A central graphic featuring a globe of the Earth. A large white arrow curves around the top of the globe, pointing right. A large blue arrow curves around the bottom of the globe, pointing left. The globe is set against a background of a sunset or sunrise sky with a bright sun on the right.

ADVANCES IN
**CLIMATE-SMART
AGRICULTURE**
AND
AGRO-ENERGY SYSTEMS



**ADVANCES IN CLIMATE-SMART AGRICULTURE
AND AGRO-ENERGY SYSTEMS- 2026**

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AUTHORS

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HAMAIUNOVA Valentyna Vasylivna

SYDIAKINA Olena Viktorivna

KHONENKO Liubov Hryhorivna

ZELINSKYI Yurii Andri

Iqra Saddique MASIH

Emmanuel Ugochukwu ANASO

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PREFACE

This volume brings together a collection of scholarly contributions that explore the critical role of agriculture in addressing global challenges related to climate change, food security, and sustainable development. As environmental pressures intensify and resource constraints become more pronounced, the need for climate-resilient and efficient agricultural systems has become increasingly urgent.

The chapters in this book address key themes such as the diversification of crop systems through niche phytoenergy crops, the implementation of climate-smart agricultural practices, and the development of sustainable livestock production strategies. These studies highlight innovative approaches to enhancing productivity while reducing environmental impacts, particularly through the efficient use of resources and the mitigation of greenhouse gas emissions.

By adopting an interdisciplinary perspective, this volume integrates insights from agricultural science, environmental studies, and sustainability research. It contributes to academic discourse while also offering practical implications for farmers, researchers, and policymakers seeking to develop resilient and sustainable food systems.

It is hoped that this book will serve as a valuable resource for scholars and practitioners interested in agriculture, climate change, and food security, while encouraging further research on sustainable and innovative solutions for the future of global food production.

Editorial Team

April 20, 2026

Türkiye

CHAPTER 1
**NICHE PHYTOENERGY CROPS AS A COMPONENT
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¹BAKLANOVA Tetiana Viktorivna

²HAMAIUNOVA Valentyna Vasylivna

³SYDIAKINA Olena Viktorivna

⁴KHONENKO Liubov Hryhorivna

⁵ZELINSKYI Yurii Andriiovych

¹State Institution “Mykolaiv State Agricultural Experimental Station of the Institute of Climate-Smart Agriculture of NAAS of Ukraine”, Ukraine, hlushkot@ukr.net, ORCID ID: 0000-0002-6699-2693

²Mykolayiv National Agrarian University, Department of Agriculture, Geodesy and Land Management, Ukraine, gamajunova2301@gmail.com, ORCID ID: 0000-0002-4151-0299

³Kherson State Agrarian and Economic University, Department of Crop Production and Agroengineering, Ukraine, sydiakina_o@ksaeu.kherson.ua, ORCID ID: 0000-0001-8812-6078

⁴Mykolayiv National Agrarian University, Department of Crop Production and Horticulture, Ukraine, khonenkolg@i.ua, ORCID ID: 0000-0002-5365-8768

⁵State Institution “Mykolaiv State Agricultural Research Station of the Institute of Climate-Smart Agriculture of the National Academy of Agrarian Sciences of Ukraine”, Ukraine, zelinskiy948@gmail.com, ORCID ID: 0009-0004-1033-7878

INTRODUCTION

Under conditions of global climate change, characterized by rising average annual temperatures, increased precipitation variability, intensified droughts, and a higher frequency of extreme weather events, agricultural systems are experiencing substantial transformational pressures. These processes directly affect crop productivity, soil water regimes, and the stability of agroecosystems, particularly in risk-prone agricultural zones (IPCC, 2022; Lesk et al., 2016). The Southern Steppe of Ukraine is among the most vulnerable regions, where climate-induced stress factors already constrain agricultural productivity and increase production risks.

Additional pressure on agricultural production is exerted by contemporary economic and geopolitical factors, including market instability, supply chain disruptions, limited resource availability, and the impacts of military actions. Under such conditions, the implementation of adaptive, resource-efficient, and environmentally sustainable farming systems becomes increasingly important (FAO, 2021; KSE Institute, 2025). One of the major directions for enhancing agroecosystem resilience is the diversification of cropping systems.

Diversification of agricultural production is considered an important approach to enhancing agroecosystem resilience, as it reduces dependence on a limited range of crops, increases biodiversity, optimizes the use of natural resources, and stabilizes yields under conditions of climate variability (Altieri et al., 2015; Lin, 2011). It also plays a significant role in improving soil agrophysical and biological properties, reducing the spread of pests and diseases, and increasing the efficiency of water and nutrient use.

The issue of diversification is particularly relevant in Ukraine due to the excessive concentration of sunflowers (*Helianthus annuus* L.) in the cropping structure. In many regions, its share exceeds scientifically justified crop rotation limits, leading to soil degradation, a decline in organic matter content, deterioration of soil structure, and increased phytosanitary pressure (Chekhova, 2021; Hamaiunova et al., 2019). Under such conditions, monoculture-based systems become environmentally and economically unsustainable, especially in the context of climate change.

