nzossie et al., 2016). Staple food crops such as millet and sorghum which are crucial for household food security are particularly affected. For example, sorghum yields dropped from 1.1 tonnes per hectare in 2000 to less than 0.8 tonnes per hectare in some departments by 2022 (MINEPAT, 2022). This decline threatens the livelihoods of over 730,000 people, including many women and youth who depend heavily on subsistence agriculture.

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In sub-Saharan Africa, this vulnerability is even more pronounced. The region is among the most exposed to climate change effects due to low adaptive capacities, heavy dependence on rain-fed agriculture, and multiple socio-economic challenges (Ofori et al., 2021; Sani & Chalchisa, 2016). Extreme weather events are becoming more frequent and severe, threatening the livelihoods of millions of farmers. For example, in East Africa, recurrent droughts have caused crop failures, large-scale population displacement, and increased food insecurity (Bryan et al., 2013; Verma et al., 2025). Adaptation challenges are compounded by limited access to infrastructure, agricultural extension services, and financing.

In Cameroon, climate change affects the entire country, but its impacts are particularly pronounced in the sudano-sahelian zone in the northern part of the country. This region experiences high climate variability: declining rainfall, rising temperatures, frequent droughts, floods, soil degradation, and biodiversity loss (Bienvenu et al., 2023; Raimond et al., 2020; Traore, 2022). According to the UN, 80% of agricultural land in this area is degraded. Lake Chad, which plays a crucial role in the region's water balance, has lost 95% of its surface area over the past sixty years (United Nations High Commissioner for Refugees [UNHCR], 2021). These harsh conditions threaten the food security of approximately 730,000 people, including many women and youth (Douswe, 2023).

In this context, smallholder farmers, often reliant on traditional practices, develop adaptation strategies based on their perceptions, local knowledge, and available resources (Gashure & Wana, 2023; Soumaoro, 2022; Takpa et al., 2022). However, these perceptions are influenced by various factors such as socioeconomic characteristics, gender, geographic location, and type of agricultural activity (Intergovernmental Panel on Climate Change, 2023; Kabore et al., 2019; Momangi et al., 2023; Ngoukwa et al., 2023). For instance, some farmers associate climate change with declining rainfall, while others link it to rising temperatures or violent winds (Ofori et al., 2021; Oumarou et al., 2017; Raimond et al., 2020). Other studies highlight that farm income per hectare is linked to adaptation strategies implemented, access to credit, education level, fertilizer use, and government support (Asravor, 2023).

However, few studies examine farmers' perceptions based on the intensity or combination of these criteria. Differentiated assessments by territory or social category remain limited. Despite numerous efforts to strengthen farmers' resilience to climate change, there is still a lack of a solid analytical and action-oriented framework that takes local specificities into account.

It is within this framework that the present study is situated. It combines a mixed qualitative and quantitative approach to thoroughly explore the differentiated perceptions of smallholder farmers according to gender, socio-professional category, and geographic location along the sudano-sahelian gradient of Cameroon. This approach not only identifies manifestations of climate change as locally perceived but also analyzes adaptation strategies implemented, while accounting for social and territorial disparities often overlooked in the literature.

The study thus aims to answer the following questions:

- What are the major environmental problems faced by villages in Northern Cameroon over the past five years?

- How do smallholder farmers perceive the degree of manifestation of these environmental problems?
- What measures have been taken by this population to address these issues?

Does the level of appreciation of environmental variations vary according to gender and category of farmers along the sahelian gradient?

1.1. Problem Statement

Climate change is one of the most significant challenges facing rural communities worldwide, particularly in ecologically vulnerable areas such as the sudano-sahelian region of Cameroon. This region is characterized by high climatic variability, including prolonged droughts, unpredictable floods, rising temperatures, accelerated soil degradation, and dwindling water resources most strikingly illustrated by the dramatic shrinkage of Lake Chad, which has lost nearly 95% of its surface area over the past sixty years (Gaymard et al., 2015; Raimond et al., 2020; UNHCR, 2021).

Observations gathered from several villages in the region, including Pintchoumba, Bamé, Bang, Gadas, and Douroum, reveal direct impacts on the livelihoods of smallholder farmers. They report a continued decline in agricultural yields, the gradual disappearance of traditional millet and sorghum varieties, and major disruptions in the agricultural calendar, which was once regulated by relatively predictable seasons. For instance, in Gadas, farmers now say that the rainy season begins nearly a month later than it did twenty years ago, severely affecting planting and harvesting cycles.

In response to these disruptions, local communities have developed empirical adaptation strategies rooted in indigenous knowledge, such as the observation of natural indicators (e.g., bird migrations or the flowering of certain plant species), community-based cooperation, and the diversification of crops and income sources. In Bamé, for example, some households are turning to agroforestry or off-season vegetable gardening to compensate for losses in staple crops.

However, local perceptions of climate change, which shape these adaptive practices, remain insufficiently documented and rarely integrated into public policies or climate resilience programs. Few studies have explored how farmers perceive the intensity and frequency of climatic events, especially in relation to variables such as gender, type of agricultural activity, geographic location, or access to resources (Kabore et al., 2019; Momangi et al., 2023; Ngoukwa et al., 2023). Yet these perceptions play a crucial role in shaping risk awareness, responses to environmental change, and the adoption of appropriate adaptation measures.

This lack of integration of local experiences and knowledge constitutes a major obstacle to the design of inclusive, effective, and sustainable adaptation strategies (Akinkuolie et al., 2025; Bryan et al., 2013). A deeper understanding of farmers' worldviews, their primary concerns, and the adaptive responses they develop is thus essential to inform public policy, support community-led initiatives, and foster climate resilience grounded in local realities.

This study offers a novel contribution by integrating local perceptions of climate change with territorial, social, and occupational dimensions, aiming to develop tailored and context-sensitive adaptation strategies in Cameroon's sudano-sahelian region.

1.2. Research Objectives

1.2.1. General Objective

The general objective of this study is to analyze smallholder farmers' perceptions of climate change in the sudano-sahelian region of Cameroon and to examine the adaptive responses they implement, taking into account the lived experiences in the affected villages.

The study is grounded in field observations conducted in several communities, including Pintchoumba, Bamé, Bang, Gadas, and Douroum, where farmers have expressed growing concerns about shifting rainfall patterns, declining soil fertility, and emerging socio-economic vulnerabilities. The adaptation strategies observed vary depending on gender, social status, primary occupation, available resources, and proximity to markets or agricultural services.

1.2.2. Specific Objectives

To identify how smallholder farmers describe climate change based on their local experiences, highlighting observed indicators (e.g., delayed rains, excessive heat, disappearance of local species) and the perceived impacts on their farming activities, crops, and immediate environment.

To document the main concerns expressed by farmers, particularly regarding food security, soil exhaustion, and the erosion of traditional knowledge linked to the agricultural calendar.

To inventory the adaptation strategies adopted across villages along the sahelian gradient, with a focus on indigenous knowledge and farmer-led innovations. These include the use of early-maturing crop varieties, crop rotation, community savings mechanisms, and ancestral water conservation techniques such as stone bunds and infiltration pits.

To analyze how perceptions of climate change vary by gender, socio-professional status, and types of agricultural activity (e.g., crop farming, livestock rearing, or agro-pastoralism), in order to better understand the diversity of vulnerabilities and adaptive capacities among respondents.

2. Methodology

2.1. Description of the Study Area

This study focuses on five villages located along the sahelian gradient of Cameroon (see Figure 1): Pintchoumba, Bamé, and Bang in the North Region, as well as Gadas and Douroum in the Far North Region. This selection follows a south-to-north ascending gradient, from southern sahelian zones to the most northern areas, allowing for a detailed understanding of climatic, environmental, and socio-economic dynamics. These villages are distributed across the departments of Faro, Bénoué, and Mayo Louti (North Region), and Mayo Kani and Diamaré (Far North Region).

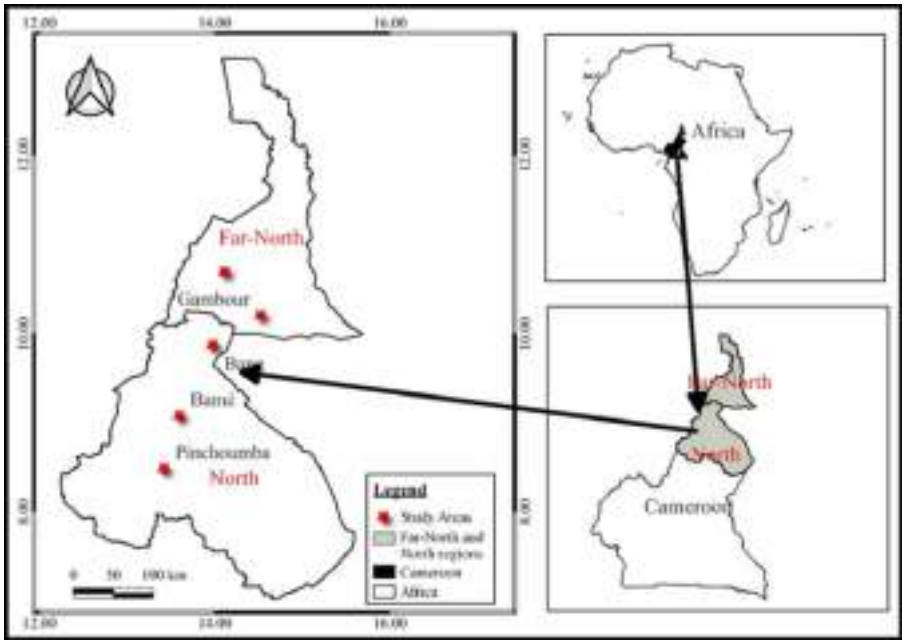


Figure 1. Location maps of the study areas.

The North Region extends between 9.2458° North latitude and 13.3145° East longitude, covering approximately 66,550 km², which represents 14.2% of the national territory (Beauvilain, 1989). Each village in this region faces specific climatic challenges:

At Pintchoumba, increasing rainfall irregularity and soil degradation have led to declining millet and sorghum yields, undermining food security and pushing farmers to diversify their crops. These climatic stresses also reduce fodder availability, weakening livestock health and productivity. Consequently, both crop farming and animal husbandry are increasingly vulnerable, resulting in greater reliance on external food sources.

At Bamé, prolonged droughts followed by sudden floods cause severe soil erosion, crop losses, and disruptions to the agricultural calendar. Farming households struggle to maintain stable production cycles, while livestock often suffers from disease outbreaks due to water contamination and insufficient pasture regeneration. These fluctuations lead to unstable incomes and food supplies for local populations.

In Bang, water scarcity for irrigation and livestock deeply affects agro-pastoral practices. Crop yields are steadily declining, particularly for rainfed cereals, while the lack of grazing areas and watering points threatens livestock survival. As a result, some households reduce herd sizes or sell animals prematurely. This dual pressure contributes to rising food insecurity and drives a shift toward non-agricultural income activities.

The Far North Region, situated around 10.5847° North latitude and 14.2623° East longitude, is the most densely populated region of Cameroon, sharing borders with Chad and Nigeria. Its sudano-sahelian climate features a seven-month dry season and a five-month rainy season. Rainfall ranges from 900 mm in the south to less than 350 mm in the extreme north. Vegetation is sparse, dominated by species such as *Piliostigma reticulatum*, *Dichrostachys cinerea*, and *Tetrapogon*

cenchriformis. Traditional agriculture relies mainly on rainfed crops such as Muskuwaari sorghum, millet, and cowpea.

In Gadas, severe water shortages and accelerated soil degradation have resulted in reduced crop diversity and poorer pasture quality. Farmers report decreased yields of staple crops, while herders face declines in animal weight and reproductive performance. Water scarcity frequently triggers conflicts over access to wells and grazing corridors, destabilizing agro-pastoral systems.

In Douroum, located in the region's most arid zone, conditions are extreme, with recurrent droughts, soil salinization, and a generalized decline in agricultural productivity. Farming is increasingly unsustainable, and livestock losses due to thirst, disease, and malnutrition are common. The limited natural resource base intensifies competition between communities, increasing the risk of conflict and forced migration.

The impacts of these environmental pressures are significant for local communities. Declining crop yields, livestock mortality, and loss of arable land exacerbate food insecurity and rural poverty (Bryan et al., 2013; Njoya et al., 2022). Women, who play a central role in food production, are particularly vulnerable due to their limited access to productive resources and agricultural service . These dynamics contribute to social tensions, especially between farmers and herders, amid shrinking water and grazing resources (Sani & Chalchisa, 2016). Such tensions threaten social cohesion and complicate local conflict and resource management.

In sahelian countries with similar soil and climatic conditions to Cameroon's sudano-sahelian zone, farmers face comparable challenges. Households adopt diverse resilience strategies, including crop diversification, seasonal migration, small-scale trading, collection of non-timber forest products, and community-based mutual aid (Bauer et al., 2022; Fabien & Enock, 2022; Mossie & Chanie, 2024; Toure & Zerbo, 2022). However, these strategies remain constrained by inadequate infrastructure, poor extension services, and limited access to credit and climate information (Verma et al., 2025).

Therefore, a better understanding of local specificities and farmers' perceptions of climate change is essential to guide relevant, equitable, and sustainable adaptation policies.

2.2. Development of the Data Collection Tool

The data collection process was carried out in three distinct phases. First, a literature review was conducted to define climate change in the study area and to identify the main environmental factors contributing to this phenomenon. The results of this literature review were synthesized into a guide that served as the basis for the second phase, the monographic study. This study was conducted using a focus group approach and field observation. The focus groups allowed us to analyze in depth the general situation concerning climate change and environmental factors, while field observation was useful to verify the relevance of the information collected. The monographic study was carried out at the village level to obtain general impressions from different categories of producers and as a group. The results of these two phases formed the basis for developing the individual questionnaire. At the end of this stage, it was found that the majority of the population had a memory of past environmental events over a period of about five years. For this reason, information was collected over a 5-year period.

The third and final phase involved designing the questionnaire. The primary objective of this phase was to assess the perception of climate change by the population individually. Another objective was to establish a list of harmful environmental factors faced by the population and to identify the measures they implement to address these issues locally. Next, the degrees of these findings and the actions taken by the producers were collected, and we obtained very variable responses. Regarding the producers' perception, the recorded events were evaluated using a 3-level Likert scale to describe their intensity. This attitude or multiple scales allowed us to measure different concepts. By operationalizing the qualitative information, it enabled us to transform it into quantified data. It is presented as a three-level measurement scale. Scores from 1 to 3 were used to describe the degree of perception, represented by: 1- "very intense," 2- "moderate," and 3- "not at all."

2.3. Selection of Households: Category of Producers

This study employed a snowball sampling technique to select households, necessitated by the absence of comprehensive records on agro-pastoral farmers in the targeted villages. Snowball sampling, a non-probabilistic method based on peer referrals, was particularly suitable for identifying key local actors while respecting social and community dynamics.

2.3.1. Implementation Procedure

The sampling process was conducted in several stages:

Initially, key informants were identified through collaboration with traditional authorities, community leaders, and local farmers' organizations. These initial respondents, recognized as prominent farmers within their communities, served as seeds for the sampling chain.

Subsequently, these farmers recommended other individuals meeting the following criteria:

(i) active involvement in agriculture, livestock rearing, or both;
(ii) minimum residency of ten years in the village to ensure familiarity with local socio-environmental dynamics;
(iii) voluntary consent to participate in the study.

This approach generated a convenience sample targeting those most representative of local agro-pastoral practices, while considering accessibility and willingness to participate.

2.3.2. Sample Composition

Based on prior research indicating that over 70% of the local population engages in agro-pastoralism (Lasseur et al., 2019; Morgan & Solarz, 1994), the study surveyed 50 households per village, totaling 250 households across five villages. The sample breakdown per village was:

- 30 agro-pastoral households (combined agricultural and livestock activities);
- 10 purely agricultural households;
- 10 purely livestock-rearing households.

Gender representation was intentionally ensured, with women constituting 30% of the sample. This reflects the study's focus on the gendered dimensions of climate change adaptation and acknowledges women's crucial, yet often under-recognized, role in food production and natural resource management.

2.4. Data Collection

The questionnaire designed for this study incorporated multiple environmental factors affecting agro-pastoral systems, including rainfall variability, temperature fluctuations, and specific phenomena such as the disappearance of certain crops and trees, floods, extreme heat waves, severe cold, strong winds, heavy rains, early or late onset and cessation of rains, irregular or insufficient rainfall during the growing season, drying up of rivers and lowered water levels in ponds within Mayo, river siltation, animal epidemics, pasture drought, reduction in tree size, decrease in grass size and density, soil degradation and infertility, field siltation, sand encroachment, as well as increased incidence of plant diseases and crop at-tacks by animals (birds, livestock).

The primary objective was to understand farmers' perceptions of these phenomena and the adaptation strategies they employ to address these challenges. To this end, enumerators, assisted by local guides, conducted face-to-face, individual interviews with each farmer in every village. This method enabled the collection of detailed information on:

- The perceived impacts of various environmental factors on their agricultural and livestock activities;
- Adaptation strategies implemented by farmers, including crop diversification to mitigate risks, adjustment of agricultural calendars in response to changing climatic conditions, adoption of drought- and disease-resistant crop varieties and livestock breeds, improved water resource management (reuse and storage), sea-sonal migration to access better grazing conditions, and engagement in alternative income-generating activities such as small trade and collection of non-timber forest products;
- Community-based mutual aid and resource-sharing practices as forms of collective resilience;
- Constraints faced in implementing these strategies, notably limited access to reliable climate information, infrastructure, credit, and agricultural extension services.

This mixed qualitative and quantitative data collection approach provides a nuanced understanding of local adaptation dynamics in response to environmental pressures, offering critical insights to inform climate adaptation policies at the regional level.

2.5. Data Analysis

To achieve the objectives of this study, two primary analytical approaches were employed: descriptive data analysis and comparative analysis of means. The descriptive analysis involved calculating key statistical measures such as means and standard deviations for each environmental phenomenon reported by the farmers. This process enabled us to quantify farmers' perceptions and assess the variability and distribution of responses within the dataset. Descriptive statistics provided a foundational understanding of how different groups experienced and perceived climate change-related impacts.

To explore differences in perception across various socio-professional categories, specifically farmers, herders, and agro-pastoralists, within each village, means and variability measures were

computed separately for each group. This approach allowed for a nuanced comparison of perceptions at both the group and village levels. Following the descriptive stage, a comparative analysis of means was conducted to identify statistically significant differences in the perception of climate change impacts among groups and between villages. This analysis helped to highlight social and spatial variations in climate change awareness and experience. All analysis was conducted using R and Excel software. R was primarily used for statistical calculations and comparative testing, while Excel supported data organization and initial visualization.

This combined methodological framework enabled a robust quantification of farmers' perceptions and a systematic comparison across demographic and geographic variables, thereby providing clear insights into the differentiated impacts of climate change as perceived by local agro-pastoral communities.

3. Results

3.1. Indicators Reflecting Climate Change

Farmers' perceptions of climate change are grounded in key agro-climatic parameters that directly affect the success or failure of agricultural activities. In this study, these indicators were defined based on farmers' observations of the following environmental variations:

- Changes in rainfall patterns: irregularity, intensity, onset and cessation dates of the rainy season, droughts, and floods.
- Temperature fluctuations: extreme heat waves and periods of intense cold.
- Transformations in local vegetation: disappearance or decline of certain crop and tree species, pasture degradation, and reduction in plant density and size.
- Other related environmental phenomena: river siltation, drying up of water points, soil erosion, and increased incidence of plant diseases and crop damage caused by animals.

These indicators reflect both measurable climatic conditions and the direct impacts experienced by farmers, providing an integrated view of perceived climate change in the study area.

3.2. Factors Influencing Perception of Climate Change: Socio-Economic Variables

The socio-economic variables selected to explain differences in perception of climate change are gender and age of farmers. These choices are theoretically justified as follows:

3.2.1. Gender and Activity Distribution

Incorporating gender and age dimensions into the analysis of climate change perceptions and adaptation strategies is crucial to understanding differentiated vulnerabilities and adaptive capacities within rural communities. Gender influences access to land, financial resources, agricultural inputs, and decision-making power factors that directly affect how individuals perceive and respond to climatic variations (Arora-Jonsson, 2011; Djoudi & Brockhaus, 2011; Nhemachena et al., 2014). For example, women often play a central role in food production and natural resource management, while simultaneously facing structural constraints limiting their adaptive capacity (Babugura et al., 2010; UNDP & UN Women, 2023). Examining gender differences highlights inequalities in exposure and access to adaptive resources, which are essential for designing more inclusive policies (Chidakwa et al., 2020).

Table 1 shows the proportions of women and men in our sample. Moving from south to north along the sahelian gradient, we notice that women are more prevalent in the south and less so in the north. For instance, 30% of those surveyed are women in Pintchoumba village, 32% in Bamé village, 26% in Bang and Gadas villages, and only 22% in Douroum village. This can be explained by the fact that as we move towards the more extreme zones, women are less heard and even less likely to own property.

Table 1. Proportions of Men and Women Based on Their Activities.

Villages	*Pintchoumba*		*Bamé*		*Bang*		*Gadas*		*Douroum*	
Gender	F(%)	H(%)	F(%)	H(%)	F(%)	H(%)	F(%)	H(%)	F(%)	H(%)
Farmers	6	14	8	12	6	14	8	12	6	14
Herders	6	14	4	16	4	16	4	16	2	18
Agro-pastoralists	18	42	20	40	16	44	14	46	14	46
TOTAL	30	70	32	68	26	74	26	74	22	78

Note: F for females, H for males.

3.2.2. Population Distribution by Age Category/Village

Age is a crucial factor as it reflects accumulated experience and the capacity for adaptive flexibility. Older farmers often possess long-term climatic memory and draw upon traditional knowledge to interpret environmental changes (Grothmann & Patt, 2005), whereas younger farmers are generally more open to innovation and changes in agricultural practices. Analyzing differences related to age thus helps to better understand intergenerational dynamics in the perception of climate risks and adaptive decision-making.

Respondents' ages were categorized as follows: young (20–35 years), middle-aged (36–45 years), elderly (46–59 years), and very elderly (60 years and above).

Figure 2 provides an overview of the characteristics of the surveyed producers regarding their age range. It shows that there are four categories of respondents: young, middle-aged, elderly, and senior.

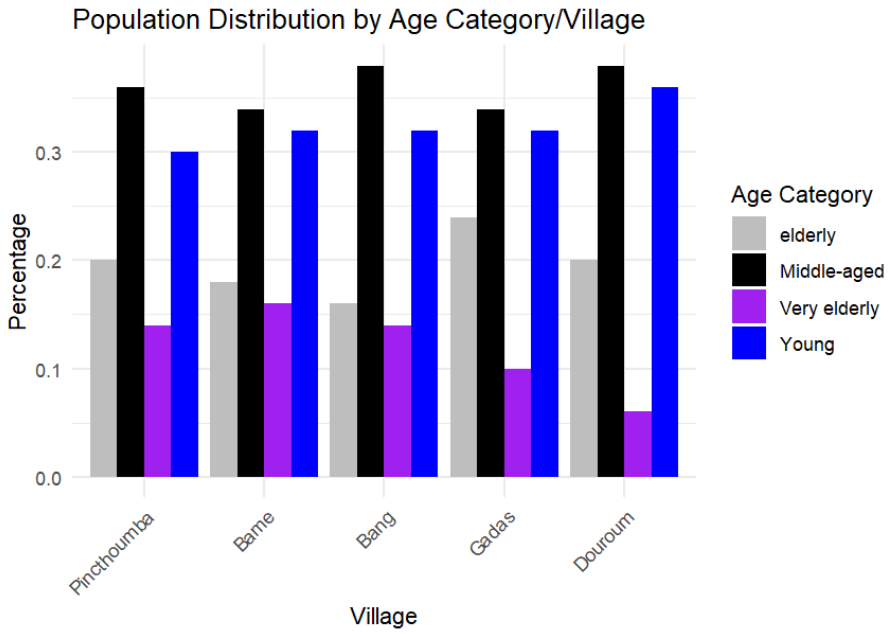


Figure 2. Population distribution by age category/village.

Based on this figure, we observe that the population in our various villages is predominantly composed of middle-aged individuals, with respective percentages of 36% in Pinctchoumba, 34% in Bamé, 38% in Bang, 34% in Gadas, and 38% in Douroum. To explain the observed changes in the different villages, producers use concepts that can be classified into three main categories: disruptions in rainfall patterns, variations in temperature, and changes observed in vegetation.

3.3. Climate Change Indicators According to Producers

Indicators of climate change in the sudano-sahelian zone of Cameroon are assessed along a south-to-north gradient, as each locality exhibits specific socio-environmental characteristics.

3.3.1. Sudano-Sahelian Gradient

The evaluation of recorded phenomena varies according to the intensity and type of activities practiced by the farmers interviewed.

Figure 3 illustrates the perception of climate phenomena by village (Pintchoumba and Bamé) and by activity (agro-pastoralists, farmers, and herders). The y-axis represents the mean perceptions, while the x-axis indicates the activities. The error bars show the variability within each group. The differences between the villages are notable, with Bamé having a higher perception of most phenomena, which could indicate greater awareness or a more significant impact of climate change in this village. Farmers, herders, and agro-pastoralists have different perceptions of climate phenomena, likely due to how each activity is affected by climate change. The variability in perceptions is significant, possibly due to personal experience, access to information, and available resources.

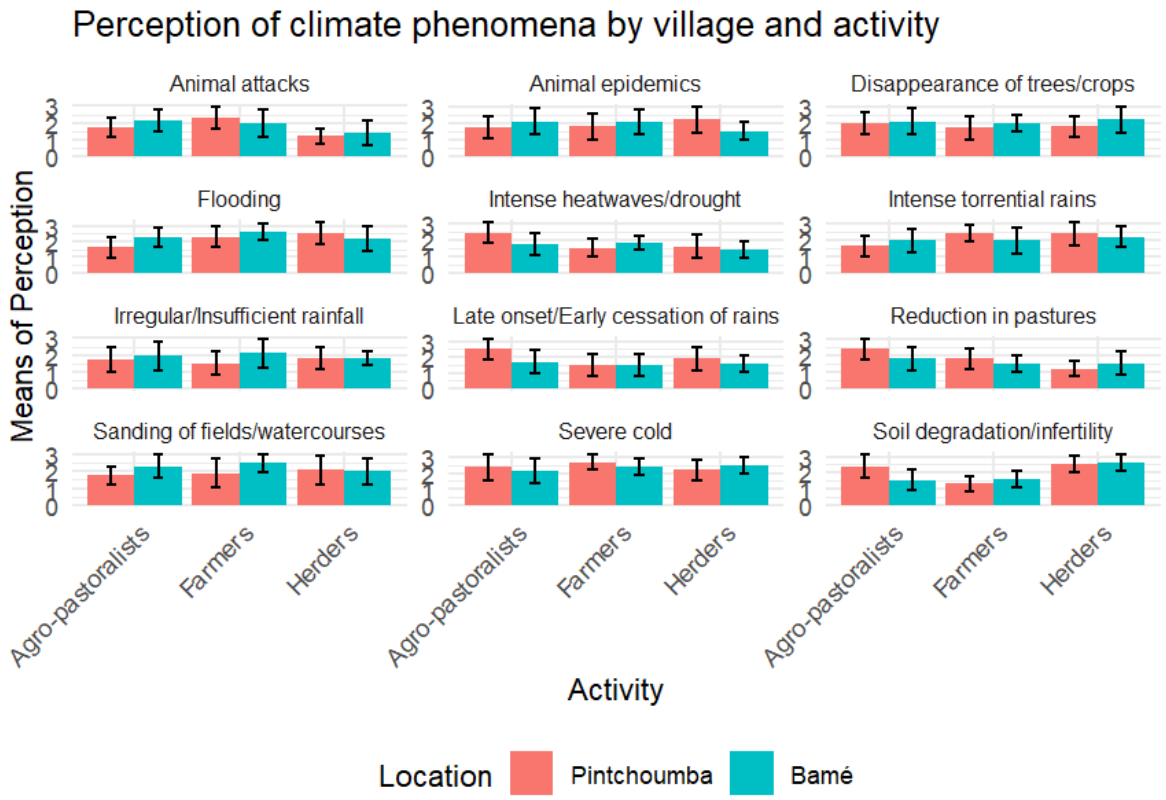


Figure 3. Phenomena recorded by producers in Pinctchoumba and Bamé.

Regarding specific phenomena, animal attacks and animal epidemics are perceived as relatively low, but Bamé has a slightly higher perception. The disappearance of trees/crops is perceived as a high phenomenon in Bamé, likely due to deforestation and land degradation. Inundations are better perceived by farmers and herders in Bamé, due to its geographical situation. Intense heatwaves/droughts are more strongly perceived by agro-pastoralists in Pintchoumba, which could be linked to the impact on pastures and livestock. Torrential rains are perceived relatively uniformly between villages and activities. Irregular/insufficient precipitation is better perceived by farmers in Bamé, which could be due to the impact on crops. The late onset/early cessation of rains is perceived as less important. The reduction of pastures is more strongly perceived by agro-pastoralists in Pintchoumba, which could be linked to drought and land degradation. The siltation of fields/watercourses is better perceived by herders in Bamé, probably due to the impact on water points and pastures. Intense cold is perceived relatively uniformly between villages and activities. Finally, soil degradation/infertility is better perceived by herders in Bamé, which could be due to overgrazing and erosion.

The differences in perception between Pintchoumba and Bamé highlight the importance of geographical location in the perception of climate change. The variable perceptions between activities show that different livelihoods are affected uniquely. Effective climate action requires strategies tailored to specific activities and locations, addressing relevant local issues and engaging the most affected communities.

This graph illustrates the perception of climate phenomena by village (Pintchoumba and Bamé) and by activity (agro-pastoralists, farmers, and herders). The y-axis represents the average perception scores, while the x-axis identifies the different activities. Error bars indicate the variability of perceptions within each group.

Notable differences emerge between the villages, with Bamé showing higher perception levels for most climate phenomena. This suggests either greater awareness or a more significant impact of climate change in this area. The perceptions also vary considerably among agro-pastoralists, farmers, and herders, reflecting the distinct ways in which each livelihood is affected by climatic variations. The variability within groups likely stems from individual experiences, access to climate information, and availability of resources.

Regarding specific phenomena, animal attacks and epidemics are generally perceived as less intense, although Bamé reports slightly higher concern. The disappearance of trees and crops is perceived as a major issue in Bamé, likely linked to deforestation and land degradation. Flooding

is more acutely perceived by farmers and herders in Bamé, which corresponds to the village's geographical vulnerability. Intense heatwaves and droughts are most strongly perceived by agro-pastoralists in Pintchoumba, probably due to their direct impact on pastures and livestock health. Torrential rains are perceived fairly evenly across both villages and all activities.

Irregular or insufficient rainfall is more sharply perceived by farmers in Bamé, likely reflecting its consequences on crop yields. The late onset or early cessation of rains is considered less problematic overall. Reduction in pasture availability is most strongly felt by agro-pastoralists in Pintchoumba, reflecting drought effects and land degradation. Field and watercourse siltation are more frequently reported by herders in Bamé, likely due to the effects on water sources and grazing areas. Perceptions of intense cold are relatively uniform across villages and activities. Finally, soil degradation and infertility are more strongly perceived by herders in Bamé, which may be attributed to overgrazing and soil erosion.

These differences in perception between Pintchoumba and Bamé underscore the importance of geographic context in shaping local experiences of climate change. Similarly, the variation in perceptions across livelihood activities highlights the need for differentiated approaches to climate adaptation. Effective responses should be tailored to specific activities and local conditions, ensuring that the concerns of the most affected communities are addressed.

3.3.2. Median Sahelian Gradient: Bang

Figure 4 illustrates how the inhabitants of Bang, a village in northern Cameroon located in the median sahelian gradient, perceive different climatic phenomena. Perceptions are divided into three groups: agro-pastoralists, farmers, and herders. The height of the bars indicates the average perception, while the error bars show the diversity of responses.

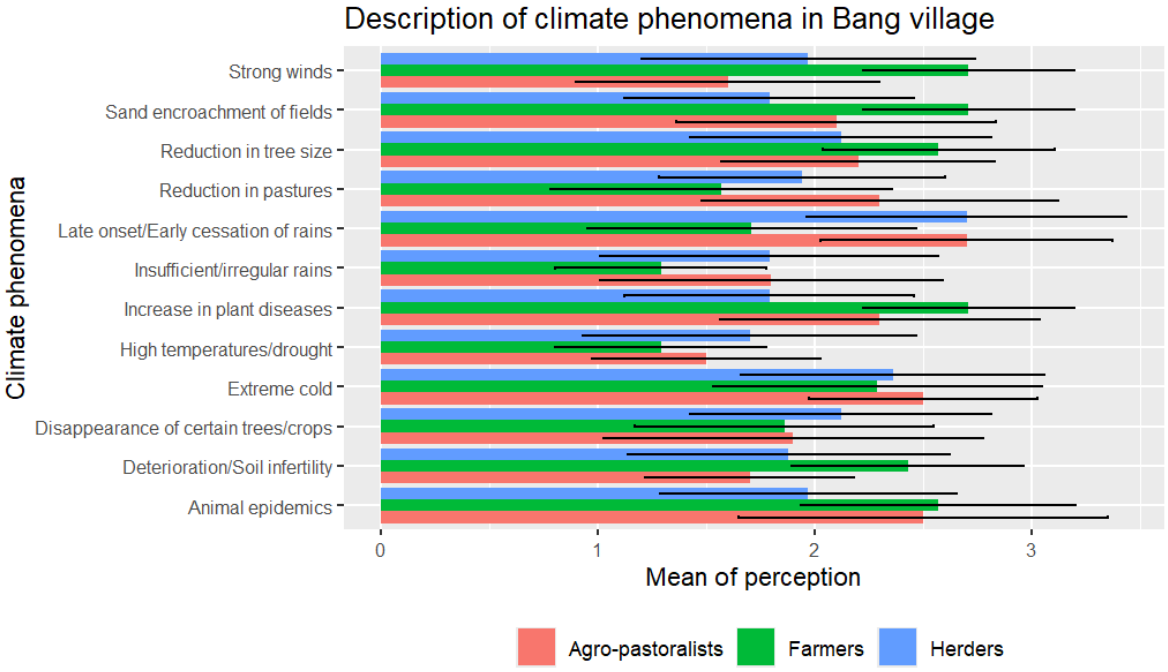


Figure 4. Description of climate phenomena in Bang village.

The most concerning phenomenon: Agro-pastoralists and herders are particularly concerned about the late onset or early cessation of rains (around 2.70), a sign of great climatic uncertainty. Farmers, on the other hand, are more sensitive to strong winds (2.71) and soil degradation (2.57), as they depend directly on the quality of the land. Herders are also concerned about the disappearance of trees and grazing areas (2.12 and 1.94), which are essential for feeding their livestock.

Less concerning phenomena: High temperatures and drought are less concerning (between 1.29 and 1.70), as is the lack or irregularity of rainfall (between 1.29 and 1.80).

Variations between groups: The standard deviations reveal that some perceptions vary greatly, such as for animal epidemics or the reduction in tree size. This suggests that these problems are experienced differently depending on the activity.

Also, by comparing with Pintchoumba and Bamé, villages in the southern Sahel, we see that the climatic issues are different. In Bang, drought and soil degradation are major problems, while

in Pintchoumba and Bamé, where the climate is wetter, other concerns emerge. It is therefore essential to put in place solutions adapted to each region to help populations adapt to climate change.

Finally, the graph highlights the direct impact of climate on activities in Bang. The main concerns relate to the lack of rain and the degradation of natural resources, making the region very vulnerable. In the southern Sahel, although conditions are slightly better, adaptation to climate change remains a priority.

The graph illustrates the perceptions of climatic phenomena among inhabitants of Bang, a village situated in the middle sahelian gradient of northern Cameroon. Perceptions are categorized into three groups: agro-pastoralists, farmers, and herders. The height of the bars in the graph represents the average perception score, while the error bars indicate the variability of responses within each group.

The most concerning phenomena vary depending on the type of activity. Agro-pastoralists and herders express significant concern about the late onset or early cessation of rains (with an average score of around 2.70), reflecting considerable climate uncertainty. Farmers, on the other hand, are particularly sensitive to strong winds (2.71) and soil degradation (2.57), due to their direct dependence on land quality. Herders also report notable concern about the disappearance of trees (2.12) and grazing areas (1.94), which are essential for livestock feeding.

Conversely, some phenomena appear less worrying. High temperatures and drought elicit relatively low concern, with perception scores ranging from 1.29 to 1.70. Similarly, irregular or insufficient rainfall is perceived as less alarming, with scores between 1.29 and 1.80.

Variations between groups are also notable. Standard deviations reveal significant differences in the perception of certain issues, such as animal epidemics or the reduction in tree size, indicating that the perceived impact of these phenomena varies depending on the activity practiced.

When comparing the results from Bang to those from other villages, such as Pintchoumba and Bamé, located in the southern Sahel, clear differences in climate-related challenges emerge. In Bang, the primary concerns are drought and soil degradation, whereas in the more humid south, other climate-related issues are more prominent. This highlights the importance of adapting resilience strategies to regional specificities to effectively address the needs of local populations.

In summary, the graph highlights the direct impact of climate on livelihoods in Bang. The main challenges are related to rainfall irregularity and natural resource degradation, making the region particularly vulnerable. Although conditions are somewhat more favorable in the southern Sahel, adapting to climate change remains a crucial priority across all areas.

3.3.3. Northern Sahelian Gradient

Considering Figure 5 and the location of Gadas and Douroum in the most sahelian zone of Cameroon's sahelian gradient, a thorough analysis reveals complex and nuanced realities. The inhabitants of these villages perceive a series of climatic phenomena as major challenges, although the intensity of these perceptions varies considerably depending on the activity and the village in question. Thus, agro-pastoralists seem particularly concerned about animal attacks and animal epidemics, reflecting their dependence on both agriculture and livestock and, consequently, a greater vulnerability to these hazards. Farmers, for their part, highlight soil degradation and infertility as paramount problems, emphasizing their direct dependence on soil health to ensure viable agricultural production. As for herders, the reduction of pastures is perceived as a dominant concern, highlighting the challenges related to the availability of land needed to feed livestock.

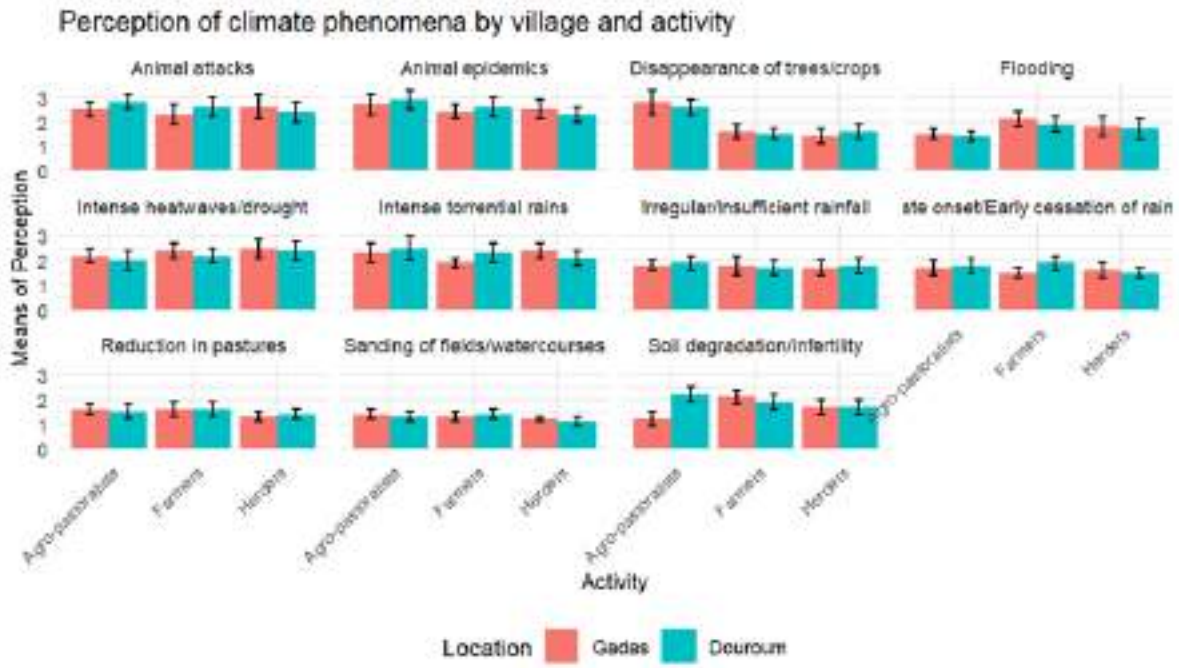


Figure 5. Description of climatic phenomena by producers in Gadas and Douroum.

While perceptions between Gadas and Douroum do not present notable differences for many phenomena, suggesting shared environmental and climatic challenges, some variations can be attributed to local microclimates, distinct agricultural practices, or socio-economic factors specific to each village. Faced with increased drought, intense heat waves, and irregular rainfall patterns, the sahelian communities, which include Gadas and Douroum, face constant challenges that threaten agricultural yields and pasture availability. In addition, soil degradation and infertility emerge as cross-cutting problems, placing additional pressure on livelihoods and agricultural production capacity. These realities underscore the imperative for targeted and context-specific interventions, whether it is to improve soil health for farmers or promote sustainable pasture management strategies for herders. In summary, the graph highlights the complexity of the climate challenges faced by the inhabitants of Gadas and Douroum, emphasizing the need to adopt integrated and adapted adaptation strategies to strengthen the resilience of these sahelian communities.

Considering the location of Gadas and Douroum in the most sahelian zone of Cameroon's sahelian gradient, the graph reveals a complex and nuanced perception of climatic phenomena by the inhabitants of these villages. The intensity of perceived challenges varies significantly according to both the type of activity and the village.

Agro-pastoralists appear particularly concerned by animal attacks and animal epidemics, reflecting their dual dependence on agriculture and livestock, which heightens their vulnerability to such hazards. Farmers, meanwhile, emphasize soil degradation and infertility as critical issues, underscoring the importance of soil health for sustaining agricultural productivity. For herders, the reduction of pastures stands out as the most pressing concern, highlighting the challenges linked to the availability of grazing land for livestock.

While many perceptions between Gadas and Douroum are similar, suggesting shared environmental and climatic stresses, some differences can be attributed to local microclimates, variations in agricultural practices, or socio-economic factors unique to each village. Faced with increasing drought, severe heat waves, and irregular rainfall, these sahelian communities continuously confront challenges that threaten both crop yields and pasture quality. Soil degradation and infertility emerge as cross-cutting issues, further straining livelihoods and production capacities.

These findings underscore the urgent need for targeted, context-specific interventions such as soil restoration programs for farmers and sustainable pasture management for herders to effectively support these communities. In summary, the graph illustrates the multifaceted nature of climate-related challenges in Gadas and Douroum and highlights the importance of integrated, locally adapted strategies to enhance the resilience of sahelian populations.

3.3.4. Measures Taken by Producers

Climate change presents numerous challenges for small-scale farmers, threatening their food security, livelihoods, and resilience to environmental shocks. In response, these rural communities have developed a range of mitigation and adaptation strategies tailored to their local realities and

expectations. These measures are aimed at sustaining agricultural productivity and managing climate-related risks in both farming and livestock systems.

Among the strategies reported by farmers are: crop substitution, acquisition of improved varieties, reforestation, construction of dikes, contour (furrow) cultivation, building animal shelters, spacing houses to reduce wind impact, planting windbreaks, brick stabilization, pruning, clearing irrigation channels, using field supports, hilling crops, early sowing, applying organic fertilizers, exploiting lowlands, building stone cordons, deep plowing, abandoning unproductive fields, veterinary and traditional livestock treatments, transhumance, cultivating forage crops, practicing fallow rotation, using phytosanitary products or biopesticides, and protecting fields from external threats.

For analytical clarity, these measures have been grouped into broader categories, which are visually represented in the graphs that follow. The main categories of adaptation strategies include:

Agricultural Practices: Encompassing actions such as the use of improved crop varieties, contour farming, deep plowing, early sowing, organic fertilization, and the exploitation of lowlands.

Crop Substitution: Referring to the replacement of traditional crops with more climate-resilient species or varieties.

Ecological Measures: Including reforestation, dike construction, windbreak planting, brick stabilization, pruning of trees, and the clearing of water and irrigation channels.

Food Storage: Addressing post-harvest management and crop conservation methods to prepare for periods of scarcity.

Forage Crop Cultivation: Focusing on the production of livestock feed, especially important during the dry season.

Preventive Livestock Treatment: Encompassing both veterinary care and traditional medicinal practices to prevent animal diseases.

Reforestation and Pruning: Aimed at increasing tree cover and managing natural vegetation sustainably.

Housing Restructuring: Involving physical modifications of housing infrastructure to reduce vulnerability to flooding, winds, or storms.

Transhumance: Referring to the seasonal movement of herds in search of better grazing conditions, a key strategy in pastoral systems.

Field Abandonment: Representing an extreme but sometimes necessary measure when land degradation or climate stress render farming no longer viable.

Table 2 enables a differentiated understanding of the adaptation strategies adopted by farmers in response to climate change. By categorizing the measures according to agricultural systems (crop or livestock), ecological approaches, or social resilience mechanisms, the table highlights the diversity and complementarity of local responses.

Table 2. Comparative summary of climate change adaptation measures implemented by farmers

Category	Measures	Objectives	Applicability Conditions	Constraints
Agronomic (Crops)	- Crop substitution - Use of improved seeds - Early sowing - Deep plowing - Exploiting lowlands - Fallowing	Maintain or reduce yield losses caused by climatic hazards	Access to technical knowledge Availability of adapted seeds Land tenure security	High seed costs Lack of technical training Limited water availability
Pastoral (Livestock)	- Transhumance - Forage crop cultivation - Veterinary treatment - Abandonment of grazing areas	Ensure livestock health and feeding during critical periods	Availability of grazing areas Access to veterinary care or traditional remedies Safe mobility routes	Land-use conflicts Livestock diseases Climatic unpredictability
Ecological/Environmental	- Reforestation - Windbreak planting - Dike construction - Stone bunds - Cleaning water channels	Restore and protect natural resources and farming infrastructure	Community engagement Access to natural resources Institutional support	High labor demand Scarcity or cost of materials
Social/Organizational	- Food storage - House spacing - Field abandonment	Reduce the structural and organizational vulnerability of households	Access to storage infrastructure Village-level coordination and planning	High cost of restructuring Lack of community organization

Source: Field survey, 2024.

It also reveals that the implementation of these strategies is conditioned not only by environmental and agronomic variables but also by institutional, financial, and socio-cultural factors. For instance, while agronomic and pastoral adaptations often depend on technical inputs and land access, ecological and infrastructural measures require collective mobilization and material support.

The table thus serves as a valuable tool for identifying entry points for public policy and development programs. It supports the targeting of the most effective and contextually appropriate strategies while drawing attention to the practical constraints, particularly in terms of cost, training, and the availability of resources, that limit the adaptive capacity of smallholder farmers.

Figure 6, illustrating the climate change adaptation strategies implemented by farmers in the villages of Pintchoumba, Bamé, Bang, Gadas, and Douroum, positioned along a sahelian gradient from south to north, reveals distinct dynamics shaped by geography, environmental vulnerability, and access to resources.