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In this context, there is a need to revise the structure of cropping systems by introducing alternative oil crops that maintain stable productivity under water deficit and elevated temperatures. Expanding the range of such crops contributes to reducing production risks, improving the efficiency of natural resource use, and enhancing the agroecological condition of soils (Konyk & Lykhochvor, 2016; Moskva, 2016).

Diversification of oil crops is an important factor in ensuring food, environmental, and economic stability of the agricultural sector. The inclusion of alternative crops in cropping systems enhances crop rotation efficiency, improves the role of preceding crops, and contributes to the overall productivity of agroecosystems (Hamaiunova et al., 2019; Chekhova, 2021). In particular, Hamaiunova et al. (2025) demonstrated that the inclusion of alternative oil crops in crop rotations in the Southern Steppe of Ukraine improves adaptation to environmental stress, enhances soil fertility, and increases the economic efficiency of production. Similarly, global studies indicate that diversification reduces vulnerability to climate extremes and stabilizes agricultural production (Ray et al., 2015).

Recent studies further confirm that the introduction of alternative oil crops enhances agroecosystems' adaptive capacity to climate change and supports the preservation of soil fertility. Specifically, Hamaiunova et al. (2025) demonstrated that diversification of oil crops in the Southern Steppe of Ukraine improves agroecosystem resilience, optimizes cropping structures, and ensures the economic viability of production systems.

In addition to agroecological benefits, diversification has significant economic implications. Less widespread oil crops enable the formation of a broader product portfolio targeting different market segments and provide oils with valuable physicochemical properties (Wen et al., 2023). Some of these crops can also serve as feedstock for bioenergy and industrial processing, further increasing their strategic importance (Zelt, 2017).

Among promising crops, particular attention is drawn to safflower (*Carthamus tinctorius* L.), mustard (*Brassica* spp.), and hemp (*Cannabis sativa* L.), which are characterized by high drought tolerance, adaptability to diverse growing conditions, and the ability to maintain stable yields even under unfavorable hydrothermal conditions (Amaducci et al., 2015).

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These crops have a wide range of applications, from food and feed production to industrial, pharmaceutical, textile, and bioenergy uses.

Industrial hemp occupies a special position among niche crops due to its high biomass productivity, significant cellulose content, and versatility of use. It serves as an important raw material for the textile, paper, construction, and composite industries, and is also considered a promising source of bioenergy feedstock. In addition, hemp can be used as a source of cellulose for the production of advanced materials, further strengthening its role in enhancing national resource independence (Amaducci et al., 2015; Small, 2015).

Therefore, diversifying oil crops is an important pathway for developing resilient, economically efficient, and environmentally sustainable agricultural systems. It facilitates the adaptation of agricultural production to climate change, improves resource-use efficiency, preserves soil fertility, and ensures the long-term stability of the agricultural sector.

1. OBJECTIVE OF THE STUDY AND ITS SCIENTIFIC RATIONALE

The aim of this study was to identify patterns in the changes of harvested area, gross production, and yield of safflower, mustard, and hemp in the world, Europe, and Ukraine over the period 2010–2024, as well as to assess the role of these crops in the diversification of crop production in Ukraine under conditions of climate change, economic instability, and structural transformation of the agricultural sector. This approach allows not only the evaluation of the extent of crop distribution but also the assessment of their potential as components of more resilient farming systems aimed at reducing production dependence on a narrow range of traditional crops. In contemporary scientific literature, crop diversification is recognized as one of the most effective strategies for enhancing the resilience of agricultural systems to climate variability, economic fluctuations, and environmental degradation of agro-landscapes. In particular, it has been emphasized that expanding the range of cultivated crops reduces production vulnerability to external factors and increases the adaptive capacity of farming systems (Lin, 2011; Feliciano, 2019).

2. DATA SOURCES AND ANALYTICAL METHODS

The study used statistical data from the international FAOSTAT database for the period 2010–2024. The analysis included indicators such as harvested area, gross production, and yield, enabling comprehensive characterization of the scale of cultivation, productivity, and development dynamics of the studied crops at the global, European, and national levels. Data processing was carried out using comparative analysis, time series analysis, and generalization methods. This approach is appropriate for identifying long-term trends, as changes in harvested area and gross production sensitively reflect the agricultural sector's response to climatic, economic, and regulatory shifts.

3. RESULTS AND DISCUSSION OF CROP DIVERSIFICATION TRENDS

To assess current development trends in niche crops and determine their role in diversifying crop production, a comparative analysis of the dynamics of harvested area for safflower, mustard, and hemp worldwide, in Europe, and in Ukraine over the period 2010–2024 was conducted (Table 1). The analysis of this indicator is particularly informative, as harvested area is the most responsive to changes in economic viability, demand for processed products, agro-climatic conditions, and regulatory policies. In addition, its dynamics allow for assessing the actual level of integration of alternative crops into cropping systems and identifying directions for further expansion of production.

In a broader context, such an assessment is consistent with contemporary approaches that consider diversification as a key factor in enhancing the adaptability of agricultural systems to environmental changes (Lin, 2011; Feliciano, 2019).

The analysis of the dynamics of harvested area of niche crops reveals significant differences in the rates and patterns of their development, confirming the heterogeneity of distribution conditions even among drought-tolerant and technologically promising crops. At the global level, safflower shows considerable variability in cultivated area, ranging from 649.5 to 1205.0 thousand hectares, with pronounced peaks in 2016 and 2022.

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Table 1 Dynamics of harvested area of safflower, hemp, and mustard in the world, Europe, and Ukraine, thousand hectares (2010–2024), thousand ha

	Safflower			Hemp			Mustard		
	Europe	World	Ukraine	Europe	World	Ukraine	Europe	World	Ukraine
2010	4.32	834.84	0.30	2.55	5.28	1.22	246.54	790.59	106.40
2011	13.51	804.10	0.22	2.85	5.57	1.19	211.62	701.08	46.90
2012	16.35	968.59	0.20	3.55	6.42	1.16	179.51	614.46	49.32
2013	74.81	896.90	0.20	3.75	6.35	1.14	212.51	657.71	54.07
2014	119.78	893.05	0.20	3.97	6.48	1.16	305.86	814.39	96.30
2015	243.83	1053.75	0.21	3.23	5.91	1,16	239.26	679.93	58,80
2016	435.82	1169.71	0.20	4.35	6.84	1.15	219.05	727,61	44.50
2017	155.71	861.52	0.21	5.62	8.15	1.16	217.57	670,15	39.50
2018	55.17	655.20	0.21	5.85	8,49	1.16	322.88	884.75	52.40
2019	107,17	649,53	0.21	7.15	42.24	1.16	344.22	851.88	48.30
2020	175.19	784.68	0.21	8,02	31.00	1,16	196,40	630.04	23.20
2021	242.53	859.84	0.21	8.86	37.32	1.16	203.43	644.20	20.40
2022	277.74	1204.97	0.21	8.68	43.62	1.16	248.74	847.12	18.50
2023	325.82	1041.00	0.21	7.10	34.98	1.16	336.42	980.11	85.00
2024	238.74	835.60	0.21	7.51	28.49	1.16	264.49	876.99	38.20

Such variability may indicate a high sensitivity of the crop to changes in market conditions and to water availability in the main production regions. This is consistent with scientific findings, which consider safflower a crop with high tolerance to water deficit and salinity stress; however, its productive performance largely depends on specific growing conditions and agronomic management (Hussain et al., 2016). In Europe, the dynamics of safflower area are even more contrasting: a sharp increase to 435.8 thousand hectares in 2016 was followed by a decline and subsequent recovery in 2021–2023. In Ukraine, safflower cultivation areas remain consistently low, indicating the underutilization of its adaptive potential under increasing aridization.

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Mustard demonstrates a more active, but also unstable, developmental pattern. Globally, its cultivated area ranges from 614.5 to 980.1 thousand hectares, with an overall expansion trend observed in 2022–2023, whereas in Europe, the dynamics follow a wave-like pattern. In Ukraine, mustard cultivation is characterized by particularly high variability in cultivated area, which may be attributed to the combined influence of domestic market conditions, export orientation, and the production's sensitivity to weather fluctuations. These trends are consistent with research findings indicating that, under climate change conditions, white mustard may gain new opportunities for expansion in Europe as an alternative oil crop, while more traditional crops, such as rapeseed, may lose part of their suitable growing areas (Jaime et al., 2018). This supports considering mustard as a crop that can enhance the flexibility of cropping systems under increasing climatic uncertainty.

In contrast to safflower and mustard, hemp exhibits a more structured developmental trajectory, particularly in Europe. In Europe, a gradual increase in cultivated area, followed by stabilization, has been observed, indicating a more systematic market formation for this crop and an expansion of its industrial applications. At the global level, changes in cultivated area are less uniform, likely associated with shifts in regulatory frameworks and fluctuations in demand for fiber, seeds, biocomposites, and other processed products. In Ukraine, hemp cultivation is concentrated in relatively stable areas, suggesting not market saturation but rather significant potential for further expansion. This interpretation is consistent with recent review studies, which consider industrial hemp a multifunctional crop with high suitability for various applications, including cultivation on marginal lands, as well as considerable potential for adaptive agricultural production and industrial processing (Blandinières et al., 2022; Dudzic et al., 2024).

Overall, the results indicate that the development of safflower, mustard, and hemp follows clearly differentiated patterns determined by a combination of agro-climatic, economic, and regulatory factors. At the same time, the sustained interest in these crops at both global and European levels confirms their importance as potential components of a renewed cropping structure.

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For Ukraine, this is particularly significant given the need to reduce dependence on excessive sunflower concentration in crop rotations, enhance the ecological stability of agroecosystems, and promote a more balanced use of agricultural resource potential. Therefore, safflower, mustard, and hemp should be considered not only as niche crops but also as promising elements of crop production diversification capable of increasing the adaptability of the agricultural sector to climatic and market changes (Lin, 2011; Feliciano, 2019; Jaime et al., 2018; Dudzic et al., 2024).