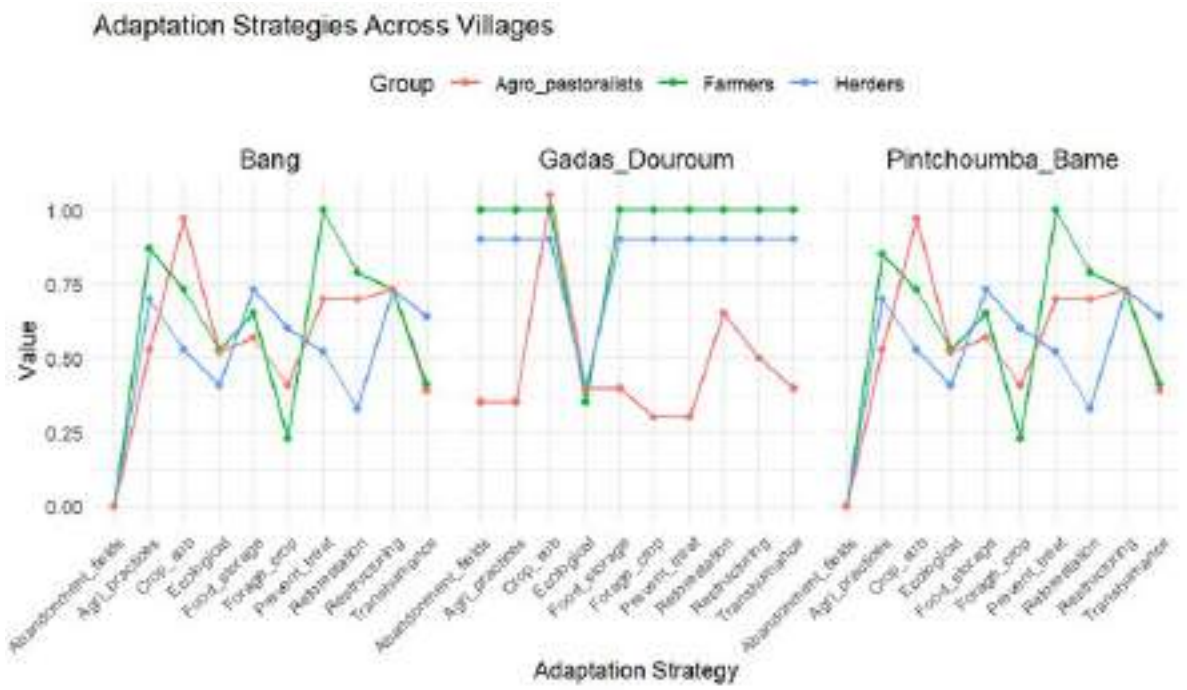


Figure 6. Strategies across villages.

In the less arid southern villages of Pintchoumba and Bamé, farmers primarily adopt agricultural practices (adoption levels around 0.8) and ecological measures (approximately 0.75), reflecting significant efforts to enhance resilience to climate variability. Herders in these areas also implement complementary strategies such as forage crop cultivation and preventive veterinary care (around 0.6). Transhumance is less common (0.4), suggesting greater stability in local pastoral resources. The widespread use of food storage and housing restructuring (values above 0.7) further highlights a strong emphasis on food security and flood risk management.

In Bang, located in the central part of the gradient and subject to higher climatic variability, the adoption of agricultural practices remains strong (0.8), but strategies are more diversified. Agro-pastoralists exhibit high adaptability, with crop substitution reaching maximum levels (value of 1). Transhumance is more widespread than in the southern villages, reflecting growing pressure on grazing resources. Here, strategies are more evenly distributed to address a broader range of climate risks.

In the more arid northern villages of Gadas and Douroum, field abandonment emerges as the dominant strategy among farmers (value of 1), indicating heightened environmental stress. While certain agricultural practices persist, they are constrained by increasingly adverse conditions. Herders rely heavily on extensive transhumance and cross-border grazing, reflecting a deep reliance on mobile livestock systems. High adoption levels (close to 1) of strategies such as food storage, use of improved seeds, reforestation, and forage cultivation are observed, although these often depend on access to external resources and institutional support.

In Bang, the most widely adopted strategies include forage crop cultivation, improved seed use, and transhumance, particularly among agro-pastoralists and herders. Farmers tend to prioritize food storage and crop substitution. More costly or socially disruptive strategies, such as field abandonment or housing restructuring, are less commonly employed.

In Gadas and Douroum, all socio-professional groups widely implement collective and innovative measures, including food storage, improved seed use, and reforestation. Field abandonment remains an option only in extreme cases.

The adaptation profiles of Pintchoumba and Bamé are relatively similar to Bang, with strong engagement in pastoral strategies by herders and agro-pastoralists, and a focus on agronomic innovation among farmers.

The adoption of climate adaptation strategies is closely linked to local contexts. Villages with better access to water, improved seeds, and infrastructure, such as Gadas and Douroum, demonstrate higher uptake of collective and innovative approaches. Conversely, in areas marked by land-use conflicts, high climatic stress, or limited resources, communities tend to adopt more accessible measures such as transhumance or crop substitution.

Strategic choices also vary by livelihood type. Herders and agro-pastoralists prioritize livestock-related measures transhumance and forage cultivation, while farmers focus on conventional

agronomic solutions, such as improved seed use, food storage, and crop diversification to secure production.

Some strategies, despite their effectiveness, remain underutilized due to high costs or technical complexity. For instance, field abandonment and housing restructuring are generally last-resort solutions. In contrast, more affordable and accessible practices such as improved seeds, food storage, and reforestation are widely adopted, particularly when supported by technical assistance or institutional programs.

This comparative analysis of adaptation strategies along the sahelian gradient underscores the need for differentiated, context-sensitive policies. In southern areas, the emphasis is on sustainable intensification and ecosystem management. In the central zone, communities diversify their strategies to respond to growing variability. In the northernmost villages, farmers and herders adopt more survival-oriented approaches. These findings highlight the necessity of tailoring adaptation interventions to local realities, resource availability, and the unique socio-economic fabric of each region.

4. Discussion

The analysis of producers' profiles reveals a predominance of male respondents, typically heads of households, and mostly married. The average age of these heads of household, 35 years, indicates a relatively mature population, likely possessing experiential knowledge and long-term awareness of climatic changes. Gender distribution shows a clear spatial disparity: women are more present in southern villages (30–32%) than in northern ones (22–26%), reflecting unequal access to land ownership and public representation. This disparity is more pronounced in agroecologically extreme zones, where patriarchal norms are more deeply entrenched. A gendered approach to perception analysis thus provides a deeper understanding of local adaptation dynamics and the differentiated needs of each group (Nhemachena et al., 2020; UNDP & UN Women, 2023).

Smallholder farmers along the sahelian gradient of Cameroon perceive climate change through direct, tangible impacts on their daily activities rather than through systematic observation of meteorological trends. These perceptions are grounded in their lived experience of recurrent climatic events such as reduced rainfall, delayed onset and early cessation of rains, droughts, floods, violent winds, vegetation loss, and soil degradation. These findings are consistent with studies emphasizing farmers' experiential understanding of climate (Abou-Shleel & El-Shirbeny, 2014; Abdoul Habou et al., 2016; Adaawen, 2021; Yashele & Mosombo, 2017; Zhai et al., 2018).

Differences in perceived intensity are observed between villages. For instance, respondents in the extreme north report more severe irregularities in rainfall and higher exposure to desertification and violent climatic phenomena, compared to those in southern areas. These patterns align with studies conducted in other sahelian regions such as Burkina Faso reflect broader dynamics described by Momangi et al. (2023). Additionally, increased incidence of plant diseases, a recurrent concern across all sites, is perceived as one of the indirect effects of climatic disruptions.

The effects of climate change are strongly mediated by the respondents' primary livelihood activities. Farmers report soil degradation and declining crop yields, especially for maize, a major staple. In the livestock sector, herders are particularly vulnerable to the reduced availability of water and forage due to irregular rainfall. Northern Cameroon, especially, faces recurrent forage deficits, making it a hotspot for resource-based tensions and conflicts among pastoral communities. These conditions exacerbate livestock morbidity and reduce productivity, consistent with findings in other parts of West Africa (Kabore et al., 2019; Mekila et al., 2023).

To cope, farmers have adopted a range of strategies: the use of short-cycle crop varieties, reforestation, early sowing, intercropping, field protection against animals, and crop diversification. These practices are widely documented in the literature (Diallo et al., 2023; Soumaoro et al., 2022; Takpa et al., 2022). However, their implementation is constrained by limited financial means and access to technical support. Even widely accepted practices such as reforestation face barriers, as their success depends on factors often beyond the control of smallholders, such as cost, required surface area, and ecological conditions (Mosquera-Losada et al., 2012; Sani & Chalchisa, 2016).

To address these constraints and strengthen farmers' resilience, various intervention measures have been proposed. One of the most important is capacity building, which involves enhancing local skills through targeted training (e.g., on agroecology, reforestation, water management, seed selection). In Burkina Faso, for instance, the Yelemani project demonstrated the effectiveness of such training in improving farmer resilience (Ouédraogo & Ouédraogo, 2023).

Another essential strategy is access to agricultural inputs. The provision of microcredit or subsidies for the acquisition of improved seeds, irrigation systems, or post-harvest tools facilitates farmers' adaptation to climate change. The *One Acre Fund* program in Kenya is a clear example of this approach, having strengthened the resilience of over 500,000 smallholder farmers (Kropff et al., 2023).

Infrastructure development, especially in the water sector, also plays a crucial role. These infrastructures, intended for agriculture and pastoralism, help reduce vulnerability to drought and inter-community conflicts. In Niger, community-managed water points have fostered social cohesion (Seibou et al., 2023).

Economic diversification offers another path to sustainable adaptation. Promoting off-season farming, agroforestry, or small-scale processing helps reduce dependence on climate-sensitive activities. In Ethiopia, agroforestry diversification under the *Sustainable Land Management* project has contributed to improved food security (Gashure & Wana, 2023).

Gender inclusion and the valorization of traditional knowledge are also key levers. Recognizing the role of women and indigenous practices promotes more equitable and locally appropriate solutions. In Mali, the *Femmes et Terroirs* program significantly increased women's participation in forest governance (Salam et al., 2006).

Finally, participatory climate monitoring strengthens community preparedness for environmental changes. The collection of local data and the shared analysis of this information help tailor responses to specific needs. In Tanzania, this approach has improved the sustainability of water projects (Mgoba & Kabote, 2020).

Building on such participatory approaches, targeted measures have been developed to address the specific needs of different agroecological zones. In southern zones, where conditions are more favorable, efforts focus on empowering women through cooperatives and seed banks, and promoting organic farming and composting via farmer field schools. In central zones, marked by greater climatic variability, interventions include the deployment of rainwater harvesting systems, mobile agricultural and veterinary services, and the establishment of farmer innovation centers. In the more arid northern zones, strategies involve the installation of solar-powered micro-irrigation systems, the promotion of climate micro-insurance, the reinforcement of cross-border livestock mobility, and the expansion of assisted natural regeneration (ANR). In Niger, ANR has successfully restored over five million hectares of degraded land (Perring et al., 2018).

Altogether, these experiences highlight the urgent need for contextualized adaptation policies that reflect agroecological realities, socio-economic vulnerabilities, and cultural specificities. The success of local adaptation strategies depends on their technical feasibility, economic viability, and social acceptability. Effective implementation requires strong engagement from local institutions and sustained support from development partners.

5. Conclusions

This study has explored local perceptions of climate change and the adaptation strategies implemented by agro-pastoral communities in the sudano-sahelian zone of Cameroon. Drawing on data collected in five villages distributed along a sahelian gradient from the more humid south to the arid north, it examined the impact of seven major climatic phenomena, including extreme heatwaves, floods, heavy rainfall, and disruptions in the agricultural calendar (late or early rains, shortened seasons). These changes are perceived as serious threats by local farmers due to the profound disruptions they cause to both agricultural and pastoral livelihoods.

The findings underscore the significant socio-economic repercussions of climate variability, affecting crop yields, livestock productivity, and the integrity of natural ecosystems. The study reveals a wide range of endogenous adaptation strategies shaped by household socio-economic characteristics, environmental exposure, and available resources. These practices illustrate a remarkable adaptive capacity but also highlight the limitations of local knowledge when operating in isolation. Greater integration of traditional practices with scientific approaches is necessary to develop tailored, effective, and sustainable climate adaptation strategies.

Importantly, the study emphasizes the heterogeneity of climate impacts and responses across the villages studied. It confirms the need for context-specific policies that take into account local agroecological conditions, socio-economic vulnerabilities, and the differentiated roles of farmers, herders, and agro-pastoralists. Particularly concerning are the high levels of concern reported for flooding, deforestation, and pasture degradation issues that call for urgent policy action to promote sustainable land management and climate-resilient agriculture.

The study has certain limitations. The use of snowball sampling, though appropriate in the field context, reduces the statistical representativeness of the sample. Climate perceptions, based on memory, may be biased, especially in the absence of long-term meteorological data. Additionally, focusing on only five villages limits the generalizability of the findings to the broader Sahelian region or neighboring countries with different contexts.

To deepen and expand these results, longitudinal studies combining perceived data with objective climate measurements are recommended. Large-scale probabilistic surveys would improve representativeness. It is also necessary to assess adaptation strategies using economic, social, and environmental indicators. Finally, more research should include women and youth, whose voices remain insufficiently heard.

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Abbreviations

The following abbreviations are used in this manuscript:

UN Women	United Nations Entity for Gender Equality and the Empowerment of Women
UNDP	United Nations Development Programme
MINEPAT	Ministry of Economy, Planning and Regional Development (Cameroon)
UN	United Nations
UNHCR	United Nations High Commissioner for Refugees
ANR	Assisted Natural Regeneration

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Agricultural & Rural Studies

Review

Integrated Natural Resource Management and Sustainable Livelihoods: A Review of Ecosystem-Based Approaches for Sustainability and Community Resilience

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Abstract: This review explores the essential link between sustainable livelihoods and the natural resource management (NRM), stressing the importance of ecosystem health for ensuring long-term socio-economic and environmental stability. The research looks at significant strategies like the Sustainable Livelihoods Framework, community-based natural resource management (CBNRM), and ecosystem-based adaptation (EbA), which foster resilience, fairness, and participatory governance. It underscores that diverse livelihoods, traditional ecological knowledge, and inclusive decision-making enhance community resilience to climate change and resource-related vulnerabilities. Recent research developments highlight integrated planning approaches that take into account the connections among land, water, energy, and biodiversity, while addressing issues of climate resilience and social equity. Technological tools, market-oriented incentives, and innovative policies are acknowledged for their role in improving NRM effectiveness. Crucially, this review emphasizes the importance of collaboration among various stakeholders and the integration of indigenous knowledge to ensure relevance to specific contexts. The future of NRM is dependent on aligning ecological sustainability with human development objectives through adaptive, inclusive, and knowledge-driven approaches. Ultimately, the review calls for a transformative shift towards comprehensive, integrated, and community-focused frameworks for natural resource governance that can effectively tackle global environmental and livelihood issues.

Keywords: sustainable livelihoods; natural resource management; climate change; ecosystem-based management; ecosystem services; community resilience

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1. Introduction

Sustainable livelihoods are vital for building resilient communities worldwide through the responsible management of natural resources (Morse, 2025; Su et al., 2025). This ensures long-term economic, social, and environmental benefits. The health of the environment is closely linked to human well-being, especially for rural communities reliant on agriculture, fishing, and forestry. Unchecked exploitation of these resources can lead to environmental degradation and threaten livelihoods. Sustainable livelihood approaches promote practices that enhance resource productivity, strengthen resilience against shocks, empower local communities, and ensure fair benefit distribution (Chiang, 2024). Understanding the interactions between social, economic, and ecological systems is essential for developing effective, context-specific strategies to address resource management challenges (Natarajan et al., 2022).

Diversifying income sources is crucial for sustainable livelihoods. Communities should broaden their strategies beyond a single resource to manage risks and seize opportunities. For instance, a fishing community might supplement its income through eco-tourism, agroforestry, or small-scale handicrafts. This approach not only helps households withstand shocks like climate change but also reduces pressure on individual resources, promoting long-term sustainability (A. Kumar et al., 2023; Mazibuko, 2013; Natarajan et al., 2022). Combining traditional knowledge with modern technology is also vital. Indigenous communities possess valuable insights into sustainable resource management that can be integrated with contemporary practices (Galappaththi & Schlingmann, 2023). Technologies like remote sensing and mobile applications can enhance mon-

itoring and decision-making, leading to more effective resource management. It's important to ensure these tools are accessible and user-friendly to avoid digital divides and reliance on external expertise.

Inclusive governance and participatory decision-making are essential for sustainable livelihood initiatives. These efforts are most effective when local stakeholders, including marginalized groups like women, indigenous peoples, and youth, actively participate throughout all project stages (Bansal et al., 2024). This involvement fosters ownership and empowers communities, enhancing the legitimacy and effectiveness of interventions. Strong partnerships among government agencies, civil society, academia, and the private sector are crucial, built on transparency, accountability, and respect for customary rights and traditional governance systems. Additionally, addressing the root causes of vulnerability and promoting social justice are key to sustainable livelihoods. This means tackling structural inequalities and ensuring equitable distribution of benefits to reduce poverty and foster social stability. Policymakers should also integrate environmental sustainability into broader agendas, such as poverty reduction and climate resilience, to balance social, economic, and environmental goals.

Sustainable livelihoods can be achieved through effective natural resource management, fostering resilient and equitable communities in harmony with nature (A. Kumar et al., 2023; Arslan et al., 2022; Muchunguzi, 2023; Natarajan et al., 2022). By adopting principles of diversification, integration, participation, and equity, stakeholders can optimize local resources to enhance livelihoods, conserve biodiversity, and protect ecosystem services for future generations. This requires a collective effort guided by a commitment to sustainability and social justice. By working together, we can create an inclusive future for people and the planet. This study advocates for a shift in natural resource management that acknowledges ecosystem complexity and human diversity, promoting harmonious coexistence between communities and the natural world.

This research enhances the understanding of sustainable livelihoods by merging ecosystem-based management with participatory governance and adaptive capacity. It shows how localized resource strategies, when aligned with broader ecological and institutional frameworks, promote long-term sustainability. The study highlights recent advancements, such as integrating traditional ecological knowledge with digital tools, applying sustainable livelihood frameworks in climate planning, and supporting diversified livelihood portfolios for resilience. Unlike previous studies focused on either environmental or economic outcomes, this review identifies links between equity, resilience, and regeneration, providing a multi-faceted view for natural resource governance. This transdisciplinary approach lays the groundwork for community-driven resource models that are scalable and replicable.

This study examines the connection between natural resource management and sustainable livelihoods, emphasizing how resource practices can bolster community resilience and protect the environment. Despite existing research on sustainable resource use (Morse, 2025; Natarajan et al., 2022; Shah et al., 2021; Singh et al., 2024; Su et al., 2025), there is still a gap in identifying effective strategies that enhance livelihoods and adaptive capacity in the face of challenges like climate change. The literature also lacks comprehensive frameworks that combine community-based approaches, equitable governance, and income diversification for sustainable, long-term solutions.

To explore the links between sustainable livelihoods and the management of natural resources, this study utilizes a qualitative literature review approach that integrates various findings. We systematically gathered and examined scholarly articles, case studies, and policy documents published over the past two decades (2005–2025), using major academic databases such as Scopus, Web of Science, and Google Scholar. The focus was on selecting works that discuss ecosystem-based approaches, livelihood diversification, participatory governance, and climate resilience in various ecological and socio-economic settings. The thematic analysis is organized around principles derived from the Sustainable Livelihoods Framework and ecosystem-based management, facilitating a critical synthesis of strategies for implementation and their results. This methodology guarantees a thorough understanding of existing practices, challenges, and innovations in the governance of natural resources and community resilience. The main aims and objectives of this study are: (a) to explore the connection between sustainable livelihoods and NRM; (b) to examine the role of natural resources in supporting sustainable livelihoods; (c) to discuss approaches to sustainable livelihoods and NRM, including various frameworks and community-based strategies; and (d) to highlight the relationship between NRM, climate change adaptation, and ecosystem-based approaches that promote resilience.

The study is organized into the following segments to provide a comprehensive understanding of sustainable livelihoods and natural resource management:

- *Section 2* explores the interconnections between natural resources and sustainable livelihoods, highlighting their mutual dependence.
- *Section 3* examines various approaches to sustainable livelihoods and natural resource management, providing insights into practical frameworks and strategies.

- *Section 4* focuses on natural resource management in the context of climate change adaptation, emphasizing the importance of resilience and adaptive capacity.
- *Section 5* presents an ecosystem-based approach to sustainable livelihoods, underscoring a holistic strategy that aims to balance human well-being with the preservation of ecological integrity.
- *Section 6* discusses Integrated Resource Planning (IRP) for natural resource management—an inclusive and strategic approach to achieving sustainable development by managing interconnected natural systems holistically. IRP serves as a comprehensive framework that addresses the interdependencies and cumulative impacts of resource use on the environment, economy, and society.
- *Section 7* outlines future perspectives and emerging research trends in natural resource management, pointing toward more adaptive, inclusive, and sustainable practices.
- *Section 8* concludes the study by synthesizing key findings and reinforcing the importance of integrated, ecosystem-based, and community-driven approaches to ensure the sustainability of natural resources and the well-being of present and future generations.

2. Natural Resources and Sustainable Livelihood

Natural resources are fundamental to sustainable livelihoods, supplying the raw materials and ecosystem services essential for human societies. These resources, which include fertile soils, clean water, forests, fisheries, and minerals, are critical for sustenance, income, and overall well-being for millions globally (Ahmed et al., 2020; Arslan et al., 2022). However, the unsustainable exploitation and degradation of these resources threaten livelihood security, biodiversity, and ecosystem resilience, particularly in rural and marginalized communities, worsening poverty, inequality, and vulnerability (Ahmed et al., 2020). Sustainable livelihood approaches seek to address these challenges by encouraging responsible stewardship and equitable management of natural resources to ensure their long-term viability and fair distribution of benefits (Arslan et al., 2022; Shah et al., 2021; Singh et al., 2024; Mensah & Amoah, 2024). This involves holistic and participatory strategies that balance the needs of present and future generations while protecting the ecological integrity and cultural diversity of various landscapes and seascapes. These initiatives recognize the intrinsic value of nature and the interconnectedness between human well-being and environmental health, fostering a harmonious relationship between people and the planet based on equity, resilience, and intergenerational justice. Through collaborative action and shared stewardship, communities can harness natural resources' transformative power to build resilient, inclusive, and prosperous societies within planetary boundaries.

Natural resources play a crucial role in shaping community livelihoods and well-being worldwide (Figure 1). These resources encompass elements such as land, water, forests, minerals, fisheries, and biodiversity, forming the basis for various economic activities like agriculture, fishing, forestry, mining, and tourism (Lienert & Burger, 2015; Li et al., 2024; Sangha, 2020). They provide essential raw materials, food, energy, and other ecosystem services vital for human survival and development. Beyond their instrumental value for human welfare, these resources hold intrinsic value, contributing to cultural identity, spiritual significance, and aesthetic enjoyment. Unsustainable exploitation and degradation of natural resources pose significant threats to sustainable livelihoods and environmental sustainability. Overexploitation of fisheries, deforestation, soil erosion, water pollution, and habitat destruction are examples of harmful practices. These activities undermine ecosystem resilience and threaten the livelihoods of millions who depend directly on natural resources. The concept of sustainable livelihoods has emerged as a comprehensive approach to promoting human well-being while preserving ecosystem integrity.