Safflower (*Carthamus tinctorius* L.) is a valuable oilseed crop characterized by a high level of ecological plasticity and adaptability to arid growing conditions. Its ability to maintain stable productivity under water deficit, high temperatures, and low soil fertility contributes to its distribution in arid and semi-arid regions worldwide. Owing to its well-developed taproot system, safflower efficiently utilizes deep soil moisture reserves, which represents a key mechanism of its drought tolerance (Emongor, 2010; Singh & Nimbkar, 2006). In addition, the crop is capable of adapting to stress conditions through morphological and physiological adjustments, resulting in improved water-use efficiency (Kaya et al., 2007).

Beyond its agroecological advantages, safflower has considerable economic importance. Its seeds contain high-quality oil rich in polyunsaturated fatty acids, which is widely used in the food, pharmaceutical, and industrial sectors (Weiss, 2000). Despite these benefits, safflower cultivation in Ukraine remains limited, underscoring the crop's underutilized potential as an important component of agricultural diversification.

Mustard is one of the most dynamic and promising niche oilseed crops. It is characterized by a short growing season, high adaptability to diverse soil and climatic conditions, and a wide range of applications, from food production to bioenergy (Rakow & Raney, 2003). Mustard is particularly valuable as a green manure crop, as its incorporation improves soil organic matter content, enhances soil structure and water-holding capacity, and stimulates soil microbial activity (Kirkegaard et al., 1993). Moreover, due to its biofumigation properties, it can reduce the incidence of soil-borne pathogens and pests (Matthiessen & Kirkegaard, 2006).

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The inclusion of mustard in crop rotations increases yields of subsequent crops and improves soil nutrient status (Kirkegaard et al., 2008). However, significant fluctuations in its cultivated area are largely driven by market conditions, export orientation, and demand instability, which increases production risks.

In today's climate change context, safflower and mustard can be considered important components of oilseed diversification, contributing to increased resilience of agroecosystems and to the economic efficiency of production (Ray et al., 2015).

Hemp is a multifunctional technical crop with broad prospects for use across various industries and is of strategic importance to Ukraine. Due to its high cellulose and strong fiber content, it is considered a valuable raw material for the textile, paper, construction, bioenergy, and composite industries (Amaducci et al., 2015; Dudzic et al., 2024; Blandinières et al., 2022). At the same time, in the context of war, the search for domestic sources of strategic raw materials necessary to sustain national production and strengthen the state's resource independence becomes particularly relevant for Ukraine (FAO, 2022).

In this context, hemp is of practical interest as a potential source of cellulose-containing raw materials for specialized applications in certain high-tech areas (Zakrevska, 2024; Salentijn et al., 2015). Cartridges with hemp-based gunpowder are characterized by a lower mass, which significantly reduces the total weight of the ammunition (Coffeeshop.ua, n.d.; Ukrinform, 2022; Johnson, 2018). This is important for the military, who are in full gear for a long time. In addition, such ammunition is characterized by improved ballistic properties: increased bullet speed (up to 800 m/s), higher flight range, and firing efficiency (ZN.UA, 2022, Smith, 2019).

Hemp cellulose burns more intensely than cotton, leaving minimal residue, and is less sensitive to moisture, which provides better storage conditions (Kostic et al., 2008). Historically, the development of materials based on plant cellulose has contributed to the improvement of many technical products (Rowell et al., 2000). For a long time, the main source of suitable cellulose components was cotton, but the search for alternative plant raw materials has led to increased attention to hemp (Small & Marcus, 2002).

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Hemp raw materials are considered a promising alternative to traditional cellulose sources due to their physicochemical properties, high fiber content, and good technological characteristics (Amaducci et al., 2015).

This is especially important for Ukraine, which seeks to build its own raw material base and reduce dependence on imported resources (FAO, 2022). Hemp as a source of cellulose has a number of advantages, including high productivity, significant biomass yield and wide processing capabilities (Karus & Vogt, 2004). Hemp cellulose is characterized by valuable technological properties, which determines its interest in the production of special materials (Faruk et al., 2012). The high fiber content, which can reach up to 80%, determines its prospects for various industrial applications (Kostic et al., 2008).

In addition, hemp is widely used in other industries. Its fiber is used in the production of fabrics, paper, ropes, building materials, biocomposites and other innovative products (Salentijn et al., 2015). Hemp fibers are characterized by high strength, durability and resistance to mechanical loads, which makes them promising for modern industrial production, in particular in areas where a combination of lightness, strength and environmental friendliness of the material is required (Faruk et al., 2012).

Cultivation of industrial hemp is economically feasible, since the crop is characterized by relative unpretentiousness to growing conditions, resistance to certain adverse factors and high biomass yield per unit area (Amaducci et al., 2015). This increases its importance as a raw material base for various sectors of the economy and creates the prerequisites for expanding its scope of application. Thus, hemp has significant strategic development potential, which is due to its multifunctionality, wide possibilities of industrial processing and growing demand for products on the domestic and world markets (Salentijn et al., 2015).