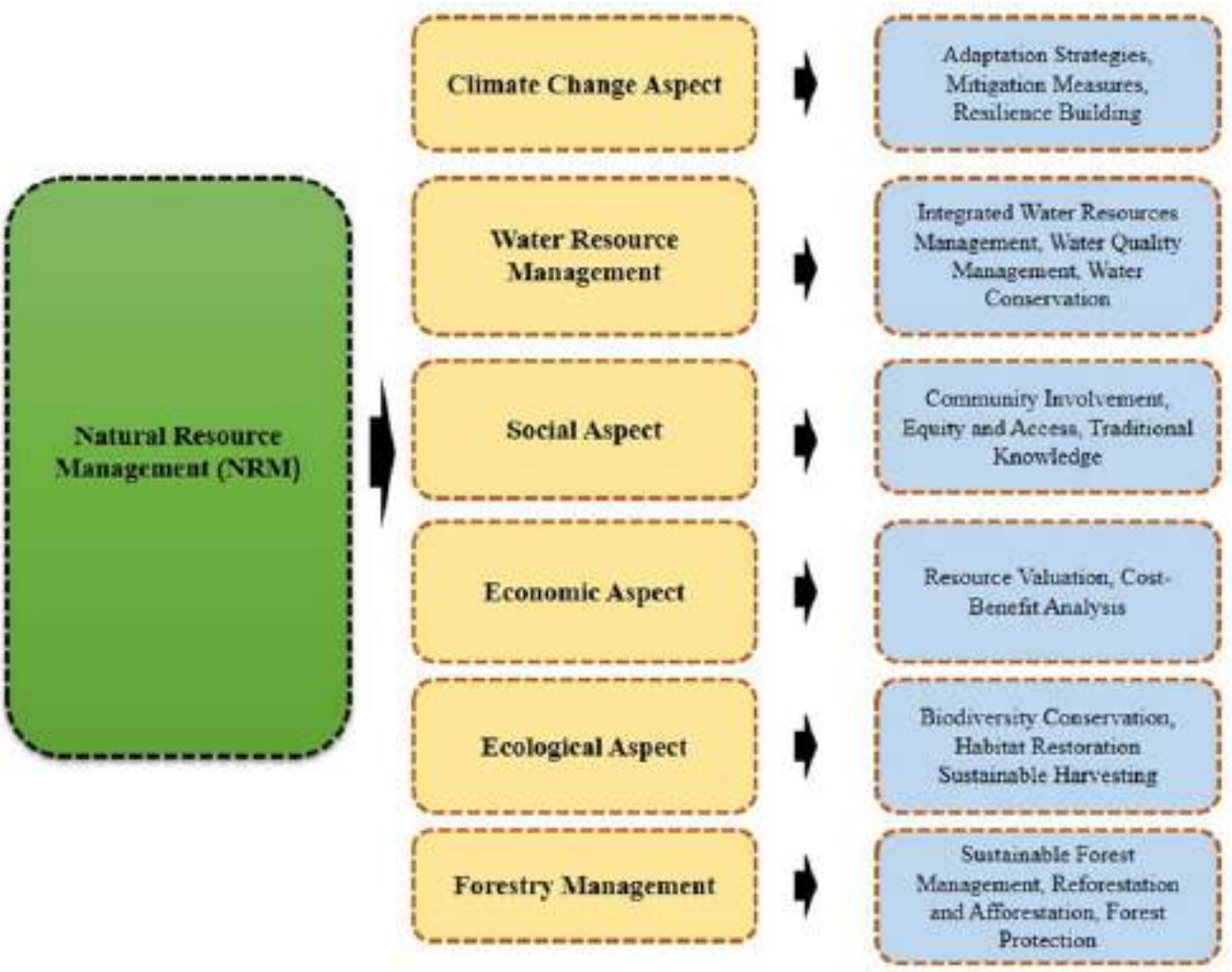


Figure 1. Different aspects of natural resource management.

Sustainable livelihoods recognize the interconnectedness of social, economic, and environmental systems (Nhamo et al., 2020; X. Ma et al., 2021). This approach emphasises integrated and participatory strategies that balance the needs of present and future generations, guided by the principle of sustainability (Natarajan et al., 2022). This involves meeting current needs without compromising future generations' ability to meet theirs. Central to this concept is resilience—the capacity of individuals, households, and communities to withstand and recover from shocks and stresses while maintaining well-being. Building resilience requires addressing the root causes and underlying vulnerabilities of poverty and environmental degradation. To enhance resilience, a multifaceted approach is essential, involving diversification of livelihood strategies, strengthening social networks, improving access to resources and services, and fostering adaptive capacity to cope with uncertainty and change. Sustainable livelihood interventions aim to break the cycle of poverty and promote inclusive and equitable development, ensuring that all community members can thrive (C. Wang et al., 2016; V. Kumar et al., 2015). The following are the key principles that support sustainable livelihoods (Alobo Loison, 2015; Davies, 1996):

- ***Participatory decision-making:*** It is important to involve local communities, especially marginalized groups such as women, indigenous peoples, and youth, in all stages of project planning, implementation, and evaluation to ensure that interventions are contextually relevant, socially acceptable, and sustainable in the long term.
- ***Integrated resource management:*** Sustainable livelihood approaches acknowledge the interconnectedness of social, economic, and environmental systems, and seek to integrate natural resource management with broader development objectives such as poverty reduction, food security, and climate resilience.
- ***Equity and social justice:*** For sustainable livelihood interventions to help reduce poverty, inequality, and exclusion, especially among vulnerable and marginalized populations, equitable access to resources, opportunities, and benefits must be promoted.

- ***Adaptive management:*** Approaches that embrace uncertainty and change, like adaptive management, emphasize learning-by-doing, experimentation, and flexibility to adjust strategies and actions based on new information, feedback, and evolving circumstances.
- ***Sustainable consumption and production:*** To promote sustainable lifestyles and livelihoods, it is necessary to minimize resource use, reduce waste and pollution, and adopt eco-friendly technologies and practices that enhance resource efficiency and environmental sustainability.

Natural resources play a crucial role in supporting sustainable livelihoods and human well-being (Morrison, 2015). However, their responsible management is critical to ensuring their long-term viability and equitable distribution of benefits. By embracing principles of sustainability, resilience, equity, and participation, communities can harness the transformative potential of natural resources to build a more prosperous, inclusive, and environmentally sustainable future for all. Natural resources and sustainable livelihoods are a complex and interconnected set of elements that are dependent on one another (Table 1).

Table 1. Elements of Natural Resources and Sustainable Livelihood.

Elements	Description	References
Ecosystem Services	Ecosystem services are the benefits that humans get from ecosystems, such as food, water, timber, climate regulation, flood control, recreation, spiritual values, and nutrient cycling. Sustainable livelihoods rely on the protection and sustainable use of these ecosystem services to support human well-being.	Li et al., 2024; J. Wang et al, 2024; Nungula et al., 2024; Roy et al., 2024;
Livelihood Strategies	Livelihood strategies include the different activities and resources that people use to support their livelihoods and meet their needs. These strategies may include agriculture, fishing, forestry, hunting, gathering, small-scale businesses, wage labor, remittances, and social safety nets. Sustainable livelihood approaches aim to diversify and strengthen these strategies to improve resilience and reduce vulnerability to shocks and stresses.	Habib et al., 2023; Liu et al., 2023
Natural Resource Management	Natural resource management involves the care and governance of natural resources to ensure their sustainable use and conservation. This includes sustainable agriculture, fisheries management, forest conservation, watershed management, soil conservation, biodiversity conservation, and integrated water resources management. Sustainable livelihood initiatives seek to promote participatory and integrated approaches to natural resource management that balance ecological, social, and economic objectives.	Baddianaah & Baaweh, 2021; Y. Xu & Zhao, 2023
Access to Resources and Assets	Access to resources and assets like land, water, forests, fisheries, credit, technology, education, and social capital is crucial to shaping livelihood opportunities and outcomes. Sustainable livelihood approaches aim to improve access to these resources and assets, especially for marginalized and vulnerable groups, to promote equitable and inclusive development.	Chuong, 2023; L. Ma et al., 2024; Z. Xu et al., 2023
Capacity Building and Empowerment	Capacity building and empowerment initiatives aim to improve the knowledge, skills, capabilities, and agency of individuals, households, and communities to participate effectively in decision-making processes, manage natural resources sustainably, and adapt to change. This may involve education, training, extension services, technology transfer, institution building, and strengthening of local governance structures.	Dushkova & Ivlieva, 2024
Market Access and Value Chains	Access to markets and participation in value chains are essential for converting natural resources into livelihood opportunities and income generation. Sustainable livelihood approaches seek to enhance market access, improve value addition, strengthen market linkages, and promote fair trade practices to ensure that producers receive a fair share of the value created along the supply chain.	Bagchi et al., 2021; Ruben, 2024; Tagwi & Chipfupa, 2023

Table 1. *Cont.*

Social Protection and Safety Nets	Social protection mechanisms such as social assistance, insurance, savings, and asset-building programs play a crucial role in reducing vulnerability and improving resilience to shocks and stresses. Sustainable livelihood approaches advocate for the design and implementation of social protection policies and programs that are sensitive to the needs and priorities of marginalized and vulnerable groups.	Fitrinitia & Matsuyuki, 2023; Kundo et al., 2023
Gender Equality and Social Inclusion	Gender equality and social inclusion are underlying principles of sustainable livelihoods that aim to ensure that all individuals, regardless of gender, age, ethnicity, or socio-economic status, have equal rights, opportunities, and voice in decision-making processes and access to resources and benefits. This involves addressing underlying power imbalances, discriminatory norms, and barriers to participation and inclusion.	Chikwe et al., 2024; Lwamba et al., 2022

The Sustainable Livelihoods Framework for the 21st century provides a holistic approach to improving the living conditions of vulnerable populations. It focuses on the interplay among people's assets, the institutional environment, and external factors (Natarajan et al., 2022). Central to this framework are five types of capital—human, natural, financial, physical, and social—that communities use in their livelihood strategies (Figure 2; Natarajan et al., 2022). These strategies are shaped by structures and processes, including government institutions and cultural norms, within a context of vulnerability marked by shocks and trends. The framework aims for sustainable outcomes, such as enhanced well-being, reduced vulnerability, and improved food security. In the 21st century, it has been adapted to address global challenges like climate change, gender disparities, urbanisation, and digital access, making it a vital tool for sustainable development planning.

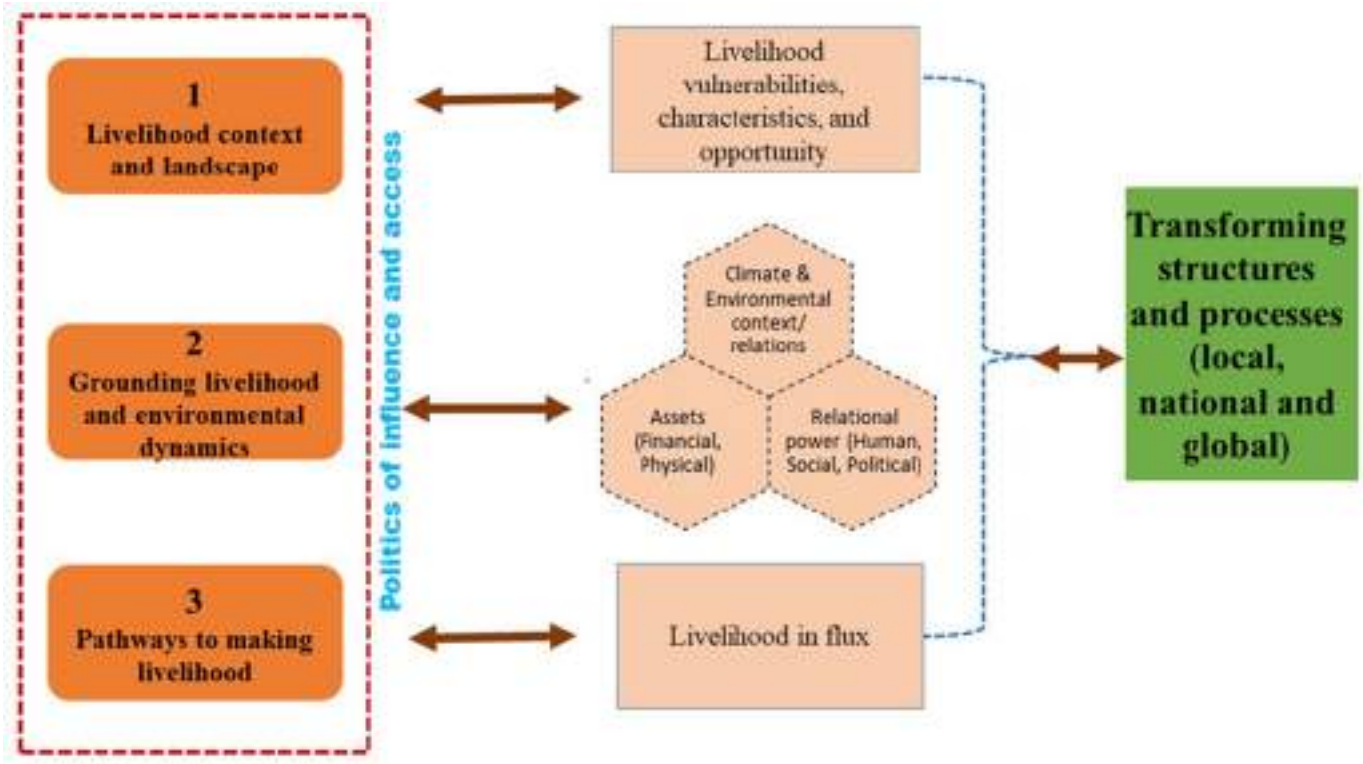


Figure 2. A sustainable livelihoods framework for the 21st century.

3. Approaches to Sustainable Livelihood and Natural Resource Management

The connection between sustainable livelihood approaches and natural resource management is vital for achieving long-term environmental and economic stability (C. Wang et al., 2016). These strategies aim to improve community well-being while ensuring the sustainable use and conservation of natural resources. One notable approach is the Sustainable Livelihoods Framework (SLF) developed by the Department for International Development, which emphasizes five core asset

categories: human, social, natural, physical, and financial capital. By developing these assets, the SLF seeks to enhance the resilience and adaptive capacity of communities (Tambe, 2022). Human capital involves skills, knowledge, and health; social capital includes networks and relationships; natural capital refers to resources such as land, water, and biodiversity; physical capital comprises infrastructure and tools; and financial capital covers savings, credit, and income.

Integrating natural resource management within sustainable livelihood strategies requires several key principles (Pani & Mishra, 2022). Firstly, community participation and local governance are essential. Involving local communities in decision-making ensures that resource management strategies are tailored to their specific needs and knowledge, fostering ownership and responsibility. Participatory approaches, such as CBNRM, empower communities to manage resources sustainably and equitably. Secondly, adopting an ecosystem-based approach is crucial. This holistic management of resources considers the interconnections between different ecosystem components and their services. For example, Integrated Water Resource Management (IWRM) addresses the entire water cycle and its interdependencies with land and other resources, promoting coordinated development and management to maximize economic and social welfare without compromising ecosystem sustainability. Incorporating traditional ecological knowledge (TEK) is also essential. Indigenous and local communities often have extensive environmental knowledge and sustainable practices developed over generations. Recognizing and integrating TEK into modern NRM strategies can enhance their effectiveness and cultural relevance.

Economic diversification is another key strategy. By diversifying income sources, communities can reduce dependency on a single natural resource, which is vulnerable to environmental changes or market fluctuations (Lashitew et al., 2021). Examples of diversified livelihood options include agroforestry, ecotourism, and sustainable fisheries, which can reduce pressure on natural resources while providing economic benefits. Considering the broader policy and institutional context is important for the success of sustainable livelihood and natural resource management approaches. This includes creating supportive policies, legal frameworks, and institutional arrangements that promote sustainable practices and ensure fair access to resources. For instance, strengthening property rights and tenure security can motivate individuals and communities to invest in sustainable resource management practices. In conclusion, sustainable livelihood approaches and natural resource management are closely linked. By focusing on diverse asset development, active community participation, ecosystem-based approaches, traditional knowledge integration, economic diversification, and supportive policies and institutions, these strategies can significantly contribute to creating more resilient and sustainable communities. This comprehensive and integrated approach is essential for addressing the complex challenges of sustainable development and environmental conservation in the face of global changes.

To implement the key strategies discussed, various methods and evaluation mechanisms for impact have been extensively utilised in the field. In CBNRM, methodologies commonly include Participatory Rural Appraisal (PRA), stakeholder mapping, the formation of resource user groups, and periodic community monitoring via scorecards or focus group discussions (Delgado-Serrano et al., 2018; Lara et al., 2018). Effectiveness is often assessed through ecological indicators (such as changes in forest cover and biodiversity metrics) and socio-economic measures (like household income diversification and governance participation scores; Pani & Mishra, 2022). In IWRM, tools like hydrological modelling (for example, SWAT), GIS-based watershed assessments, and scenario planning are used (Nath et al., 2024). Success is gauged using metrics such as water use efficiency, water quality indices, and outcomes related to multi-stakeholder conflict resolution. The SLF uses baseline livelihood evaluations, asset pentagon analyses, and longitudinal surveys to monitor changes in human, social, natural, physical, and financial capital over time (Tambe, 2022). TEK is collected via ethnographic approaches like oral histories, seasonal calendars, and participatory mapping, with validation carried out through comparative ecological studies and cultural acceptance surveys. These methodological tools not only facilitate the design of context-specific strategies but also enable thorough monitoring and adaptive management, which enhances the long-term sustainability and replicability of these approaches. In addition, the different key principles and strategies of sustainable livelihood and natural resource management are mentioned in Table 2.

Table 2. Principles and Strategies of Sustainable Livelihood and Natural Resource Management

Principle	Description	Example Strategies	References
Community Participation and Local Governance	Engaging local communities in decision-making to ensure relevant and effective management.	CBNRM, PRA	Aazami & Shanazi, 2020; Weiskopf et al., 2020
Ecosystem-Based Management	Holistic management that considers ecological interdependencies.	IWRM, Integrated Coastal Zone Management	Fortuna et al., 2024; Reis-Santos et al., 2023
Traditional Ecological Knowledge	Utilizing indigenous knowledge for sustainable practices.	Co-management of protected areas, Indigenous agricultural practices	Sinthumule, 2023
Economic Diversification	Reducing dependency on single resources by diversifying income sources.	Agroforestry, Ecotourism, Sustainable Fisheries	Jolo et al., 2022; Muhamad, 2023
Supportive Policy and Institutional Frameworks	Creating policies and institutions that support sustainable and equitable resource use.	Land tenure security, Environmental regulations	Ahmad et al., 2023

Furthermore, the concept of sustainable livelihood and natural resource management is closely interlinked, creating a mutually beneficial relationship that enhances both human well-being and environmental sustainability. The SLF underscores the importance of developing and utilizing various forms of capital (human, social, natural, physical, and financial) to boost the resilience and adaptability of communities (Karki, 2021; Su et al., 2021). Efficient NRM plays a pivotal role in this framework by ensuring the sustainable management of natural resources, which form the natural capital, to uphold long-term livelihoods.

- Natural resources like land, water, forests, and biodiversity are essential for many rural livelihoods. Sustainable management of these resources ensures their availability and productivity for future generations. Practices such as agroforestry, sustainable agriculture, and community-managed fisheries not only conserve natural resources but also improve the livelihoods of local communities by providing diverse and sustainable sources of income (Ismail et al., 2013).
- Community Participation and Governance involving local communities in NRM processes ensures that management strategies are aligned with their specific needs and knowledge, fostering a sense of ownership and responsibility. For instance, implementing CBNRM initiatives empowers communities to sustainably manage resources, resulting in improved conservation outcomes and enhanced livelihoods through activities such as ecotourism and sustainable harvesting (Jagers et al., 2018).
- Ecosystem-based approaches entail implementing management strategies to preserve the health of ecosystems, thereby ensuring the continuity of the essential services they provide, such as clean water, fertile soil, and a stable climate. These services play a critical role in sustaining agricultural productivity, reducing vulnerability to natural disasters, and facilitating diverse livelihood activities (Doughan, 2020).
- Indigenous and local communities possess extensive knowledge about sustainable resource management practices refined over generations. Integrating TEK with modern NRM strategies enhances their effectiveness and cultural relevance, ensuring that resource management practices are sustainable and locally appropriate (Fernández-Llamazares et al., 2021).
- Reducing dependency on a single natural resource through diversification strategies such as agroforestry, sustainable tourism, and non-timber forest products can help buffer communities against economic shocks and environmental changes. This diversification not only provides additional income streams but also reduces pressure on any one resource, contributing to its sustainability (Cheng et al., 2020).

- Supportive policies and institutional frameworks are essential for sustainable livelihoods and NRM. Policies that secure land tenure and access rights, enforce environmental regulations, and promote equitable resource distribution support sustainable resource use and help communities invest in sustainable livelihood strategies.

The reviewed literature highlights the multifaceted role of community-based tourism (CBT), natural resource management, and technological innovation in advancing sustainable development goals (SDGs). Homestays, a vital component of CBT—especially in rural areas—exhibit potential in contributing to SDG1 (No Poverty) and SDG11 (Sustainable Cities and Communities) by engaging local families and retaining decision-making at the community level. However, challenges remain in evaluating their broader impacts on livelihoods. In parallel, studies focused on environmental sustainability reveal the intricate relationship between economic growth, tourism, natural resource utilization, and ecological degradation. While urbanization and tourism contribute to CO_2 emissions, information and communication technology (ICT) demonstrates promise in mitigating these environmental impacts (Begum et al., 2025). Furthermore, research indicates that sustainable energy policy and socio-economic development significantly influence ecological footprints, particularly in rapidly developing countries like China (Zhu et al., 2024). Conversely, findings from resource-rich Asian economies present a more nuanced perspective, revealing that natural resource rents and energy security are negatively associated with ecological degradation, which challenges traditional assumptions of the environmental Kuznets curve (Zhang et al., 2024). Additionally, a district-level analysis in West Bengal utilizing the Sustainable Livelihood Security Index uncovers notable spatial disparities in ecological, economic, and social indicators, providing valuable insights for policy interventions aimed at enhancing regional resilience and equitable development (Roy et al., 2024). Collectively, these studies emphasize the critical importance of integrating livelihood, environmental, and technological dimensions to develop inclusive and sustainable development strategies.

4. Natural Resource Management and Climate Change Adaptation

Natural resource management and climate change adaptation are closely intertwined, with effective NRM playing a crucial role in enhancing the resilience of ecosystems and communities to the impacts of climate change (Weiskopf et al., 2020). Climate change poses significant threats to natural resources, including water scarcity, soil degradation, loss of biodiversity, and increased frequency of extreme weather events. These changes can undermine the livelihoods of communities that rely on these resources, making adaptation strategies essential for sustainable development (Ampaire et al., 2020; Maja & Ayano, 2021).

- ***Water Resource Management:*** As climate change alters precipitation patterns and intensifies droughts and floods, sustainable water resource management becomes crucial. IWRM is an approach that promotes the coordinated development and management of water, land, and related resources. It aims to maximize economic and social welfare without compromising the sustainability of vital ecosystems. Techniques such as rainwater harvesting, efficient irrigation systems, and watershed management are essential to ensuring water availability for agriculture, drinking, and other uses (Xiang et al., 2021).
- ***Sustainable Agriculture and Soil Management:*** Climate change affects agricultural productivity through changes in temperature, rainfall patterns, and increased incidence of pests and diseases. Sustainable agriculture practices, such as conservation tillage, crop rotation, organic farming, and agroforestry, can enhance soil health and fertility, reduce erosion, and improve water retention. These practices not only help in adapting to changing climatic conditions but also in sequestering carbon, thereby mitigating climate change (Fahad et al., 2021).
- ***Forest Management and Reforestation:*** Forests act as carbon sinks, absorbing CO_2 from the atmosphere, and play a critical role in climate regulation. Sustainable forest management practices, including reforestation and afforestation, are vital for climate change adaptation and mitigation. Community-based forest management can empower local communities to protect and sustainably use forest resources, enhancing biodiversity and ecosystem services such as water regulation and soil stabilization (Hazarika et al., 2021).
- ***Coastal Zone Management:*** Rising sea levels and increased storm surges due to climate change pose significant risks to coastal areas. Integrated Coastal Zone Management involves the sustainable management of coastal resources to protect against erosion, flooding, and habitat loss. Strategies include the restoration of mangroves and coral reefs, which act as natural barriers against storms and provide critical habitats for marine life. Additionally, sustainable fisheries management helps maintain fish stocks and the livelihoods of coastal communities (Gallina et al., 2020).
- ***Biodiversity Conservation***: Biodiversity enhances ecosystem resilience, enabling ecosystems to recover from disturbances and maintain functionality under changing climatic conditions.

Conservation strategies, such as the establishment of protected areas, habitat restoration, and the implementation of biodiversity corridors, are crucial for preserving genetic diversity and ecosystem services. Biodiversity conservation also supports the livelihoods of communities that depend on ecosystem services for food, medicine, and cultural values (Brown et al., 2022).

- ***Disaster Risk Reduction**:* NRM strategies that incorporate disaster risk reduction (DRR) can significantly reduce the vulnerability of communities to climate-related hazards. Measures such as the construction of flood defenses, sustainable land-use planning, and the restoration of wetlands and floodplains can mitigate the impacts of extreme weather events. Early warning systems and community-based disaster preparedness programs are also essential components of DRR (Weichselgartner & Pigeon, 2015).

By effectively linking NRM with climate change adaptation, we can enhance the resilience of both natural ecosystems and human communities. This integrated approach ensures that natural resources are managed sustainably, providing a buffer against the adverse impacts of climate change while supporting sustainable livelihoods and promoting overall well-being. Through collaborative efforts involving governments, communities, and various stakeholders, we can develop and implement strategies that address the complex challenges posed by climate change, securing a sustainable future for generations to come. Figure 3 illustrates the interconnected relationship between ecosystems, people, and climate change, emphasizing the dual roles of natural resource management in both climate change mitigation and adaptation. Climate change has both positive (indicated in purple) and predominantly negative (indicated in black) impacts on ecosystems and human communities, which influence each other in various ways. Ecosystem-based mitigation strategies, such as reforestation and river restoration, can play a crucial role in reducing greenhouse gas emissions and mitigating the effects of climate change (Morecroft et al., 2019). Concurrently, ecosystem-based adaptation strategies enhance the resilience of both ecosystems and human populations. These strategies include wetland restoration, protecting and expanding natural or semi-natural areas, increasing landscape connectivity, species translocation, and restoring natural fire regimes. These approaches not only help ecosystems adapt to changes in climate but also support biodiversity conservation and promote the livelihoods and well-being of local communities. However, it is important to note that the figure also highlights potential maladaptations—such as creating forests in ecologically unsuitable areas—which could result in unintended ecological consequences (Morecroft et al., 2019).

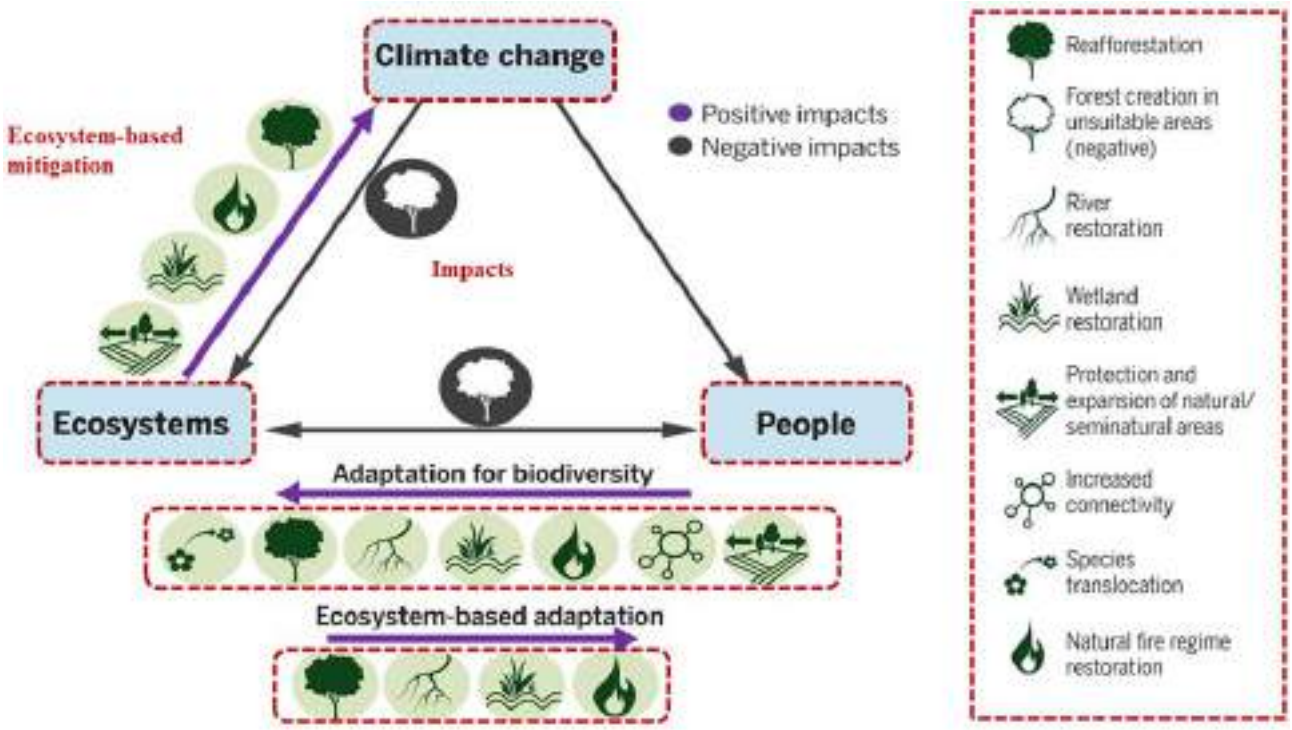


Figure 3. Ecosystem-Based Approaches for Climate Change Adaptation and Natural Resource Management (Redrawn from Morecroft et al., 2019)

5. Ecosystem-Based Approach for Sustainable Livelihood

An ecosystem-based approach to sustainable livelihoods through effective natural resource management is a comprehensive strategy that aims to balance human needs with the preservation of ecological integrity. This approach acknowledges that the well-being of communities and the sustainability of their livelihoods are intrinsically linked to healthy ecosystems. By managing natural resources in ways that support ecosystem services, such as clean water, fertile soil, and biodiversity, this approach ensures that these resources can sustain current and future generations (Kalogiannidis et al., 2023; Nalau et al., 2018). Furthermore, EbA offer innovative and sustainable solutions that integrate ecological health with human well-being, especially in vulnerable and resource-dependent communities (Table 3). By harnessing the services provided by natural ecosystems—such as water regulation, soil fertility, carbon sequestration, and biodiversity—these approaches support resilient livelihoods while preserving the environment. The following table outlines key ecosystem-based strategies that promote sustainable livelihoods through nature-based solutions, highlighting their ecosystem services, implementation levels, and co-benefits.

- One of the core principles of this approach involves integrating conservation and sustainable use. For instance, within agricultural systems, practices such as agroforestry, crop rotation, and organic farming have been shown to enhance soil health and biodiversity. As a result, crop yields are increased, and the crops become more resilient to pests and diseases. These practices not only contribute to food security but also provide economic benefits to farmers by reducing their dependency on chemical inputs and enhancing ecosystem services such as pollination and water retention (Kalogiannidis et al., 2023).
- In coastal areas, adopting an ecosystem-based approach entails the preservation and rejuvenation of crucial habitats such as mangroves, coral reefs, and seagrasses. These ecosystems function as natural defenses against storm surges and coastal erosion, shielding inland communities from severe weather events. Additionally, they play a vital role in supporting fisheries, which serve as a cornerstone for food security and livelihoods in many coastal regions. By safeguarding these habitats, we secure the sustainability of fisheries and bolster the resilience of coastal communities in the face of climate change (Santhanam & Kundu, 2022).
- Freshwater ecosystems, such as rivers, lakes, and wetlands, are a primary focus of ecosystem-based management and require protection from pollution, over-extraction, and habitat destruction to ensure optimal water quality and availability. Implementing sustainable watershed management practices, including reforestation and establishing riparian buffers, can effectively regulate water flow, minimize flooding, and replenish groundwater supplies. These practices have far-reaching benefits for agricultural activities, drinking water supplies, and biodiversity, ultimately contributing to the well-being of those who depend on these resources (Gray et al., 2020).
- Forestry management is a critical component of this approach. Sustainable forestry practices, including selective logging, reforestation, and the preservation of old-growth forests, help to maintain the ecological functions of forests. Forests act as carbon sinks, mitigate climate change, regulate water cycles, and provide habitat for a wide range of species. Additionally, forests offer numerous products such as timber, non-timber forest products, and ecotourism opportunities, which are vital sources of income for many communities (Banerjee et al., 2019).
- Furthermore, this approach advocates for policy integration and coherence across multiple levels. It fosters the alignment of local, national, and international policies to bolster sustainable resource management. Policies that promote sustainable land use, renewable energy, and conservation can work together synergistically to enhance the effectiveness of ecosystem-based management. For example, national policies that incentivize sustainable agricultural practices can complement local efforts to protect soil and water resources, ultimately contributing to overall sustainability.
- In urban areas, using an ecosystem-based approach can help create sustainable livelihoods by incorporating green infrastructure into city planning. Urban green spaces, such as parks, green roofs, and urban forests, offer a wide range of ecosystem services, including improving air quality, regulating temperature, and providing recreational opportunities. These green spaces can improve the quality of life for urban residents, promote mental and physical well-being, and bring economic benefits through increased property values and tourism (Brink et al., 2016).

Table 3. Ecosystem-Based Approach for Sustainable Livelihoods.

Strategy	Targeted Ecosystem Services	Level of Implementation	Livelihood & Ecological Co-Benefits	Examples / Case Studies	References
Agroforestry Systems	Provisioning (food, fuel), Regulating (carbon, water)	Community/Farm-level	Enhances food security, carbon sequestration, income diversification	Silvopasture in Karnataka, India	Chavan et al., 2024; Sahoo & Wani, 2019
Sustainable Wetland Management	Regulating (flood control, water purification), Cultural	Landscape/Watershed	Reduces disaster risk, improves fishery productivity, supports tourism	Loktak Lake, Manipur	Devi et al., 2024; Huidrom et al., 2024
Mangrove Restoration	Regulating (coastal protection), Provisioning (fisheries)	Coastal/Community	Builds climate resilience, protects from storms, supports fisheries	Sundarbans Biosphere Reserve	Kar & Basu, 2023
Community-Based Ecotourism	Cultural, Supporting (biodiversity)	Local/Regional	Generates income, incentivizes conservation, empowers local communities	Ecotourism in Periyar Tiger Reserve	Vinodan & Meera, 2024
Sustainable Pasture Management	Supporting (soil health), Regulating (carbon, erosion control)	Grassland/Tribal Lands	Enhances livestock productivity, restores degraded lands, stores carbon	Banni Grasslands, Gujarat	Dey et al., 2024
Participatory Watershed Management	Regulating (water availability, erosion), Provisioning	Micro-watershed/Village	Improves irrigation, crop productivity, water access for rural livelihoods	Sukhomajri Watershed, Haryana	Bhardwaj et al., 2021
Urban Green Infrastructure	Regulating (air quality, heat reduction), Cultural	Urban/Peri-Urban	Improves urban liveability, provides jobs (nurseries, landscaping), buffers climate	Delhi Ridge Forest, Green roofs in Chennai	Ahmad & Hassan, 2023
Organic Farming with Biodiversity Buffers	Provisioning, Supporting	Farm-level	Reduces chemical inputs, improves health, increases pollinator services	Sikkim Organic Mission	Manoharmayum et al., 2025
Integrated Rice-Fish Farming	Provisioning (food), Supporting (nutrient cycling)	Farm-level	Dual food system, reduces pest use, improves nutrition	Traditional systems in Eastern India	Sathoria & Roy, 2022

An ecosystem-based approach to sustainable livelihoods through effective natural resource management is crucial for achieving long-term ecological and socio-economic sustainability (Reid

et al., 2018). This approach recognizes the interdependence between human communities and natural ecosystems, fostering resilience, enhancing biodiversity, and ensuring that natural resources continue to support the well-being of all living beings. It is a comprehensive strategy that addresses the root causes of environmental degradation while promoting sustainable development and poverty alleviation. Collaborative efforts, policy integration, and the application of sustainable practices can help create a more resilient and equitable world for present and future generations. In addition, different national and international ecosystem-based approaches towards livelihoods is depicted in Table 4.

Table 4. The different national and international ecosystem-based approaches to sustainable livelihoods.

Countries	Eco-system based approach
United States	*Chesapeake Bay Program:* The Chesapeake Bay Program is a regional partnership that brings together states, federal agencies, local governments, NGOs, and academic institutions to restore and protect the Chesapeake Bay ecosystem. The program focuses on sustainable agriculture, wetland restoration, and pollution reduction. By improving water quality and restoring habitats, the program supports local fisheries, agriculture, and tourism, providing sustainable livelihoods for the communities in the watershed (Hood et al., 2021).
India	*Joint Forest Management (JFM):* India's Joint Forest Management program involves local communities in the management and restoration of forests. The JFM model empowers local communities to sustainably manage forest resources, ensuring their participation and benefit-sharing. This approach has led to improved forest cover, enhanced biodiversity, and increased livelihoods for rural populations through the collection of non-timber forest products and eco-tourism (Bisui et al., 2023).
Australia	*Great Barrier Reef Marine Park Authority (GBRMPA):* The GBRMPA manages the Great Barrier Reef Marine Park through a comprehensive ecosystem-based approach. This includes zoning plans that protect critical habitats, fisheries management, and initiatives to reduce land-based pollution. By preserving the health of the reef, the program supports sustainable tourism and fisheries, which are vital for the livelihoods of local communities (Kuhnert et al., 2015).
Kenya	*Community-Based Natural Resource Management:* In Kenya, CBNRM programs involve local communities in managing and conserving wildlife and natural habitats. One example is the conservancy model used in regions like the Maasai Mara, where communities manage conservation areas and benefit from eco-tourism. This approach not only conserves biodiversity but also provides income and employment opportunities, promoting sustainable livelihoods (Fabricius & Collins, 2007).
European Union	*Natura 2000 Network:* The Natura 2000 network is a European Union-wide initiative aimed at protecting biodiversity through the conservation of natural habitats and wild species. It involves the designation of protected areas and the implementation of management plans that integrate sustainable land use and community involvement. This network supports sustainable agriculture, forestry, and tourism, thereby promoting sustainable livelihoods across Europe (Evans, 2012).

Table 4. *Cont.*

Latin America	*The Amazon Sustainable Landscapes Program (ASL):* The ASL program, supported by the Global Environment Facility and implemented by the World Bank, aims to protect the Amazon biome through an ecosystem-based approach. It involves sustainable land management practices, reforestation, and the promotion of sustainable agriculture and fisheries. By maintaining the ecological integrity of the Amazon, the program supports the livelihoods of indigenous communities and smallholders (Global Environment Facility, 2021).
Africa	*The Great Green Wall Initiative:* The Great Green Wall is an African-led initiative aimed at combating desertification and land degradation in the Sahel region. It involves the restoration of degraded landscapes through reforestation, sustainable agricultural practices, and the creation of green jobs. This initiative enhances food security, water availability, and resilience to climate change, thereby supporting the livelihoods of millions of people in the region (Mirzabaev et al., 2022).
Global	*The Ecosystem-based Adaptation (EbA) Approach by UNEP:* The UNEP promotes the EbA approach, which uses biodiversity and ecosystem services to help people adapt to the adverse effects of climate change. This approach is implemented in various countries through projects that restore ecosystems, such as mangroves, forests, and wetlands, to protect communities from climate impacts while providing sustainable livelihoods through eco-tourism, sustainable agriculture, and fisheries (Donatti et al., 2020).

6. Integrated Resource Planning for Natural Resource Management

IRP for Natural Resource Management is a strategic approach aimed at achieving sustainable development by holistically managing natural resources. IRP is a comprehensive framework that considers the interdependencies and cumulative impacts of resource use on the environment, economy, and society. This approach goes beyond traditional, sector-specific planning methods by integrating various resource types—such as water, land, energy, and minerals—into a single cohesive strategy. The goal is to optimize resource utilization, minimize environmental degradation, and ensure long-term sustainability (Carvallo et al., 2021).

One of the core principles of IRP is stakeholder engagement. This involves actively involving all relevant parties, including government agencies, private sector entities, local communities, and non-governmental organizations, in the planning process (Gautam et al., 2024). The inclusive approach ensures that diverse perspectives and knowledge systems are incorporated, leading to more balanced and equitable resource management solutions. For example, in watershed management, IRP would coordinate water use for agriculture, industry, and domestic purposes while ensuring the protection of aquatic ecosystems and maintaining water quality standards. When making decisions in IRP, having data is crucial. Planners use advanced modeling tools and GIS to simulate different scenarios and assess the potential impacts of various management strategies. This helps identify the best solutions that balance resource availability, economic development, and environmental conservation (Gautam et al., 2024). For example, in forestry management, IRP could involve creating models to predict the effects of logging on biodiversity and carbon sequestration.

Climate change adaptation and mitigation are essential components of IRP, given the growing pressures on natural resources caused by changing climate conditions. IRP frameworks include measures to enhance climate resilience, such as promoting drought-resistant crop varieties in agriculture or designing water management systems capable of withstanding extreme weather events. By aligning resource management strategies with climate goals, IRP contributes to reducing vulnerability and enhancing the adaptive capacity of communities and ecosystems. Additionally, the IRP advocates for the utilization of renewable resources and the implementation of circular economy principles. This involves promoting the reuse and recycling of materials, minimizing waste, and transitioning to sustainable energy sources. The goal of the IRP is to lessen the environmental impact of resource utilization. For example, in energy planning, the integration of solar, wind, and biomass energy sources can reduce reliance on fossil fuels and help to mitigate greenhouse gas emissions. Economic efficiency in IRP involves optimizing resource allocation, reducing waste,

and employing economic instruments like subsidies and taxes to encourage sustainable resource use and fund conservation initiatives (Sadeghi et al., 2024).

Monitoring and evaluation are crucial elements of IRP to guarantee that the strategies being implemented are effective and adaptable. Continuous assessment permits the modification of plans based on real-time data and emerging challenges. Performance indicators associated with environmental health, resource productivity, and socio-economic outcomes assist in tracking progress and informing policy adjustments (Gautam et al., 2024). In essence, Integrated Resource Planning for Natural Resource Management is a proactive and all-encompassing strategy that advocates for sustainable development by integrating the use of natural resources with ecological and socio-economic objectives. Through active stakeholder engagement, informed decision-making based on data, climate resilience, incentivizing renewable resource utilization, maximizing economic efficiency, and continual monitoring, IRP establishes a robust framework for effectively addressing the multifaceted challenges of resource management in the 21st century. Table 5 mentions the different IRP for NRM across different countries.

Table 5. Integrated Resource Planning for Natural Resource Management across different countries.

Country	Approach to IRP/NRM	Key Features	References
United States	Comprehensive planning through EPA	Multi-sectoral collaboration, long-term forecasts	Donatti et al., 2020; Hood et al., 2021
Canada	Federally coordinated with provincial input	Emphasis on sustainable development, indigenous rights	Donatti et al., 2020; Gautam et al., 2024
Australia	State-led frameworks (e.g., NRM Regions)	Community engagement, adaptive management	Sadeghi et al., 2024
Germany	Integrated federal and state planning	Strong environmental standards, renewable energy focus	Sadeghi et al., 2024
Brazil	Mixed federal and state planning	Amazon protection, biodiversity conservation	Kuhnert et al., 2015
South Africa	National Development Plan and IRP	Inclusive growth, resource efficiency	Gautam et al., 2024
China	Centralized planning with regional autonomy	Renewable energy expansion, ecological restoration	Donatti et al., 2020
India	National Action Plans for Climate Change	Green growth strategies, biodiversity conservation	Sadeghi et al., 2024; Kuhnert et al., 2015

7. Natural Resource Management: Research Trend and Future Perspectives

Recent studies in NRM reveal an increasing alignment between ecological sustainability, social equity, and adaptive governance. A significant trend is the combination of ecosystem-based and community-based management strategies that comprehensively address environmental preservation alongside local livelihood requirements (Doughan, 2020; Fabricius & Collins, 2007; Muchunguzi, 2023). Researchers are increasingly highlighting the importance of participatory resource governance, as local engagement boosts the legitimacy and efficiency of conservation initiatives (Jagers et al., 2018; Pani & Mishra, 2022). At the same time, research points out how livelihood assets—including natural, social, human, financial, and physical capital—affect sustainable livelihood strategies (Liu et al., 2023; Su et al., 2025), especially among vulnerable rural communities. Tools such as the Sustainable Livelihood Framework (Karki, 2021; Morse, 2025) and socio-ecological modeling (C. Wang et al., 2016) are being utilized to assess resilience and adaptive capacity in the face of climatic and economic challenges (L. Ma et al., 2024; Li et al., 2024). Moreover, the significance of diversifying economies and enhancing resource use efficiency is emphasized to lessen reliance on extractive industries and boost resilience in resource-rich yet economically vulnerable areas (Jolo et al., 2022; Muhamad, 2023; Y. Xu & Zhao, 2023).

Research in integrated land and water resource planning also indicates a movement toward transdisciplinary approaches that connect ecosystem services, land use, and community well-being (Kalogiannidis et al., 2023; Xiang et al., 2021). Gender equality and social protection frameworks are increasingly recognized as vital policy priorities to secure inclusive, sustainable adaptation results (Kundo et al., 2023; Lwamba et al., 2022). Concurrently, acknowledgement of traditional ecological knowledge as a crucial asset in biodiversity preservation and climate adaptation broadens the epistemological foundation of NRM (Fernández-Llamazares et al., 2021; Sinthumule, 2023). Furthermore, with rising concerns about environmental degradation, research has focused on technological advancements like AI, remote sensing, and big data analytics to enhance the monitoring and management of resources (Xiang et al., 2021). Nature-based solutions, agroforestry systems, and circular bio-economy models are increasingly embraced to promote sustainability in both rural and urban settings (Manoharmayum et al., 2025; Nungula et al., 2024).

Natural resource management currently encounters several significant challenges and transformative possibilities. The future demands a clear transition towards sustainable practices that ensure equity for future generations, adopt renewable resources, and reduce ecological impacts. Addressing climate change in the management of natural resources is crucial, which involves reducing greenhouse gas emissions, adapting to altered climate patterns, and robustly safeguarding biodiversity. Advancements in technology—such as artificial intelligence, remote sensing, GIS, drones, and environmental modeling—are improving accuracy in resource assessment, extraction regulation, conservation planning, and ecosystem service valuation. These innovations should be integrated into community-based management frameworks for real-time monitoring and adaptive decision-making. Future research must prioritize implementation-oriented strategies, such as pilot projects, living labs, and multi-stakeholder platforms that test scalable, replicable solutions in diverse ecological and social contexts. Effective policy frameworks must align with these technological capabilities to balance economic development with environmental stewardship, while ensuring fair access and preventing unsustainable exploitation. Collaborative efforts among governments, communities, businesses, and NGOs are vital for confronting complex problems through integrated and multi-scalar strategies. Additionally, ensuring water and food security amidst climate fluctuations and population growth is a pressing issue. Urban growth requires thoughtful land use planning to preserve ecosystem services and protect biodiversity. Furthermore, raising public awareness and enhancing environmental education are critical to fostering a conservation mindset and encouraging behavioral change. In summary, the future of natural resource management hinges on sustainability, technological innovation, effective governance, collaboration, and public engagement. Addressing these aspects holistically through both policy and practice can help mitigate environmental degradation and ensure that natural resources are managed responsibly for future generations.

Building on the trends and insights previously mentioned, it is essential to propose creative strategies that can influence future management of natural resources. Firstly, co-innovation platforms that include local communities, scientists, and policymakers should be established to develop context-specific solutions through participatory learning and experimentation. Secondly, incorporating circular bioeconomy models and nature-based solutions into standard development planning can improve resource-use efficiency while minimizing waste and environmental harm. Thirdly, utilizing digital technologies such as AI, blockchain, and remote sensing can enhance monitoring, enforcement, and decision-making, particularly in decentralized governance contexts. Furthermore, TEK into adaptive management efforts can add cultural significance and sustainability to ecological restoration initiatives. Lastly, creating incentive-based mechanisms—like payments for ecosystem services, green microfinance, and certifications for climate-smart practices—can encourage sustainable behaviors among both producers and consumers. These inventive strategies present transformative opportunities to connect policy, science, and practice, ensuring equitable and efficient management of natural resources amid growing socio-ecological complexities.