In modern Ukraine, this crop is important not only from an agrarian and economic perspective, but also for building national raw material security, developing its own production of special materials, and strengthening the state's resilience in the face of military challenges (FAO, 2022). At the same time, the stability of hemp cultivation areas in Ukraine indicates the presence of organizational and regulatory restrictions, which confirms the need to improve state policy to support the industry (FAO, 2022).

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Overall, niche crops are an important factor in diversifying crop production in Ukraine. Under conditions of climate change, increasing aridization, and rising risks associated with conventional farming systems, their cultivation may help enhance the resilience of agricultural production, improve the efficiency of resource use, and expand the export potential of the agricultural sector.

To assess the productivity of niche crops and determine their adaptive potential under different soil and climatic conditions, a comparative analysis of the yield dynamics of safflower, hemp, and mustard worldwide, in Europe, and in Ukraine over the period 2010–2024 was conducted.

Yield is one of the most important indicators of crop production efficiency, as it integrates the effects of environmental conditions, agronomic practices, and the level of production intensification.

The analysis of this indicator enables not only evaluating the extent to which the biological potential of crops is realized but also identifying patterns of change over time and the sensitivity of crops to climate variability and management-related factors. Such analysis becomes especially relevant in the current global climate change, characterized by rising temperatures, water scarcity, and increasing risks to agricultural production.

The data presented in the table reflect interregional differences in the yields of niche crops and allow identification of general patterns in their formation, as well as prospects for their use as an element of crop diversification.

The analysis of the yield dynamics of niche crops (safflower, hemp, and mustard) worldwide, in Europe, and in Ukraine over the period 2010–2024 indicates varying levels of stability and adaptability among the studied crops.

It was found that safflower seed yield worldwide is characterized by relatively stable values ranging from 0.73 to 0.93 t/ha, with only minor fluctuations depending on the year of cultivation (Fig. 1). In Europe, variability is more pronounced, ranging from 0.46 to 0.80 t/ha, which may be associated with instability of climatic conditions and the structure of cultivated areas. In Ukraine, safflower seed yield remains stable at 0.50–0.52 t/ha, confirming the crop's high adaptability, though it also indicates an under-realized productive potential.

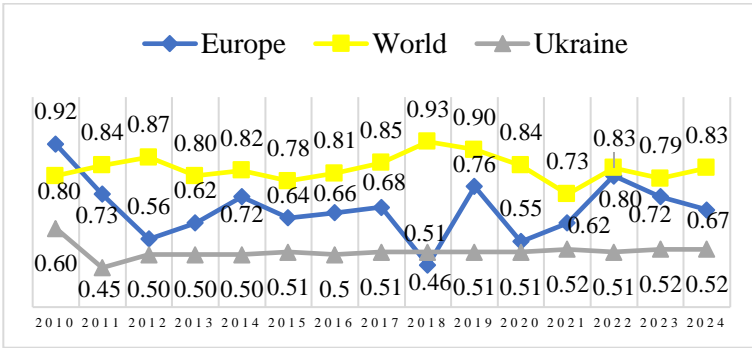


Fig. 1. Dynamics of safflower seed yield, t/ha

Hemp is characterized by moderate yield variability in Europe (0.27–0.49 t/ha) and considerably greater variability worldwide (0.43–1.11 t/ha), where peak values were recorded in 2019–2020 (Fig. 2). In Ukraine, the crop shows relatively stable yields (0.50–0.55 t/ha), which indicates its adaptation to local soil and climatic conditions, but also points to the limited adoption of intensive cultivation technologies.

Mustard has the highest productivity among the studied crops. Globally, its seed yield ranges from 0.74 to 1.09 t/ha, with an upward trend observed in 2020–2022 (Fig. 3). In Europe, yield ranges from 0.49 to 0.82 t/ha, while in Ukraine it ranges from 0.56 to 0.98 t/ha. In certain years (2021 and 2023), peak values were recorded, indicating the considerable productive potential of this crop under favorable conditions.

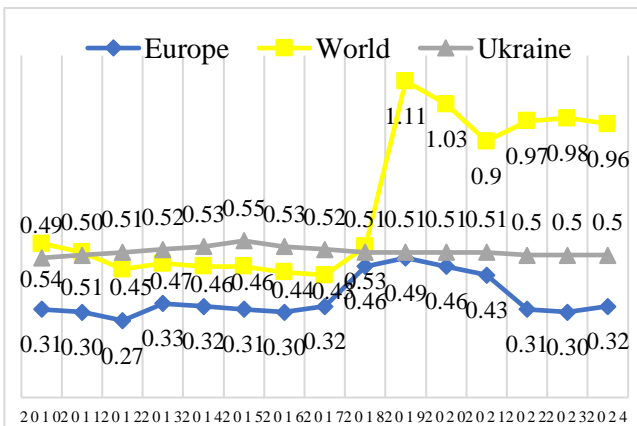


Fig. 2. Dynamics of hemp seed yield, t/ha

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The results indicate that yields of niche crops are less variable than their cultivated areas, confirming their high ecological plasticity. Safflower is characterized by stable productivity even under fluctuations in cultivated area, which makes it suitable for arid conditions. Hemp shows relatively uniform yield indicators in Ukraine, whereas at the global level, its productivity depends heavily on the level of technological development. Mustard is the most productive crop among those studied; however, its yield is more sensitive to weather conditions and agronomic factors.