8. Conclusion

In conclusion, the quest for sustainable livelihoods through proficient management of natural resources is a complex task that requires a comprehensive and integrated strategy. The issues brought about by population expansion, climate change, and depletion of resources necessitate a shift away from conventional resource-focused methods and the adoption of ecosystem-based approaches. This study highlights that sustainable livelihoods hinge on the amalgamation of ecological well-being with human development to cultivate resilient and flourishing communities. A core element of this strategy is the acknowledgement of how ecosystems are interconnected. Effective management of natural resources should encompass entire ecosystems in the decision-making processes, emphasizing conservation and sustainable utilization. Key measures to sustain the regenerative potential of natural resources for future generations include establishing protected areas, implementing sustainable harvesting practices, and safeguarding biodiversity. The involvement of communities is vital for ensuring that the governance of natural resources is inclusive and culturally

appropriate. Empowering local stakeholders in the decision-making process promotes a sense of ownership, aligns management with the needs of the community, and enhances the effectiveness and sustainability of initiatives. The diversification of livelihoods also emerges as an essential approach to lessen reliance on single resources and bolster resilience against environmental and economic disruptions. Through strategies such as eco-tourism, agroforestry, and value-added ventures, communities can enhance their capacity to adapt and alleviate pressure on natural ecosystems. Integrated resource planning is crucial for achieving sustainable development, necessitating the coordination of ecological, social, and economic objectives through aligned strategies. Regulatory frameworks, enforcement mechanisms, and supportive policies are fundamental in curbing overexploitation and fostering sustainable practices. Furthermore, market-based incentives—like eco-labeling, payments for ecosystem services, and sustainability certification—can motivate producers and consumers to make environmentally friendly choices. Adaptation strategies that tackle climate change—such as sustainable agriculture, water management, forest preservation, and disaster risk reduction—are essential for protecting livelihoods in vulnerable regions. Beyond the immediate findings, this study holds significant theoretical and practical implications. It adds to the increasing body of literature that advocates for integrated and participatory governance of natural resources. By connecting community-driven initiatives with ecosystem-based management and sustainable development, the research offers a conceptual and operational framework that can guide policy innovation, institutional changes, and grassroots actions. The outcomes support the advancement of global initiatives such as the SDGs, particularly those aimed at alleviating poverty (SDG 1), taking action on climate (SDG 13), promoting gender equality (SDG 5), and protecting ecosystems (SDG 15). In summary, this study advocates for a fundamental shift in the governance of natural resources and the securing of livelihoods. By embracing complexity, encouraging innovation, and ensuring participatory inclusiveness, sustainable livelihoods can be realized in ways that are environmentally responsible, socially equitable, and economically viable. This holistic approach benefits current generations while also preserving ecological foundations for future prosperity, thereby paving the way for long-term sustainability and resilience.

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Abbreviations

The following abbreviations are used in this manuscript:

NRM	Natural Resources Management
CBNRM	Community-Based Natural Resource Management
EbA	Ecosystem-based Adaptation
IRP	Integrated Resource Planning
SLF	Sustainable Livelihoods Framework
IWRM	Integrated Water Resource Management
TEK	Traditional Ecological Knowledge
CBT	Community-Based Tourism

SDGs	Sustainable Development Goals
DRR	Disaster Risk Reduction
JFM	Joint Forest Management
GBRMPA	Great Barrier Reef Marine Park Authority
ASL	The Amazon Sustainable Landscapes
UNEP	United Nations Environment Programme
EPA	Environmental Protection Agency
PRA	Participatory Rural Appraisal
GIS	Geographic Information Systems

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Agricultural & Rural Studies

Review

Advancing Sustainable Utilization of Date Palm, *Phoenix dactylifera*, a Multifunctional Resource for Agro-Industrial Applications

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Abstract: The date palm (*Phoenix dactylifera L.*), a versatile crop in arid regions, offers immense potential beyond its edible fruit. Rich in compositions of carbohydrates, dietary fibers, proteins, vitamins, and antioxidants, dates are widely consumed, while other plant parts (seeds and leaves) are frequently overlooked. Traditionally discarded or repurposed to low-value uses like animal feed, these by-products possess untapped potential for high-value applications. Hence, this review presents comprehensive analysis of multifunctional applications of date palm resources, emphasizing their role in bioproduct developments as food, cosmetics and pharmaceuticals. A key innovation of this work lies in its holistic approach to date palm utilization, framed within the context of the circular bioeconomy. In addition to product-oriented applications, this review introduces a novel concept of using date palm as biomonitoring and bioremediation agent. The plant's physiological responses to environmental pollutants and contaminants position it as a promising tool for environmental assessment and remediation. This dual-purpose role enhances the eco-logical and economic value of the date palm. This review also examines traditional and modern irrigation systems used in date palm cultivation, comparing their efficiency, adaptability, and sustainability. Furthermore, this review identifies research challenges, including the need for standardization of extraction and processing methods, as well as outlines future directions for enhancing the global impact of date palm-based biorefineries, particularly through the integration of precision irrigation and remote sensing. This review contributes original insights to the evolving discourse on sustainable resource utilization, positioning the date palm as a climate-resilient, low-waste innovation model crop.

Keywords: *Phoenix dactylifera*; date palm; antioxidant; irrigation; biomonitoring

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1. Introduction

Date palm (*Phoenix dactylifera* L.; family: Arecaceae or Palmae), is among the earliest man-cultivated tree species (Al-Mssallem et al., 2013), especially prominent in regions, for instance, the Arabian Peninsula (United Arab Emirates, Saudi Arabia, Oman, Jordan), Iran, Pakistan, and the United States, because it can endure challenging environments with diverse temperatures, salinity, water scarcity and arid climate conditions. Statistically, over 5,000 varieties of date palm species have been documented globally.

Symbolised as life in the desert, the date palm is morphologically characterised by a growing height of up to 20 m and distinguished by features of feather-like leaves with fibrous extensions radiating from a central crown. Its fruit is nutritionally rich, containing a diverse spectrum of functional compounds, for example, carbohydrates, dietary fibres, minerals, vitamins, and antioxidants. Beyond its fruit, different sections of the tree are utilised in traditional and modern applications: the trunk and the leaf midribs serve as materials for infrastructure and biofuel production; fronds are utilised for the building of roofs and huts; leaflets are crafted into baskets and mats; and the

coarse fibres around the leaf bases (known as fibrillum) are repurposed into ropes, packaging and padding. Moreover, date palm also plays a role in environmental monitoring. It has been employed as a biomonitor to assess heavy metal accumulation and air pollution in specific regions (Al-Khashman et al., 2011; Al-Khlaifat & Al-Khashman, 2007; Al-Shayeb et al., 1995; Jafari et al., 2023; Tengberg, 2012).

Date palm fruit is highly valued for its rich nutritional and medicinal attributes. Unique among fruits, it has served as a dietary staple for thousands of years, sustaining millions of people across various cultures. Archaeological evidence from sites such as Sabiyah in Kuwait and Dalma Island in the UAE reveals early consumption of dates, as indicated by the discovery of carbonised seeds and stones (Ahmed et al. 2013; Tengberg, 2012). In Islamic tradition, dates hold special significance, especially prominent during the sacred month of Ramadan, as they are commonly served as customary food in iftar practices for breaking the daily fast, a practice dating back to the time of Prophet Mohammed (Peace Be Upon Him) and referenced in the Holy Quran (Al-Dashti et al., 2021). One of the remarkable features of date palm fruit is its edibility across three progressive ripening phases: khalal (fresh and firm), rutab (soft and succulent), and tamar (fully ripe; Al-Mssallem et al., 2013). The transition to the tamar stage typically occurs 150 to 200 days post-pollination, at which point the fruits develop dark colouration with a tender and chewy mouthfeel. In this period, the fruits contain a high number of natural sugars, for instance, fructose, glucose, and sucrose. This stage also marks the lowest moisture content, making the fruit ideal for long-term storage (Aleid et al., 1999; Sawaya et al., 1983).

Dates hold a prominent cultural and social significance in the Middle Eastern nations and among Arab communities. They are traditionally served during important occasions, including weddings, birth celebrations, communal gatherings, festive occasions, and religious celebrations. Fresh dates are especially prized for their flavour and texture. The market offers a wide range of date-based products, such as homemade delicacies, pastries, baked goods, confectioneries, beverages, date paste, flour, jams, milk, ice-cream, syrup, and even fermentation items like wine, alcohol, and organic acids. Despite their well-known nutritional and therapeutic benefits, dates remain underappreciated in other parts of the world. This is partly due to limited scientific literature, much of which is rooted in Islamic prophetic traditions (Vayalil, 2012; Zaid & de Wet, 1999).

Globally, date cultivation is a significant agricultural sector, with an annual production of approximately 5.4 million metric tonnes. Over the past decade, the industry has grown by approximately 18%, yielding 8.53 million metric tons across 1.11 million hectares of farmland (Alotaibi et al., 2023). In 2001, five countries (Egypt, Iran, Saudi Arabia, Pakistan, and Iraq) accounted for nearly 69% of the world's date output. Including Algeria, the UAE, Sudan, Oman, and Morocco raises this figure to 90%, highlighting the regional concentration of date farming (Botes & Zaid, 1999). Arab countries collectively have more than 85 million cultivated date palm trees, with the highest concentrations found in regions such as Saudi Arabia, UAE, Tunisia, Morocco, Algeria, Iran, Iraq, and Egypt (Al-Omran et al., 2019), making these nations central to global date palm cultivation. Recent data indicate that Saudi Arabia cultivates over 28 million date palms across approximately 160,000 hectares. This extensive cultivation supports nearly 120,000 farms, which collectively contribute around 55% of the nation's total date fruit production (Mansour & Chockalingam, 2020). In Qatar, date palms are the most extensively grown fruit trees, contributing approximately 7.2% to the country's total agricultural output (Islam et al., 2020).

Date palms can be replenished within a relatively short period. After planting, these trees typically begin fruiting in 4 to 8 years, and consistent yields suitable for commercial use are usually achieved within 7 to 10 years (Al-Dakheel et al., 2022; Alnaim et al., 2022). Primarily grown in the hot, arid zones of Southwest Asia and North Africa, dates are marketed worldwide as a premium fruit and confectionery crop. They also remain a vital subsistence food in desert regions. Recent years have seen growing scientific interest in the potential health benefits of dates, prompting numerous laboratory and animal-based studies focused on their phytochemical composition. Scientific evidence suggests that dates are a rich source of nutrients and are believed to support overall well-being. Despite their naturally elevated sugar content, many date varieties have a low glycemic index, challenging the misconception that dates are comparable to candy and contribute to chronic diseases.

While several reviews have been published on the nutrient profile and associated health impacts of dates, a significant gap remains in the literature regarding the comprehensive valorisation of date by-products, particularly date seeds, within the context of bioproduct development and waste management. Existing literature tends to focus predominantly on dietary aspects, leaving a gap in understanding the multifunctional applications of these underutilised resources. The innovation of this review lies in the novel and multidisciplinary perspective on the utilisation of date palm components within the framework of the circular economy, integrating its applications in pharmaceutical and environmental domains. Hence, this review introduces several key breakthroughs. First, it explores the underutilised potential of date palm by-products, especially date seeds, in the

development of high-value products, supported by relevant metrics, and explores their role in advancing circular bioeconomy and biorefinery models. More comprehensive exploration is necessary to validate their health potentials, elucidate mechanisms of action, and establish their role as a functional and medicinal food globally (Vayalil, 2012). Secondly, this review explores the use of date palms in environmental monitoring, particularly for detecting heavy metal accumulation and air pollution, an area rarely addressed in existing review studies. Third, this review also compares the traditional irrigating system, highlighting the role of emerging irrigation technologies to enhance water-use efficiency and support climate-resilient agriculture. Finally, we discuss current challenges and future research directions for expanding the global utilisation of date palms.

2. Methodology

This review aims to assess recent literature to address the research question concerning the multifunctional applications of date palm components, especially date seed in bioproducts development and environmental remediation. A systematic literature search is conducted using several academic databases, including Google Scholar, Web of Science, and Scopus, to identify relevant research and review articles on *Phoenix dactylifera* or date palm on the aspects of biomedical, agricultural, and environmental sciences. Databases such as Web of Science and Scopus are recognised for their selective indexing of peer-reviewed research, ensuring scholarly rigour and credibility. In contrast, Google Scholar offers a wider range of sources, including unpublished manuscripts, conference proceeding papers, and other academic materials, such as these, dissertations, technical reports, institutional repositories, and book chapters. The search includes studies published in English from 2000 to 2025, without predefined date restrictions. The search strategy is developed using keywords related to date palm, for example: (“date palm” OR “Phoenix dactylifera”) AND (“nutritional value” OR “medicinal properties” OR “bioremediation” OR “irrigation” OR “biochemical composition” OR “health benefits”). The initial search yields a large volume of records in terms of academic journals, theses, dissertations, book chapters, and conference proceedings, which are then screened in multiple stages. First, deduplication of records across databases, followed by screening of titles and abstracts for relevance, and lastly, full-text articles are retrieved for those meeting the criteria to confirm eligibility based on the inclusion criteria. The studies are included based on the inclusion criteria, including focus on *Phoenix dactylifera*, date palm in the context of cultivation (traditional and modern approaches), application of various date palm components (bioproducts synthesis and bioremediation), experimental or modelling studies, published in English and accessible in full text. Studies that were conceptual, outside the defined timeframe, lacking methodological rigour, non-English articles, inaccessible full texts, or focused on unrelated topics were excluded. The extracted data are further synthesised through content analysis, allowing for classification into a few sections. These include irrigation systems, bioproduct valorisation of date palm components (fruits and seeds), date palm as the bioremediation agent, challenges, and future research directions. Acronyms and technical terminology are clearly defined in the nomenclature section to ensure clarity and consistency throughout the analysis. The challenges identified in the literature are categorised into thematic areas, including technological barriers, resource constraints, and gaps in knowledge related to bioproduct valorisation. Each challenge is further analysed to uncover underlying causes and potential avenues for future research. The findings are organised and illustrated using tools, such as figures and tables, to enhance comprehension of current trends. This approach highlights the economic value of date palm cultivation and its associated bioproducts.

3. Irrigation Management - Date Palm Cultivation

Due to their drought tolerance and high resilience in dry climates, date palms are a suitable choice for farming in water-constrained regions, particularly during the mid to late growing seasons. Unlike many traditional winter crops, it can thrive with minimal irrigation and in saline conditions, making it an ideal choice for arid and semi-arid environments. Furthermore, their flexibility in soil requirements, including sandy, saline, and calcareous soils, allows date palms to be cultivated in a broad spectrum of terrains without competing with other seasonal crops (Ghazzawy et al., 2022). Climate is a key determinant in the successful cultivation and productivity of date palms. Key environmental factors, for example, temperature, rainfall, humidity, sunlight, and wind, significantly influence the suitability of a location for successful date palm cultivation.

Efficient irrigation is essential for the healthy growth and successful production of date palms, particularly within oasis agroecosystems. Table 1 illustrates various irrigation systems used for date palm farming. Understanding the root distribution of date palms is essential for effective water management. When soil is separated into four equal horizontal layers, root distribution tends to be uneven across soil depths, with the majority, around 40%, located in the uppermost layer of the soil profile. The concentration gradually decreases with depth, with approximately 30% in the second

layer, 20% in the third, and only 10% reaching the deepest section. Water uptake mirrors this distribution, with the majority absorbed from the upper soil layers.

Table 1. Different irrigation methods of date palm farming (Liebenberg & Zaid, 1999).

Irrigation method	Description	Advantages	Disadvantages
Flood irrigation	The oldest and most widely practised method	- Low operational cost - Ease of implementation - Cheap installation cost, especially in relatively flat terrains	- Low efficiency - Labour-intensive - Non-targeted irrigation, which leads to wastage - Unsuitable for sandy soils
Furrow and basin irrigation	An improved version of flood irrigation designed to address its limitations	- Low operational cost - Ease of implementation - Cheap installation cost, especially in relatively flat terrains	- High labour requirements - Disruption of mechanized farming
Sprinkler irrigation	Recognised as one of the earliest modern irrigation methods, it is developed to enhance water efficiency and support the automation of agricultural processes	- Efficient water usage - Simplified scheduling and management - Reduced labour requirements - Adaptability to terrain, even in areas with uneven or challenging topography	- High installation cost - Elevated operational expenses - Sensitivity to environmental conditions - Unsuitability for young palms
Micro irrigation	Originally developed in South Africa to stabilise mine dumps by preventing wind erosion of sand, it is later adapted for agricultural use, particularly for irrigating trees and various crops.	- Efficient water usage - Lower operational costs - Easy to schedule and manage by automation - Targeted watering - Topography flexibility - Low labour demand - Customizable spray patterns	- High installation costs - Requires clean water Affected by environmental conditions
Drip irrigation	The most recent advancement in irrigation technology was developed in Israel, specifically designed to maximise water efficiency in agriculture under conditions of scarcity.	- High efficient water use - Low operational costs - Low labour demand - Simple management - Targeted application - Terrain flexibility - Automation-friendly - Customizable spray patterns	- High installation costs - Strict water quality requirements to prevent clogging - Monitoring challenges

For mature date palms, the root system typically extends to a depth of around 5 meters and spreads within a 3-meter radius from the trunk. Water extraction is most efficient in the top 150 cm of soil—40% absorbed within the first 50 cm, 70% from the top 100 cm, and 90% from the top 150 cm. Beyond this point, water uptake drops sharply, contributing only about 10%. In contrast, young date palms have a much shallower root system, typically extending 25 to 50 cm deep and spreading laterally within a 10 to 30 cm, which varies according to the size of the individual plant.

Therefore, irrigation must be carefully targeted within these zones to ensure water reaches the active root area. Over-irrigation that penetrates deeper soil layers can hinder proper root development. Localized irrigation techniques, for example, drip or micro-irrigation, are more efficient and suitable than traditional flood irrigation. For newly planted tissue culture-derived date palms, the portion of soil accessible for water uptake is minimal, necessitating frequent and precise watering. Extra attention is required when planting in sandy soils, which have low water retention capacity (Liebenberg & Zaid, 1999).

Water delivery methods for date palm cultivation vary depending on local hydrological conditions, available technology, and traditional practices. Today, mechanical pumping from underground water sources via wells is widely used. Historically, water was raised using manual or

animal-powered devices such as the Egyptian shaduf, a technique common in the ancient Near East. Additionally, water was transported from rivers or distant aquifers through open channels or underground systems like the falaj or qanat, which reflect the ingenuity of traditional irrigation infrastructure (Costa, 1983; Eyre, 1994). These systems involve channeling groundwater through a network of tunnels and conduits to irrigate date palm plantations. Widely used across the Middle East and North Africa, they exemplify the ingenuity of traditional water management practices developed to support agriculture in arid and desert climates, particularly in Middle Eastern countries.

The natural tolerance of date palms to heat and drought makes them a strategic crop for food production. The study by Allbed et al. (2017) demonstrated a notable decrease in the climate compatibility required for successful date palm cultivation, driven by shifting weather patterns and rising temperatures. Drought, which is influenced by fluctuations in temperature and rainfall patterns, affects date palm in a multifaceted way, as shown in Figure 1 (Akensous et al., 2022). Investigation of drought stress on the physiological and biochemical responses of four date palm cultivars (Khalas, Barhee, Hilali, and Ashrasee) in arid conditions revealed that severe drought diminished leaf formation, reduced biomass yield, and impaired physiological performance (Khalas and Barhee cultivars demonstrated greater drought tolerance, whereas Ashrasee was the most sensitive), highlighting the potential of deficit irrigation and cultivar selection as strategies for conserving water and maintaining productivity in arid agriculture (Ali-Dinar et al., 2023). Date palms require adequate irrigation with good-quality water to reach their full yield potential (Allbed et al., 2017). Hence, emerging technologies, such as sensor-driven irrigation systems, offer a more sustainable alternative by optimizing water use and maintaining productivity. Mohammed et al. (2021a) developed a fully automated subsurface irrigation system (CSIS) to remotely manage water use for date palm cultivation. Using sensors and the ThingSpeak cloud platform, this system monitored climate and soil moisture in real time, enabling precise irrigation scheduling. The sensor-based method (S-BIS) demonstrated greater effectiveness compared to the time-based scheduling (T-BIS), targeting irrigation to the root zone when plants can most effectively utilize it. In contrast to conventional surface irrigation, CSIS methods significantly reduced water usage by approximately 60%, improving water productivity and maintaining soil moisture near field capacity. These results highlighted CSIS with S-BIS as a promising solution for sustainable date palm irrigation in arid regions (Mohammed et al., 2021a). Mohammed et al. (2021b) also evaluated the effects of controlled deficit irrigation using drip (DI) and subsurface (SI) micro-irrigation systems on water use efficiency, gas exchange, yield, and fruit quality of Khalas date palms. Conducted over two seasons at King Faisal University, the research used IoT-based monitoring to guide irrigation scheduling at 50%, 75%, and 100% of crop evapotranspiration (ETc), compared to conventional surface irrigation. Results showed that SI consistently outperformed DI, especially at the 50% ETc level, as well as maintained fruit quality comparable to full irrigation, reducing water use. In short, high efficiency in managing irrigation is essential for widespread adoption in date palm cultivation across countries with arid and semi-arid climates. Modern irrigation systems for date palm cultivation using sensors and the Internet of Things represent a significant shift from traditional irrigation methods. These technologies not only improve water-use efficiency but also align with the principles of sustainable utilization and the circular bioeconomy by minimizing resource waste and optimizing input-output ratios. The adoption of irrigation methods needs to focus on their cost-effectiveness and scalability. Regional variations in the use of irrigation methods are often influenced by policy incentives, infrastructure, and farmer awareness. However, a critical gap remains in the integration of real-time data analytics and IoT-based monitoring. Future research should focus on developing adaptive irrigation models tailored to arid climates, incorporating recycled water sources with low capital and operational costs, thereby reinforcing the circular bioeconomy framework in date palm farming.

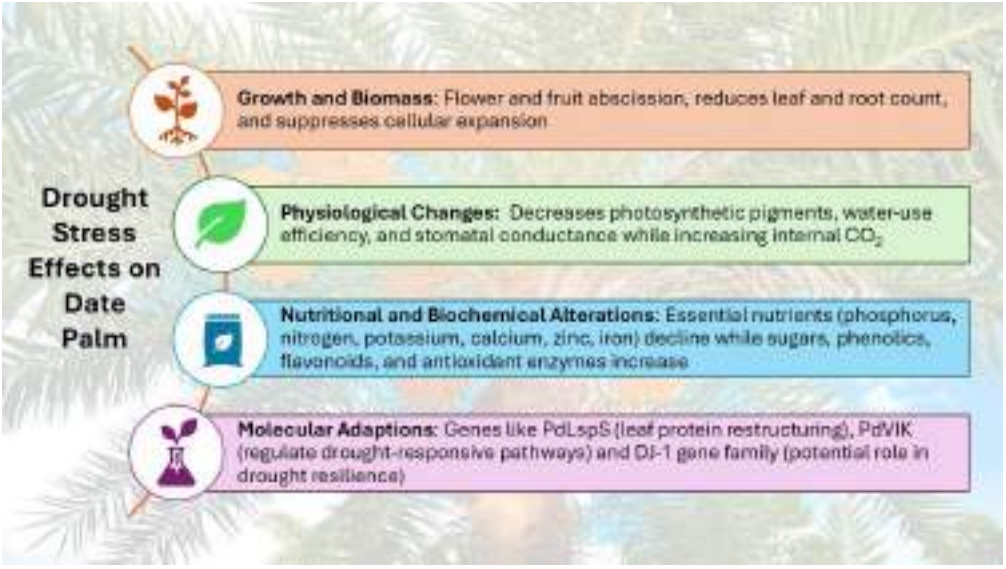


Figure 1. Impact of drought stress on date palm. Adapted from Akensous et al. (2022).

4. Date Palm Components

This section provides a comprehensive overview of the two primary components of the date palm that are of nutritional and medicinal interest: the date palm fruit (Section 4.1) and the date palm seed (Section 4.2). Each subsection explores the unique characteristics of these components, focusing on their nutritional composition, health benefits, and medicinal properties. By analyzing both the fruit and seed separately, this section aims to highlight their distinct contributions to human health and their potential for value-added applications in different industries.

4.1. Fruit

Globally, over 600 distinct varieties of date palm have been identified, each differing in shape, taste, and other sensory attributes. Some well-known cultivars include Ajwah, Medjool, Deglet Noor, Barhi, Zahidi, Khadrawy, and Fard, among many others cultivated across various regions (Al-shahib & Marshall, 2003; Chaira et al., 2009; Chandra et al., 1992; Habib & Ibrahim, 2009). The fruiting cycle of the date palm occurs annually and involves five developmental stages following pollination, culminating in full ripeness over approximately seven months. Ripe dates typically range in colour from yellow to reddish-brown and grow in large clusters. Each bunch can weigh up to 10 kg, and a mature palm may produce around ten bunches per season, yielding approximately 100 kg of fruit (Zaid, 2024). The date fruit is composed of two main parts: the edible pulp and the seed (also referred to as the pit or kernel). The pulp accounts for approximately 85–95% of the entire fruit weight (Bentrad & Hamida-Ferhat, 2020; Mrabet et al., 2019), while the seed makes up the remaining 5–15%, depending on the variety (Fernández-López et al., 2022).