In general, it has been established that niche crops can maintain a relatively stable yield even under conditions of climate change, thereby enhancing their role in crop production diversification. Particularly promising is the expansion of cultivation in Ukraine, where a combination of relatively stable productivity and insufficient realization of the potential of these crops is observed.

The analysis of gross safflower production indicates significant variability of this indicator both globally and in Europe (Table 2). Worldwide, production volumes fluctuated between 587.2 and 1002.6 thousand tons, with the highest value recorded in 2022, reflecting market instability and the crop's dependence on market conditions. In Europe, variability was even more pronounced: from 4.0 thousand tons in 2010 to 288.4 thousand tons in 2016, followed by a decline with subsequent partial recovery. In Ukraine, gross safflower production remained consistently low—at the level of 0.10–0.11 thousand tons—confirming the limited spread of the crop and the insufficient utilization of its potential.

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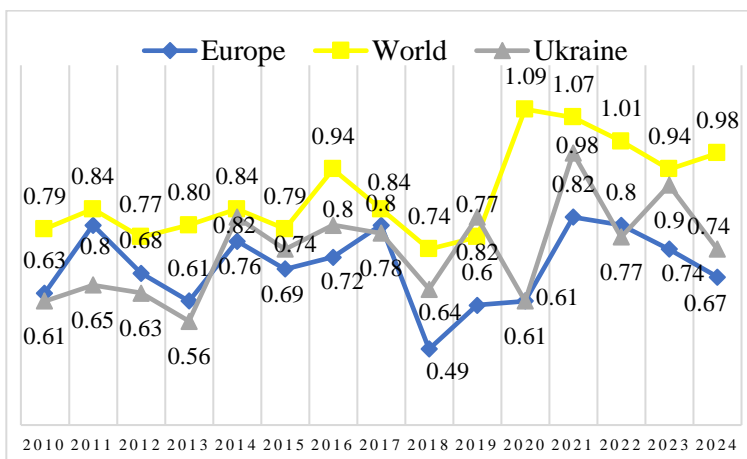


Fig. 3. Dynamics of mustard seed yield, t/ha

Hemp production exhibited a more moderate trend in Europe and pronounced fluctuations globally. In Europe, production volumes gradually increased from 0.79 to 3.83 thousand tons in 2021, followed by a slight decline. Globally, total production ranged from 2.72 to 46.74 thousand tons, with a sharp increase in 2019, likely driven by changes in demand and the expansion of hemp product applications. In Ukraine, this indicator remained almost unchanged at 0.57–0.63 thousand tons, indicating stability but limited crop development dynamics.

Table 2 Dynamics of gross production of niche crops (safflower, hemp, and mustard) in the world, Europe, and Ukraine (2010–2024), thousand tons

Pik	Safflower			Hemp			Mustard		
	Europe	World	Ukraine	Europe	World	Ukraine	Europe	World	Ukraine
2010	3.99	664.72	0.18	0.79	2.84	0.60	155.21	623.52	64.40
2011	9.80	678.28	0.10	0.85	2.84	0.60	169.06	588.98	30.30
2012	9.11	844.43	0.10	0.97	2.89	0.60	121.50	474.09	30.98
2013	46.07	721.63	0.10	1.23	3.00	0.59	130.68	525.27	30.17
2014	85.78	730.65	0.10	1.25	2.95	0.62	232.57	682.76	79.44
2015	157.17	825.33	0.11	1.02	2.72	0.63	164.00	536.13	43.55
2016	288.43	947.78	0.10	1.31	3.01	0.61	157.04	686.50	35.58
2017	106.03	735.56	0.10	1.79	3.52	0.60	174.98	564.18	31.00

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2018	25.37	609.02	0.11	2.71	4.46	0.59	159.36	658.60	33.34
2019	81.30	587.20	0.11	3.48	46.74	0.59	206.94	656.35	39.53
2020	96.75	656.16	0.11	3.72	32.02	0.59	119.56	685.27	14.04
2021	151.50	627.47	0.11	3.83	33.43	0.59	167.03	687.15	19.92
2022	222.73	1002.61	0.11	2.67	42.30	0.58	200.15	852.23	14.17
2023	234.38	819.67	0.11	2.11	34.10	0.58	248.71	923.96	76.91
2024	159.72	692.52	0.11	2.37	27.41	0.57	177.70	862.02	28.42

Mustard showed the greatest variability in gross production. Globally, its production ranged from 474.1 to 924.0 thousand tons, with peak values recorded in 2023–2024, indicating growing demand for this crop. In Europe, significant variability was also observed, ranging from 119.6 to 248.7 thousand tons. In Ukraine, mustard production showed particularly sharp fluctuations: from 14.0–14.2 thousand tons in 2020–2022 to 79.4 thousand tons in 2014 and 76.9 thousand tons in 2023. Such dynamics indicate a high dependence of the crop on economic conditions, profitability levels, and market trends.

The obtained results indicate that the gross production of niche crops is determined not only by their biological characteristics but also by market, technological, and institutional factors. Safflower has a high adaptive potential; however, its production in Ukraine remains at a minimal level, underscoring its underestimation within the cropping system. Hemp demonstrates stability in Ukraine and gradual growth in Europe, confirming its potential, particularly through the development of processing and the expansion of its application areas. Mustard proved to be the most dynamic crop, capable of rapidly responding to changes in demand, making it an important yet riskier element of diversification. Overall, the analysis of gross production confirms that niche crops exhibit different levels of realization of their production potential in Ukraine. This highlights the need for a more flexible approach to crop structure formation, focused on combining adaptive, economically attractive, and strategically perspective crops.

The scientific novelty of the study lies in conducting a comprehensive comparative analysis of the dynamics of cultivation of niche crops—safflower, mustard, and hemp—at the global, European, and Ukrainian levels over the period 2010–2024.

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Regional features of the formation of cultivated areas, yields, and gross production were identified, and the role of these crops as an important element in adapting agricultural production to climate change and diversifying crop production was substantiated.

The practical significance of the obtained results lies in their potential to optimize the structure of sown areas, increase the resilience of agricultural production, and reduce production risks. The findings can be used to develop strategies for niche crop production, build diversified agroecosystems, and design state support programs for the agricultural sector.

CONCLUSIONS

A comprehensive analysis of cultivated areas, yields, and gross production of safflower, hemp, and mustard at the global, European, and Ukrainian levels has shown that the studied crops differ significantly in both their distribution scale and the patterns of realization of their productive potential. It was established that gross production is determined by the interaction of two main components—sown area and yield level—while their ratio and degree of influence vary across crops, regions, and production conditions.

For safflower, the main factor driving variability in gross production is changes in cultivated area, whereas yield remains relatively stable over time. This indicates the crop's high ecological plasticity and its ability to maintain stable productivity even under unfavorable conditions. At the same time, the limited distribution of safflower in Ukraine indicates its underutilized potential as a drought-tolerant alternative crop suitable for conditions of climate aridization.

Mustard shows significant variability in both cultivated areas and yields, resulting in the most dynamic pattern of gross production among the studied crops. This indicates a high sensitivity of mustard to changes in market conditions, weather factors, and the level of technological support. At the same time, in favorable years, the crop demonstrates high productivity, confirming its considerable potential as a component of crop production intensification and diversification.

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Hemp, unlike other crops, is characterized by more stable cultivated areas in Ukraine and moderate yield variability, which ensures relatively stable production levels. Such dynamics indicate a high degree of adaptation of the crop to local soil and climatic conditions. At the same time, significant fluctuations are observed globally, driven by regulatory frameworks, market demand, and the expansion of industrial applications for hemp products.

The generalization of the study results showed that the yield of niche crops, in most cases, shows lower variability than that of their cultivated areas. This confirms their relatively high ecological plasticity and their ability to maintain stable productivity under changing environmental conditions. At the same time, cultivated areas act as the main regulator of production volumes, as they respond more rapidly to economic incentives, changes in demand, and agricultural policy.

At the regional level, it was found that Ukraine has significant potential to expand production of niche crops, due to favorable soil and climatic conditions, the availability of scientific support, and the need to optimize the structure of sown areas. However, the limited distribution of the studied crops indicates the presence of constraining factors, among which economic, technological, and regulatory-organizational components play a key role.

Overall, the results indicate that safflower, mustard, and hemp exhibit distinct developmental patterns; however, all can be considered important reserves for diversifying crop production in Ukraine. Their wider introduction may enhance agroecosystem resilience, reduce production risks, optimize resource use, and contribute to a more balanced structure of agricultural production.

In the future, expanding areas under niche crops should be considered a priority for adapting the agricultural sector to climate change, enhancing product competitiveness, and ensuring the long-term stability of crop production. Further research should focus on improving cultivation technologies, increasing the realization of crop genetic potential, and providing economic justification for their introduction across Ukraine's diverse soil and climatic zones.

Summary generalization

- Niche crops offer greater yield stability than traditional crops under conditions of climate variability, making them an effective means of enhancing the adaptability of agroecosystems in risk-prone farming areas.
- The main limiting factor in the development of niche crops in Ukraine is not their biological potential, but rather the institutional and economic conditions for their implementation, which necessitate improving support policies and providing technological assistance for production.

Practical recommendations

1. Optimization of cropping patterns

It is advisable to gradually increase the share of safflower, mustard, and hemp in crop rotations, especially in the conditions of the Southern Steppe of Ukraine, in order to reduce soil pressure and minimize risks associated with excessive sunflower monoculture.

2. Development of adaptive cultivation technologies

It is necessary to implement resource-saving, biologically oriented technologies to enhance crop productivity under conditions of moisture deficit and elevated temperatures.