Dates are known for their high caloric content, typically ranging from 307 to 354 kcal per 100 grams, and are a rich source of bioactive compounds (Baliga et al., 2011; Bentrad & Hamida-Ferhat, 2020; Rybicka et al., 2021). Table 2 presents the typical nutritional profile of date palm fruit, highlighting its macronutrient and micronutrient content. The concentration and composition of biocompounds may differ significantly, depending on the parameters, for instance, the cultivar, stage of ripeness, geographical origin, and environmental growing conditions (Eid et al., 2013; Sawaya et al., 1983). Dates are a rich source of energy, primarily due to their naturally occurring sugars such as glucose, fructose, and sucrose. Dates provide moderate amounts of dietary fibre, essential minerals (potassium, magnesium, calcium, and iron), and small quantities of protein and fat. They also contain antioxidants, particularly phenolics and flavonoids, which contribute to their antioxidant capacity. This nutritional richness makes dates a valuable component in both traditional diets and modern functional food formulations.

Table 2. Nutrient/ bioactive composition of date palm fruit.

Compounds	Composition	Reference
Carbohydrates	Make up approximately 73% of the fruit's dry weight, with glucose accounting for nearly 90% of the total sugar content, alongside notable amounts of fructose and sucrose.	(Maqsood et al., 2020)
Dietary fibres	It is estimated to range between 6.4% and 11.5% of the fruit's dry weight, comprising components, for instance, pectin, hemicellulose, lignin, resistant starch, and soluble fibres. A typical serving of 100 grams, equivalent to roughly seven to nine dates, can provide 25 to 30 grams of fibre, which meets the full daily recommended intake according to current U.S. dietary guidelines.	(Al-shahib & Marshall, 2003; Barber et al., 2020)
Protein	Roughly 3% protein and are notable for providing 23 distinct amino acids, many of which are rarely found in other commonly consumed fruits.	(Maqsood et al., 2020)
Oil (saturated and unsaturated fatty acids)	The oil content in date palm fruit varies significantly between its components. The edible flesh contains a relatively low amount of oil, ranging from 0.2% to 0.5%, whereas the seeds are much richer in lipids, comprising approximately 7.7% to 9.7% of their weight. Date seeds are known to contain up to 14 different fatty acids, although only eight of these are present in trace amounts within the fruit pulp. Among the unsaturated fatty acids found in the seeds are palmitoleic, oleic, linoleic, and linolenic acids. Notably, oleic acid constitutes a substantial portion of the seed oil, with concentrations ranging from 41.1% to 58.8%, indicating that date seeds have the potential to be a rich natural source of oleic acid.	(Al-shahib & Marshall, 2003)
Sterols	Sterol analysis of date fruits has identified a range of compounds, including cholesterol, campesterol, stigmasterol, β-sitosterol, and isofucosterol.	(Kikuchi & Miki, 1978)
Minerals	- Date palm fruits contain essential minerals, with around 15 different elements identified in their composition. The concentration of these minerals in dried dates can vary widely, ranging from as low as 0.1 mg, depending on the specific mineral and the variety of the date. - Potassium is particularly abundant, reaching up to 0.9% in the fruit pulp and approximately 0.5% in the seeds, making dates a valuable source of this vital electrolyte. - Other essential minerals found in dates are boron, calcium, cobalt, copper, fluorine, iron, magnesium, manganese, phosphorus, sodium, and zinc, all of which contribute to various physiological functions. - Date seeds also contain trace elements such as aluminium, cadmium, chloride, lead, and sulphur in varying concentrations, which may reflect environmental exposure and soil composition. - Fluorine, present in elemental form, is known for its role in dental health, particularly in preventing tooth decay. - Selenium, a trace element with antioxidant properties and a role in immune function and cancer prevention, has also been detected in dates.	(Al-shahib & Marshall, 2003)
Vitamins	- Offer a variety of essential vitamins, which are vitamin C, thiamine (B_1), riboflavin (B_2), niacin (nicotinic acid), and vitamin A.	(Al-shahib & Marshall, 2003)
Carotenoids	- Research has identified the presence of carotenoids like lutein, β-carotene, and neoxanthin in date fruits. - In Algerian varieties like Deglet Noor, Tantebouchte, and Hamraya, β-carotene concentrations were measured at 6.4, 3.3, and 2.5 μg/100 g, respectively, while lutein levels were measured at 156, 28, and 33.6 μg/100 g. - Fresh and sun-dried varieties such as Fard, Khasab, and Khalas revealed that carotenoid degradation happened during the drying process, indicating a loss of these valuable compounds with post-harvest handling.	(Al-Farsi et al., 2005; Al-Farsi & Lee, 2008; Boudries et al., 2007)

Table 2. *Cont.*

Phenolic compounds/ phenolic acids	- Amari date fruits possess higher levels of phenolic compounds compared to Hallawi dates at the same ripening stage. Specifically, Amari dates contain approximately 4.27 µmol GAE/g of phenolic acids and 1.37 µmol GAE/g of flavonols, whereas Hallawi dates exhibit lower concentrations, 0.38 µmol GAE/g for phenolic acids and 0.43 µmol GAE/g for flavonols. - The total phenolic content in various Iraqi date varieties ranges from 331 to 475 mg GAE/100 g, which is notably higher than the levels typically found in fruits such as apples, blueberries, oranges, pomegranates, papayas, bananas, and red grapes. - Tunisian date cultivars have been identified with several phenolic acids, including protocatechuic acid, vanillic acid, gallic acid, syringic acid, and p-coumaric acid, across three different varieties. - The concentration of phenolic acids of various Mauritanian date palms is significantly greater during the Khalal stage of ripening (0.729 g/100 g) compared to the Tamer stage (0.559 g/100 g). - Date seeds are nutritionally dense, containing approximately 3942 mg/100 g of phenolic compounds, and an impressive 80,400 µmol/100 g of antioxidant capacity.	(Al-Farsi & Lee, 2008; Borochov-Neori et al., 2015; Matloob & Balakita, 2016; Mohamed Lemine et al., 2014; Mrabet et al., 2016)
Flavonoids	- At the Khalal stage of ripening, the Ajwa date cultivar has been observed to contain notably higher levels of the anthocyanidin petunidin (approximately 31 mg/100 g) compared to the Barni and Khalas cultivars at the same maturity stage. - In Deglet Noor dates harvested during the Khalal stage, researchers identified a diverse profile of flavonoid glycosides originating from apigenin, luteolin, and quercetin, including 19 isomeric variants, along with the presence of flavonoid sulfates. - In Oman, the total flavonoid and phenolic contents were assessed in three prominent date varieties, Fardh, Khasab, and Khalas, at two edible stages: Rutab and Tamr. The total phenolic content ranged from 81–178 mg GAE/100 g at the Rutab stage and 194–234 mg GAE/100 g at the Tamr stage. Correspondingly, the total flavonoid content varies from 19–66 mg CEQ/100 g and 25–34 mg CEQ/100 g, respectively. - 11 Saudi date varieties were identified to contain several flavonoids, including apigenin, luteolin, quercetin, isoquercitrin, and rutin. - Research on four Tunisian date cultivars demonstrated a decline in flavonoid content as the fruit matured from the Khalal to the Tamer stage.	(Amira et al., 2012; Eid et al., 2013; Hamad et al., 2015; Hong et al., 2006; Singh et al., 2012)
Anthocyanins	- Only detected in fresh dates and may degrade or be lost during sun-drying processes. - Studies showed that Khasab exhibited the highest concentration of anthocyanins at approximately 1.5 mg/100 g, followed by Fard with 0.9 mg/100 g, and Khalas with 0.87 mg/100 g. - A strong correlation has been observed between the concentration of anthocyanins and the intensity of fruit colouration.	(Al-Farsi et al., 2005)

Note: Units are presented as originally reported in the respective studies (mg/100 g, µg/100 g, µmol/100 g, mg GAE/100 g, mg CEQ/100 g, µmol GAE/g) to preserve data accuracy and reflect differences in analytical methods. Due to variations in testing protocols and reporting standards, converting all values to a single unit may introduce rounding errors or misrepresent the precision of the original data.

As demonstrated in Table 2, date fruits are recognised for their abundance of bioactive constituents with potential nutraceutical properties and contribute positively to human well-being. These biocompounds have been associated with a wide range of health-promoting effects, such as antioxidant, antimicrobial, antimutagenic, antihyperlipidemic, and anti-inflammatory activities. Beyond their distinct taste and texture, dates are also valued for their therapeutic potential, with

studies linking their consumption to a lower risk of chronic diseases, including cardiovascular disorders, certain cancers, and other health conditions (Bentrad & Hamida-Ferhat, 2020), as demonstrated in Table 3.

Table 3. Potential health benefits of date fruit.

Bioactive compounds	Health benefits	References
Carbohydrates	A 28-day intake of date seed and date flesh in powder form showed notable effects on blood biomarkers. Xylose (72.2%) and galactose (41.6%) were the main monosaccharides. Date seed powder showed stronger antibacterial activity and promoted cell growth effectively. Clinical results showed that date seed powder lowered C-reactive protein and triglycerides, and increased red blood cell counts.	(Noorbakhsh & Rabbani Khorasgani, 2023)
	In a mouse model, Deglet Noor date polysaccharides (DP) promoted the growth of beneficial bacteria like *Lachnospiraceae_NK4A136* and *Ruminococcaceae*. DP showed strong prebiotic effects and improved gut health by enhancing mucin-2 production and increasing tight junction protein expression, which strengthened the intestinal barrier. DP also reduced inflammation by lowering levels of cytokines IL-6, IL-17, and TNF-α.	(Ullah et al., 2024)
	Eating Algerian date varieties was found to have low glycemic indexes, reduced hunger and increased satiety. Algerian date varieties may be useful as functional foods that help with blood sugar control, appetite regulation, and cardiovascular health.	(Freha et al., 2016)
	A type of glucan extracted from Libyan date fruits was found to contain (1→3)-β-D-glucan linkages, which are known for antitumor or anticancer properties.	(Ishurd & Kennedy, 2005)
	Date seed polysaccharides are comprised of monosaccharides, including galacturonic acid, glucose, mannose, fructose, and galactose. They demonstrated strong antioxidant and antimicrobial activities, especially against foodborne pathogens. They inhibited enzymes linked to diabetes and high blood pressure (α-glucosidase, α-amylase, ACE) They also showed cytotoxic effects against Caco-2 and MCF-7 cancer cells.	(Jayasree Subhash et al., 2024)
Protein	Date seed protein hydrolysates had strong antioxidant, anti-inflammatory, and health-promoting properties. They inhibited lipid oxidation by 30%, β-carotene oxidation by 75% and low-density lipoprotein-cholesterol (LDL) oxidation by 60%.	
	Date seed protein hydrolysates exhibited strong antioxidant activity and blocked free radicals effectively. DPPH: 72.5% ABTS: 92.5% OH: 64.5% NO: 57.9% They also showed good reducing power, and chelated metal ions (Fe^{2+}: 73.2%, Cu^{2+}: 40.1%), preventing oxidative damage.	(Ambigaipalan & Shahidi, 2015)

Table 3. *Cont.*

	Date seed oil reduced lipid peroxidation and preserved key antioxidant enzymes, such as superoxide dismutase (SOD), catalase (CAT), and glutathione peroxidase (GPx) It also helped to protect melanocytes from oxidative injury Date seed oil could be a promising treatment for skin conditions like vitiligo and melanoma.	(Dammak et al., 2009; Ines et al., 2010)
Fatty acids and derivatives	Date palm seed oil from the "Barhi" cultivar contained mostly saturated fatty acids (50.24%), especially lauric, palmitic, and myristic acids. It also had monounsaturated fatty acids (40.33%), mainly oleic acid, and a small amount of polyunsaturated fatty acids (8.73%). The oil showed strong antioxidant activity and antimicrobial effects against several pathogens, especially *Staphylococcus aureus*. It also inhibited α-glucosidase activity, indicating potential anti-diabetic properties.	(Hammami et al., 2025)
Phenolics compounds	4 date palm cultivars (Mabroom, Safawi, Ajwa, and Mariami) were evaluated for their total phenolic content (TPC), antioxidant activity, and total anthocyanin content (TAC). Mariami had the highest TAC, while Mabroom had the lowest. Their antibacterial activity varied, with only Ajwa's methanol extract showing effectiveness against all four tested bacteria: *Staphylococcus aureus*, *Bacillus cereus*, *Serratia marcescens*, and *Escherichia coli*.	(Samad et al., 2016)
	Flavonoid glycosides from date fruits cultivated in Al Madinah, Saudi Arabia, showed strong antimicrobial activity against imipenem-resistant *Pseudomonas aeruginosa*.	(Selim et al., 2012)
	Polyphenol-rich fraction from date fruit promoted the growth of beneficial bacteria, particularly bifidobacteria. It slowed down the growth of Caco-2 colon cancer cells after 48 hours, suggesting it may help prevent colon cancer.	(Eid et al., 2014)
	Date seed extract (DSE), a polyphenol-rich compound, showed strong antioxidant and therapeutic properties. DSE can block iron-related oxidative damage to DNA and proteins and reduce the activity of enzymes linked to neurodegenerative and pigmentation disorders, such as acetylcholinesterase and tyrosinase. DSE also exhibited dose-dependent anticancer effects by reducing the proliferation of liver, colon, and breast cancer cells through apoptosis. Gene expression analysis revealed that DSE downregulated anti-apoptotic markers (BCl-2 and P21) and upregulated the tumour suppressor gene P53, outperforming even the chemotherapy drug 5-FU in some cases.	(Habib et al., 2022)
	Palm fruit pollen extract (PFPE), that are rich in polyphenols, demonstrated strong antioxidant and antimicrobial activities. It inhibited key enzymes such as acetylcholinesterase, tyrosinase, and α-amylase. In cancer cell studies, it suppressed the growth of colon (Caco-2), liver (HepG-2), and breast (MDA) cancer cells in a dose-dependent manner, causing cell death and stopping cell division.	(Habib et al., 2023)

One of the interesting facts about date palm fruits is that they offer several benefits for women's health, including potential improvements in fertility, sexual function, and during pregnancy. Jahromi et al. (2022) investigated the impact of date palm supplementation on sexual function in infertile couples. The findings revealed that women in the intervention group showed an improvement in overall sexual function scores. Specific domains such as arousal, orgasm, lubrication, pain, and satisfaction also improved significantly compared to the control group. Similarly, men in the intervention group experienced notable enhancements in erectile function, sexual desire, orgasm, and overall satisfaction. These findings suggest that one-month supplementation with date palm may positively influence sexual function in infertile couples. Date palm pollen may also enhance certain aspects of female sexual function, particularly in areas such as desire, arousal, lubrication, and overall sexual performance (Jamali et al., 2025). During the pregnancy period, consuming date fruits offers several scientifically supported benefits for both the mother and the baby. Research by Yuliana et al. (2024) indicates that date palm juice can positively influence haemoglobin levels in pregnant women, making it a promising natural supplement for managing anaemia

during pregnancy. In terms of labour, the consumption of date fruits appears to positively influence labour outcomes by shortening gestation duration and the first stage of labour, while also promoting greater cervical dilation upon hospital admission, supporting a smoother and potentially faster childbirth process (Nasiri et al., 2019). There were findings that indicated that consuming date palm sap may help shorten the active phase of labour, thereby reducing the duration of pain and anxiety experienced by the mother during childbirth (Rahmani et al., 2023). Lastly, date palm fruit consumption positively influences postpartum recovery. The presence of natural oxytocin-like compounds in dates may support uterine contractions and enhance the involution process (Saragih et al., 2020).

In short, date palm fruits comprise diverse nutritional compounds that provide nutrient support and protection against various diseases and cancers, as well as for women, particularly infertility, pregnancy, delivery, and postpartum recovery. The bioactive compounds possess antidiabetic, antimicrobial, anti-inflammatory, and anticancer effects, making them suitable for daily consumption, even for diabetes patients. However, beyond its nutritional value, a more integrative analysis reveals its potential in functional food development, bioactive compound extraction, and biorefinery applications. Comparative studies show that different date varieties vary significantly in the composition, such as sugar, antioxidant, and fibre, which can influence their suitability for specific uses. Future research should investigate the variability in the biochemical composition of different date varieties, with a focus on how these differences influence their nutritional and therapeutic properties. Comparative studies across cultivars, growing conditions, and ripening stages could provide deeper insights into the bioactive compounds present.

4.2. Seeds

In date processing industries, the seeds are often considered a by-product or waste material that are largely underutilized, with common practices involving their disposal or limited use, for example, utilized in the Arab world to prepare a naturally caffeine-free beverage (Kiesler et al., 2024) or as components in animal feed. In recent years, powdered date seeds have gained popularity as a coffee alternative, offering a similar flavor profile without the stimulating effects of caffeine (Kiesler et al., 2024). Additionally, date seeds are commonly incorporated into livestock feed, with no reported adverse effects on animal health. Date seeds with a rich chemical profile support a wide range of multifaceted applications.

Date seed oil is distinguished by its relatively high extraction yield, typically ranging from 5% to 13%. Its fatty acid profile includes both saturated and unsaturated types, with lauric and oleic acids being the most prominent. In addition to its lipid composition, the oil is enriched with health-promoting bioactive constituents such as tocopherols, tocotrienols, phytosterols, and phenolic compounds. These components contribute to its potential value across various industries, including food formulation, cosmetics, and pharmaceuticals. One notable advantage of date seed oil is its distinct dark yellow coloration, which sets it apart from conventional vegetable oils. Additionally, it exhibits a relatively high oxidative stability, allowing for extended shelf life under appropriate storage conditions (Mrabet et al., 2020). Due to high thermal stability, date seed oil is ideal for culinary applications such as cooking, frying, and seasoning, and even as a potential replacement for palm olein (Nehdi et al., 2018). The natural carotenoid content has a yellowish hue, making it ideal for margarine production without the need for synthetic colorants (Nehdi et al., 2010). The study by Basuny and Al-Marzooq (2011) demonstrated the successful substitution of conventional corn oil with date seed oil in mayonnaise formulations, resulting in improved sensory attributes.

The presence of oleic acid in date seed enhances its functionality in topical applications, as this fatty acid is known to improve skin permeability, an important feature in the delivery of active ingredients in skincare products (Mrabet et al., 2020). Studies have shown its effectiveness in reducing oxidative stress and cellular and DNA damage in skin cells due to UV-A and UV-B radiation (Besbes et al., 2004). Ines et al. (2010) investigated the chemopreventive potential of date seed oil using human epidermal keratinocyte models and found that it effectively mitigated oxidative stress induced by hydrogen peroxide, without exhibiting cytotoxicity at concentrations up to 30 μg/mL. In a related study, they observed that skin samples treated with date seed oil showed significantly reduced DNA damage, approximately four times lower, following UV-B exposure, compared to untreated samples (Dammak et al., 2010). The underlying cause of these protective responses has been linked to the oil's high levels of phenolic compounds and tocols, reinforcing its potential as a natural photoprotective agent (Dammak et al., 2010; Ines et al., 2010). The date seed oil has also been used to synthesize natural cosmetic creams, offering performance comparable to commercial products, with the added benefit of replacing synthetic ingredients with natural alternatives (Lecheb & Benamara, 2015). Date seed has also been incorporated as a component in eyeshadow formulations within the cosmetics industry (Benchelah & Maka, 2006). Date seed oil, which contains phytosterols, essential fatty acids, and other nutrients, has also been shown to promote scalp health, stimulate hair growth, and support the function of sebaceous glands and hair

follicles (Walke & Daud, 2018). Unlike synthetic skincare products that often contain parabens that are known to cause allergic reactions in sensitive skin, date seed oil offers a natural alternative with reduced risk of irritation (Alharbi et al., 2021). Beyond skincare, the oil has shown protective effects on human sperm under oxidative stress, which revealed that the oil enhanced both sperm motility and viability, particularly after 24 hours of incubation (Fatma et al., 2009). These findings highlight date seed oil shows potential as a natural component for nutricosmetics applications.

Interestingly, low free fatty acids of date seed oil are emerging as a versatile resource for biodiesel production, as demonstrated by Azeem et al. (2016). Biodiesel produced from date seed oil extracted from Zahidi, Basra, and Khazravi varieties met key fuel standards (EN14214 and ASTM D6751), showing favorable properties such as high cetane numbers (55–60.3), low iodine values (44–50), and suitable flash points (135–140 °C; Azeem et al., 2016). On the other hand, Al-Zuhair et al. (2017) conducted comparative studies using NaOH and Novozym®435 catalysts, which showed similar yields, though NaOH exhibited greater selectivity for specific fatty acids. Additionally, date seed oil has been evaluated as a feedstock for producing poly(3-hydroxybutyrate) (PHB), a biodegradable polymer (Yousuf & Winterburn, 2017). *Cupriavidus necator* was able to utilize the date seed oil as a sole carbon source via fermentation, yielding PHB with properties comparable to conventional formulations. In short, date palm seeds, often considered agricultural waste, are increasingly recognized for their potential in sustainable applications. For example, oils derived from agricultural waste, such as date seeds, are generally more cost-effective than refined edible oils in the production of bioproducts, such as the replacement of synthetic ingredients, skincare products, and biopolymers. Despite these promising avenues, critical reflection highlights limited scalability in commercial valorization, so future research should focus on integrated seed valorization strategies to convert seed biomass into multiple high-value products, thereby reducing waste and enhancing resource efficiency across the date palm value chain.

5. Date Palm as a Bioremediation Agent

Air quality is typically assessed using instrumental monitoring systems, such as bulk and wet deposition samplers, which are commonly employed to measure atmospheric pollutants. However, an alternative and increasingly recognised approach is biomonitoring, which involves evaluating the accumulation of contaminants in living organisms. This method provides valuable insights into the biological impact of air pollution and complements traditional monitoring techniques by offering a more integrated view of environmental exposure (Guéguen et al., 2011).

Using plants as natural indicators to monitor trace element deposition is becoming a widely accepted approach in environmental science. Their ability to absorb and retain pollutants, combined with their broad distribution, makes them ideal for collecting extensive environmental data. This technique is particularly useful for tracking airborne metal contaminants in urban areas. Vegetation-based monitoring is favoured for its low cost and ease of implementation, offering a practical alternative to more expensive and labour-intensive direct sampling methods. It enables researchers to examine large-scale patterns and changes over time in heavy metal pollution with minimal resources. As a result, this method provides an efficient and scalable solution for assessing environmental contamination (Bu-Olayan & Thomas, 2002). Date palm trees have been utilised in various environmental studies across multiple countries as biological indicators for assessing the distribution of heavy metals. Their natural ability to absorb and accumulate trace elements from the atmosphere and soil makes them effective tools for monitoring pollution levels. This approach has proven valuable in mapping contamination patterns and evaluating environmental health in regions where date palms are commonly cultivated, as demonstrated in Table 4.

Table 4. Role of date palm in evaluating environmental quality and exposure to pollutants.

Location	Date palm components	Findings	Reference
Aqaba, Jordan	Leaves	The highest levels of heavy metals were found in areas with heavy traffic, showing a clear link between urban activity and metal pollution. In contrast, rural and control sites had much lower levels, suggesting less contamination in those areas.	(Al-Khlaifat & Al-Khashman, 2007)
Riyadh city, Saudi Arabia	Leaves	The concentrations of metals such as lead (Pb), zinc (Zn), copper (Cu), nickel (Ni), chromium (Cr), and lithium (Li) were analysed in both washed and unwashed leaflets from different locations (urban, suburban, highway, industrial, and rural (control) sites). The results showed that more metal contamination, especially Pb and Zn, was found on the surface of unwashed leaves, pointing to air pollution as the main source. This showed that date palm leaflets can be useful tools for monitoring heavy metal pollution, especially in dry regions.	(Al-Shayeb et al., 1995)
Ahvaz city, Iran	Palm leaves and mesh fibres	The amount of potentially toxic elements (PTEs) was higher in places with more industrial activity and traffic, and lower in areas farther from roads and factories. When comparing plant parts, date palm mesh fibers accumulated more PTEs than leaflets. This was likely because the fibers have thicker layers, a rough surface, and grow longer, making them better at trapping airborne pollutants.	(Jafari et al., 2023)
Kuwait	Leaves	Date palm leaves exhibited an average isothermal remanent magnetization (SIRM) value of 120% higher than that of buttonwood (*Conocarpus erectus*), showing they are better at trapping magnetic particles. Mapping these magnetic properties showed a strong link between particulate matter (PM) and traffic-heavy areas, especially near main roads and service zones. Their strong performance as long-term pollution monitors is due to their tough structure, including multi-layered mesh fibers, a rough surface, and a long lifespan, which enhances their ability to trap and retain airborne pollutants over time.	(Almutawa & Roeland, 2022)
	Leaves, bark, fruit, and surface soil	Lead levels were measured in various parts of the date palm, including washed and unwashed leaves, bark, fruit, and surface soil. Statistical analysis using ANOVA revealed a significant difference between washed and unwashed leaf samples, indicating that a substantial portion of lead contamination is surface-bound. Since only 20% of the lead was removed by washing, about 80% was absorbed into the leaf tissue. Lead levels were highest near industrial areas, followed by highways, and then urban zones. Among the plant parts, unwashed leaves had the most lead (5.06 μg/g), followed by washed leaves (3.52 μg/g), fruit (2.88 μg/g), and bark (1.47 μg/g). Soil samples had the highest overall lead concentration (6.86 μg/g), showing that local pollution sources strongly affect lead levels in the environment.	(Bu-Olayan & Thomas, 2002)

In addition to its role as a biomonitoring agent, the date palm also shows promise as a bioremediation tool. Its natural ability to absorb and accumulate pollutants, particularly heavy metals, makes it a valuable resource for environmental cleanup efforts. The application of date palm as a bioremediation agent is a low-cost, sustainable, and eco-friendly approach to mitigate

environmental pollution. Large quantities of date palm biomass waste, including leaf, trunk fibre, and seed, are generated annually, yet much of it remains underutilised. It is estimated that a single date palm tree can produce up to 20 kg of organic waste per year (Awad et al., 2023; Faiad et al., 2022; Martis et al., 2020). The study by Awad et al. (2023) showed the potential of date palm trunk fibres (DPTF) as low-cost, renewable, and eco-friendly adsorbents for removing contaminants from water. Their robust structure and high surface area enable effective binding of heavy metals such as cadmium, making them suitable for use in sustainable wastewater treatment systems. DPTF demonstrated a notably high sorption capacity of cadmium from wastewater, reaching 51.5 mg/g at a low flow rate, which surpassed the performance of other commonly used biosorbents. Next, Basheer et al. (2021) synthesised nanostructured powder-activated carbon (nPAC) using date palm fibre as the precursor material to remove aluminium ions (Al^{3+}) from aqueous solutions. Under the optimised conditions, the nPAC demonstrated a removal rate of 99.5% and an adsorption capacity of 9.958 mg/g, which confirmed that date palm fibre-based activated carbon is a low-cost, environmentally sustainable, and effective material for the adsorption of Al^{3+}removal, offering a promising solution for eco-friendly wastewater treatment. Raw and chemically modified date palm fibre waste (RDPF and NaOH–CMDPF) were studied for their capability to remove phenol from water. Chemical treatment with NaOH significantly enhanced the adsorption capacity and achieved up to 86% phenol removal compared to untreated fibres (81%), concluding that date palm fibre waste is an affordable and green alternative for promoting sustainable water treatment and waste valorisation (Siva Kumar et al., 2023).

The development of a novel composite material (ZnO@DPS-AC) derived from date palm spikelets (DPS) was shown to be efficient for water purification, specifically targeting the removal of methyl orange (MO) dye. ZnO@DPS-AC exhibited rapid adsorption performance, removing more than 45% of MO within the first 10 minutes and achieving up to 99% removal under optimised conditions. The composite also proved effective in treating actual wastewater and removing various other contaminants, underscoring the value of converting agricultural waste into high-efficiency adsorbents (Al-Hazeef et al., 2024). Besides, Fseha et al. (2023) explored the use of biochar-based date palm fronds and leaves for the phenol adsorption from wastewater. Biochar from date palm fronds exhibited the highest removal efficiency, achieving 64% phenol reduction and an adsorption capacity of 15.93 mg/g. When used with treated synthetic wastewater, phenol removal rates of 60% and 85% were obtained, with respective adsorption capacities of 241 mg/g and 22.28 mg/g. Reusability experiments demonstrated sustained adsorption performance, reinforcing the potential of biochar-based date palm fronds as a low-cost and reusable adsorbent for phenol removal in wastewater treatment (Fseha et al., 2023). Date palm flower stalks (PFS) can serve as effective materials for treating wastewater, as demonstrated by Arroussi and Laksaci (2024). Untreated PFS was employed as a natural biosorbent for removing textile dyes. A maximum biosorption capacity of 38.522 mg/g was achieved under optimised conditions. The adsorption process was more efficient under alkaline conditions, with the point of zero charge determined to be 6.3 (Arroussi & Laksaci, 2024). Mahmoud et al. (2024) investigated the ability of biochar derived from date palm leaf midribs, produced via slow pyrolysis, for removing Pb (II) and iodine from water. The experiments showed complete removal of Pb (II) with 60 mg of biochar per 10 mL solution, while iodine removal peaked at 39.7% with 30–40 mg per 50 mL (Mahmoud et al., 2024).

Another investigation demonstrated the potential of date seeds in treating wastewater by eliminating dye pollutants. Din et al. (2024) investigated the use of oxidised activated carbon synthesised from date palm seeds (OACDS) as a sustainable material for dual environmental applications: wastewater treatment and soil moisture enhancement. OACDS can efficiently adsorb Rhodamine 6G dye, achieving up to 88.06% removal under optimal conditions. Regeneration studies revealed a 10.9% decline in adsorption capacity after five reuse cycles, suggesting good reusability and economic viability. OACDS also demonstrated promising water retention capabilities when incorporated into soil. Its application in clay and sandy soils improved moisture retention, with the clay-OACDS mixture reaching a peak retention of 16.8 mL. The material's porous and textured surface contributes to better water holding capacity, which may enhance crop productivity (Din et al., 2024). Date seed can also be used to produce biochar and shows strong potential for removing pesticides from wastewater (Mihajlović et al., 2025). Preliminary estimates suggest biochar produced from date seeds may serve as a viable alternative to commercial activated carbons, especially in decentralised or small-scale applications. Its high adsorption efficiency, capable of eliminating up to 92.6 % of carbendazim and 89.4% of linuron, demonstrates its effectiveness against persistent pesticide pollutants. This capability also suggests broader applicability for removing other micropollutants such as phenols, pharmaceuticals, endocrine disruptors, microplastics, and heavy metals. Beyond water treatment, date seed-biochar also holds promise for carbon sequestration, soil improvement, and use in sustainable construction materials, contributing to multiple Sustainable Development Goals (SDGs), as illustrated in Figure 2 (Mihajlović et al., 2025).

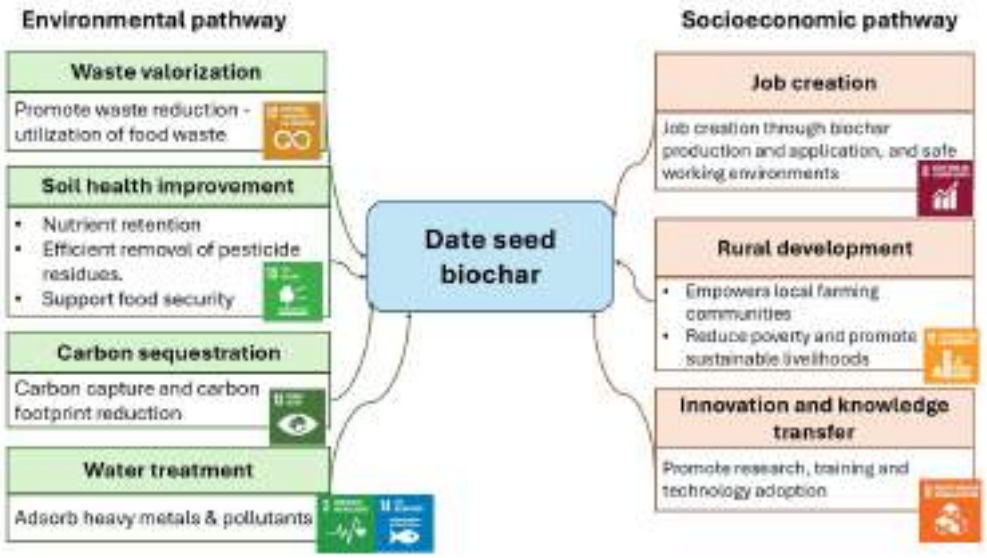


Figure 2. Transformative Pathways of Date Seed Biochar Toward Achieving SDGs. Adapted from Mihajlović et al. (2025).

To evaluate the effectiveness of date palm-derived materials in environmental bioremediation compared to conventional approaches, assessments such as comparative analysis and life cycle analysis have been conducted. Research indicates that date palm biomass can be transformed into biochar or used as an adsorbent, offering a cost-effective and sustainable alternative for pollutant removal. The study by Remmani et al. (2024) showed that biochar made from date palm seeds was efficient than commercial activated carbon in removing trichloroethylene and tetrachloroethylene from water, showing better performance. This high removal efficiency was due to the high surface area and nanotubular structure possessed by the biochar. Shaheen et al. (2022) compared date palm waste biochar with activated carbon produced from woody biomass in terms of environmental impact, cost, and adsorption performance. Using a life cycle assessment approach and Simapro 8.5 software, the results showed that date palm biochar had a lower carbon footprint, with global warming potentials (GWP) of 1.53 kg CO_{2Eq}/kg, as compared to activated carbon (8.96 kg CO_{2Eq}/kg). The cumulative energy demand (CED) for biochar was 20.3 MJ/kg, while activated carbon required 119.5 MJ/kg. The adsorption capacity was similar, but date palm biochar was cheaper with a production cost of $1.06/kg compared to $1.34/kg for activated carbon. In summary, the literature studies highlight the date palm tree as a multifunctional, eco-friendly material for environmental remediation.

6. Limitations and Future Work

Despite the growing body of literature on date palm, several research gaps remain that limit the translation of date palm into sustainable solutions. To address this, future research must be guided by research questions, supported by feasible experimental designs, and strengthened through interdisciplinary collaboration.

6.1. Research Questions

Based on the synthesis of current literature, the following research questions are proposed:

(1) How can Artificial Intelligence systems be optimized for date palm plantations under arid conditions?
(2) What are the effects of emerging postharvest and processing technologies on the physicochemical properties of different date cultivars across various ripening stages?
(3) Which extraction techniques yield the highest yield of bioactive compounds from date palm fruits and seeds, and how can these be scaled for industrial use?
(4) How can date palm be effectively used as a biomonitor for environmental applications, and what protocols are needed for regular safety assessments?

6.2. Future Studies

Date palm fruits and seeds are increasingly recognised for their nutritional and therapeutic value, which contributes to the prevention and management of chronic diseases, including diabetes, cardiovascular conditions, and certain cancers. Recent research has focused on extracting bioactive

compounds from dates using advanced techniques to develop functional foods. However, understanding their health effects is complex due to variations in date composition, extraction methods, and digestive behavior. The following future research directions are proposed to address the identified gaps.

6.2.1. Cultivar-Specific Analysis and Ripening Dynamics

Future studies should be focused on the comprehensive analysis and characterization of different date cultivars across diverse geographic regions and ripening stages to unlock their full potential. Date palm fruits experience notable transformations in their physical and chemical attributes throughout the ripening process. These changes include variations in moisture levels, sugar content, and mechanical properties such as firmness and elasticity (Ghonimy et al., 2025). Analysing the physical and mechanical traits of various date palm cultivars throughout their ripening stages is vital for enhancing postharvest strategies, refining processing methods, and tailoring their use across different industrial applications (Hassan et al., 2025). Hassan et al. (2025) used Hertz Theory to estimate the toughness of Barhi, Saqie, and Khodry dates at different ripening stages (Khalal, Rutab, and Tamar). The findings revealed that as moisture content declined during ripening, fruit size and mass decreased, leading to denser tissue in the Tamar stage. Mechanical testing revealed a significant drop in elasticity and rupture stress from Khalal to Rutab, indicating softening, followed by a slight firmness increase at Tamar due to dehydration. Measured and predicted toughness values closely matched, with minimal deviation (0.00–9.24%), confirming the model's reliability for assessing textural changes during ripening.

6.2.2. Advanced Technologies for Precision Agriculture and Postharvest Management

Recent innovations, such as edible coatings, advanced drying methods, smart packaging, and AI-driven tools like deep learning and computer vision, have enabled precise, automated classification of fruit maturity. Accurate determination of ripening stages is essential for minimising postharvest losses and preserving quality across different date palm cultivars. These technologies support precision harvesting and enhance postharvest efficiency. Khan et al. (2024) introduced a novel machine learning framework to classify date bunch types and ripeness levels and identify healthy versus white-scale disease (WSD) stages in date palm leaflets. Enhanced deep learning models, particularly VGG16, achieved high accuracy across datasets, with up to 99.7% for disease classification. The use of XAI techniques provided valuable insights into model decisions, supporting more informed and sustainable agricultural practices. At the industrial level, King Abdullah University of Science and Technology (KAUST), Saudi Arabia, is developing a robotic system for automating key agricultural tasks such as harvesting, pollination, and tree maintenance in date farming. The system uses AI-powered robotic arms equipped with high-precision visual sensors to identify and handle individual dates with speed and accuracy, reducing labour risks and improving yield quality. Field trials are set for the 2025 harvest season, with full deployment expected within three years. This Robots-as-a-Service model is proposed to make the technology accessible to smaller farms (KAUST, 2025).

6.2.3. Advanced Processing Techniques

Processing methods significantly influence sugar profiles, texture, polyphenol retention, and sensory attributes (Al-Habsi, 2025). Traditional preservation methods like sun drying, smoking, and salting remain widely used but face limitations in scalability and quality retention, making them less suitable for commercial use. The emerging processing methods, including controlled atmosphere storage, irradiation, high-pressure processing, pulsed electric fields, and cold plasma, offer chemical-free alternatives to conventional methods and address key postharvest challenges such as microbial spoilage and texture degradation, reducing postharvest losses. A preservation method that works well for one cultivar may be ineffective for another, making universal postharvest protocols impractical. As a result, preservation processes often require cultivar-specific adjustments, which complicates standardization and poses challenges for scaling and innovation in the industry. In the future, hurdle technology, an emerging approach to postharvest date treatment that combines multiple physical, chemical, and biological methods, is proposed to enhance safety, extend shelf life, and maintain quality. Techniques such as high-pressure processing, pulsed electric fields, modified atmosphere packaging, cold plasma, and irradiation work synergistically to inhibit microbial growth, control respiration, and preserve texture and nutrients. The flexibility of hurdle technology allows for tailored preservation strategies based on the specific physicochemical properties of each variety, supporting sustainable, clean-label food systems and reducing environmental impact.

6.2.4. Smart Packaging

The integration of sensor-enabled smart packaging represents a transformative advancement in postharvest management of date palm products. These intelligent systems are capable of real-time monitoring of factors like freshness and humidity, which improves storage control and shelf life. AI technologies are increasingly used to forecast spoilage trends and customise preservation

strategies based on cultivar and environmental conditions (Mondol et al., 2025). For instance, machine learning models can analyse historical data on ripening behaviour, microbial growth, and packaging performance to predict optimal storage durations and identify early signs of degradation. These predictive capabilities are particularly valuable for managing the variability in physicochemical properties across different date palm cultivars and ripening stages. From a supply chain perspective, these technologies support precision logistics, enabling real-time tracking of product quality from farm to consumer. This not only improves inventory management and reduces waste but also facilitates compliance with food safety regulations and quality assurance standards. Critically, the adoption of smart packaging and AI tools must be accompanied by the standardization of sensor technologies to ensure compatibility across packaging formats and cultivars and cost-benefit analysis to evaluate economic feasibility, particularly for small and medium-scale enterprises.

6.2.5 Scalability of the Extraction Approach for Industrial Applications

Different extraction methods, such as ultrasound-assisted, enzyme-assisted, and supercritical fluid extraction, have been utilised to extract bioactive compounds from date palm fruits and seeds. While various extraction techniques for valorising date palm biomass have been previously reviewed and evaluated, future research should focus on their scalability for industrial applications. Scaling up these methods is essential to transition from lab-scale efficiency to commercial viability, especially in regions where date palm waste is abundant. Moreover, integrating multiple extraction approaches, such as combining mechanical, thermal, and biochemical methods, could enhance the recovery of valuable compounds and ensure comprehensive utilisation of the material. A synergistic strategy not only improves yield and purity but also supports circular economy principles by minimising waste and maximising resource recovery from date palm residues.

6.2.6. Safety of Date Palm as a Biomonitoring Agent

Date palm, especially leaves, has also shown its potential as a biomonitor agent for environmental pollutants, particularly heavy metals. In the future, a quantitative analysis of the underlying adsorption mechanisms of date palm as a biomonitoring agent should be conducted. Recognising this limitation, adsorption isotherms such as Langmuir and Freundlich, along with kinetic models like pseudo-first-order and pseudo-second-order, can be applied to describe the physicochemical interactions between heavy metals and date palm tissues. These investigations will provide a more mechanistic understanding of heavy metal uptake and strengthen the scientific foundation for using date palm in environmental monitoring strategies. Variability in heavy metal uptake has also been observed across different date palm varieties. From a critical standpoint, the use of date palm as a biomonitor presents both opportunities and challenges. On one hand, its widespread cultivation and adaptability make it a practical candidate for large-scale environmental surveillance. On the other hand, the lack of standardised protocols for sampling, analysis, and interpretation limits its current utility. Future research should focus on the development of standardised biomonitoring protocols using date palm components, including sampling frequency, component selection, and analytical methods. Mapping heavy metal accumulation across cultivars and regions, supported by geospatial tools and environmental data integration, is needed. The physiological mechanisms of heavy metal uptake and translocation within the date palm components for safer consumption are also needed for investigation. AI and sensor technologies can be integrated for real-time detection and predictive modelling of contamination risks in date palm farming systems. These efforts will not only enhance food safety and public health but also position date palm as a strategic resource in environmental monitoring management.

6.2.7. Policy and Collaboration

Future work should explore policy support approaches, such as incentive programs, digital infrastructure investments, standardization, and regulatory frameworks that promote technology adoption in arid agriculture. The government can introduce subsidies or grant schemes to encourage the adoption of precision agricultural tools in date palm farming. Establishment of cultivar-specific quality standards and safety protocols will facilitate the commercialisation of fate-based bioproducts. Policies also need to consider the date palm as a biometric for heavy metals, ensuring regular testing and compliance with food safety thresholds. The complexity of challenges in date palm necessitates the interdisciplinary collaboration among academic institutions and industry to enhance knowledge exchange, community engagement, co-development of technologies, and pilot-testing in real-world settings. Cross-national collaborations are valuable for informative studies on different date cultivars' performance and technology transfer among the regions. Lastly, the involvement of local farmers in the use of digital and advanced tools ensures relevance and long-term sustainability.

7. Conclusion

In short, the versatility of the date palm has drawn significant attention lately, owing to its wide range of uses in multiple sectors across food, pharmaceutical, and nutraceutical domains. This review underscores the versatile utility of date palm fruits and their seeds, which are increasingly recognized as rich reservoirs of bioactive compounds. The sustainable utilization of every date palm component can be enhanced through circular bioeconomy principles. From fruit processing residues to fronds and seeds, each component of the date palm offers opportunities for value-added transformation, contributing to waste minimization and resource circularity. Numerous studies have documented the presence of essential nutrients, antioxidants, dietary fibers, and phytochemicals that support the health-promoting attributes. Beyond traditional consumption, the integration of date-derived ingredients into processed food products is gaining momentum in both research and commercial sectors. The health-promoting attributes of dates, for instance, their anti-inflammatory, antimicrobial, and antioxidant effects, make them ideal candidates for the formulation of functional foods aimed at improving public health outcomes. Moreover, the natural sweetness and nutrient density of dates support their use as healthier alternatives to refined sugars and synthetic additives. The growing consumer demand for clean-label and health-oriented products has further accelerated innovation in date-based food technologies. Importantly, recent studies have also identified the potential of date palm, particularly its fruits and leaves, as effective biomonitors for heavy metal contamination and air quality index. Due to their high bio-accumulation capacity, date palm components can serve as eco-friendly tools for assessing environmental pollution, especially in arid and semi-arid regions where industrial and agricultural activities pose contamination risks. By aligning its applications with sustainable development goals, particularly those related to food security, bioremediation, and responsible consumption, the date palm can serve as a model for integrated biorefinery systems in arid regions. Future research and policy frameworks should prioritize scalable technologies that reinforce the ecological and economic resilience of date palm cultivation and utilization.

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Abbreviations

The following abbreviations are used in this manuscript:

CSIS	Automated subsurface irrigation system
S-BIS	Sensor-based method
T-BIS	Time-based scheduling
DI	Drip irrigation
SI	Subsurface irrigation
ETc	Evapotranspiration
IoT	Internet of Things
GAE	Gallic acid equivalents
CEQ	mg catechin equivalents
DP	Deglet Noor date polysaccharides
LDL	Low-density lipoprotein-cholesterol
SOD	Superoxide dismutase
CAT	Catalase
GPx	Glutathione peroxidase
TPC	Total phenolic content
TAC	Total anthocyanin content

DSE	Date seed extract
PEPE	Palm fruit pollen extract
PHB	Poly(3-hydroxybutyrate)
PTEs	Potentially toxic elements
SIRM	Saturation isothermal remanent magnetization
PM	Particulate matter
DPTF	Date palm trunk fibres
nPAC	Nanostructured powder-activated carbon
MO	Methyl orange
DPS	Date palm spikelets
PFS	Date palm flower stalks
OACDS	Oxidised activated carbon synthesised from date palm seeds
SDGs	Sustainable Development Goals
GWP	Global warming potentials
CED	Cumulative energy demand
WSD	White-scale disease
AI	Artificial intelligence

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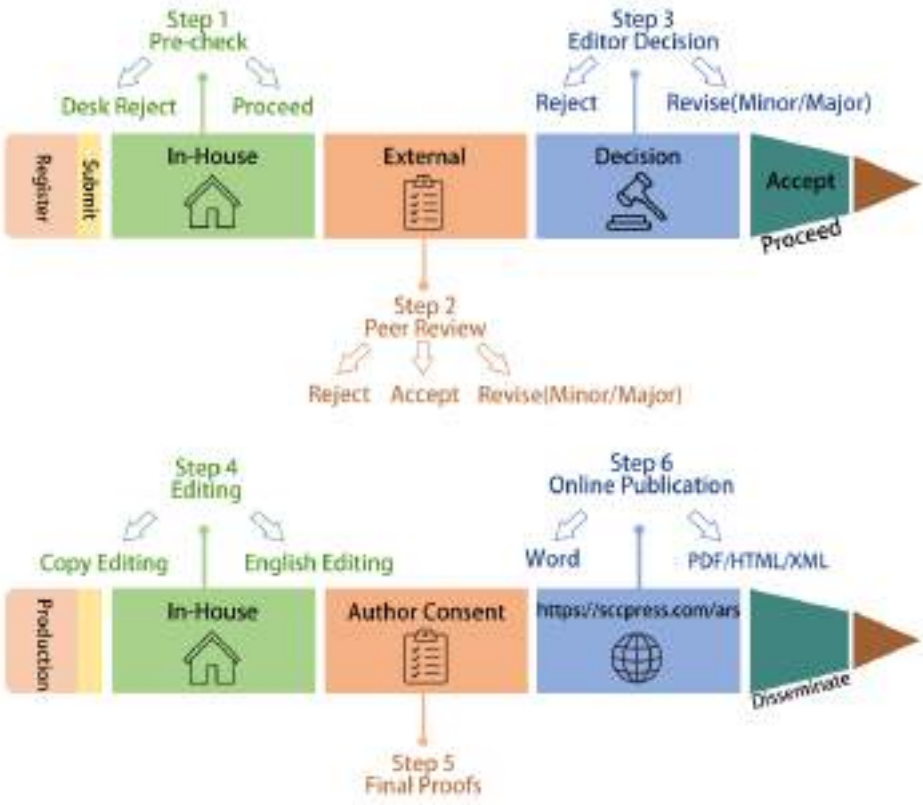
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