3. Breeding and seed supply

Expanding the use of adapted varieties and hybrids that are drought- and temperature-stress-resistant is essential to improve yield stability.

4. Development of market and processing infrastructure

Increasing the economic attractiveness of niche crops requires establishing stable marketing channels, developing domestic processing, and promoting the export of value-added products.

5. Improvement of state policy

It is necessary to improve the regulatory framework, particularly regarding the cultivation of industrial hemp, and to support producers through state incentives and innovation-driven development tools.

6. Scientific and advisory support

It is recommended to strengthen the role of research institutions in promoting niche crops by developing regionally adapted technologies, conducting demonstration trials, and providing advisory services to producers.

REFERENCES

- Altieri, M. A., Nicholls, C. I., Henao, A., & Lana, M. A. (2015). Agroecology and climate-resilient farming. *Agronomy for Sustainable Development*, 35, 869–890. <https://doi.org/10.1007/s13593-015-0285-2>
- Amaducci, S., Scordia, D., Liu, F. H., Zhang, Q., Guo, H., Testa, G., & Cosentino, S. L. (2015). Key cultivation techniques for hemp in Europe and China. *Industrial Crops and Products*, 68, 2–16. <https://doi.org/10.1016/j.indcrop.2014.06.041>
- Blandinières, H., Amaducci, S., et al. (2022). Adapting the cultivation of industrial hemp (*Cannabis sativa* L.) to marginal lands: A review. *GCB Bioenergy*, 14(9), 1005–1029. <https://doi.org/10.1111/gcbb.12979>
- Chekhova, I. V. (2021). *Formuvannia ta rozvytok rynku oliinykh kultur*. http://imk.zp.ua/images/doc/chehova_2021_monografia.pdf
- Coffeeshop.ua. (n.d.). What is the strategic importance of hemp for a country's army. <https://blog.coffeeshop.ua/ua/v-chjom-strategicheskaja-vazhnost-konopli-dlja-armii-gosudarstva>
- Dudziec, P., Warmiński, K., & Stolarski, M. J. (2024). Industrial hemp as a multi-purpose crop: Last achievements and research in 2018–2023. *Journal of Natural Fibers*, 21(1), 2369186. <https://doi.org/10.1080/15440478.2024.2369186>
- Emongor, V. (2010). Safflower (*Carthamus tinctorius* L.) the underutilized and neglected crop: A review. *Asian Journal of Plant Sciences*, 9(6), 299–306. <https://doi.org/10.3923/ajps.2010.299.306>
- FAO. (2021). *The State of Food and Agriculture 2021*. <https://doi.org/10.4060/cb4476en>
- FAO. (2022). *The role of fibre crops in sustainable development*. Food and Agriculture Organization of the United Nations.
- Faruk, O., Bledzki, A. K., Fink, H. P., & Sain, M. (2012). Biocomposites reinforced with natural fibers: 2000–2010. *Progress in Polymer Science*, 37(11), 1552–1596. <https://doi.org/10.1016/j.progpolymsci.2012.04.003>
- Feliciano, D. (2019). A review on the contribution of crop diversification to Sustainable Development Goal 1 “No poverty” in different world

ADVANCES IN CLIMATE-SMART AGRICULTURE AND AGRO-ENERGY SYSTEMS

- regions. *Sustainable Development*, 27(4), 795–808. <https://doi.org/10.1002/sd.1923>
- Hamaiunova, V. V., Khonenko, L. H., Kovalenko, O. A., & Hyrlya, L. M. (2014). Yield of mustard depending on weather conditions and seeding rate on southern chernozems. *Tavriiskyi naukovyi visnyk*, (88), 50–55.
- Hamaiunova, V., et al. (2019). Oil crops productivity. <https://doi.org/10.31734/agronomy2019.01.112>
- Hamayunova, V., Khonenko, L., & Baklanova, T. (2025). Diversification of oil crops in the Southern steppe of Ukraine. <https://doi.org/10.15587/2706-5448.2025.323953>
- Hussain, M. I., Lyra, D. A., Farooq, M., Nikoloudakis, N., & Khalid, N. (2016). Salt and drought stresses in safflower: A review. *Agronomy for Sustainable Development*, 36(1), Article 4. <https://doi.org/10.1007/s13593-015-0344-8>
- IPCC. (2022). *Climate Change 2022*. <https://www.ipcc.ch/report/ar6/wg2/>
- Jaime, R., Alcántara, J. M., Manzaneda, A. J., & Rey, P. J. (2018). Climate change decreases suitable areas for rapeseed cultivation in Europe but provides new opportunities for white mustard as an alternative oilseed for biofuel production. *PLOS ONE*, 13(11), e0207124. <https://doi.org/10.1371/journal.pone.0207124>
- Johnson, R. (2018). *Advances in propellant materials from biomass sources*. *Journal of Defense Materials*, 12(3), 45–52.
- Karus, M., & Vogt, D. (2004). European hemp industry: Cultivation, processing and product lines. *Euphytica*, 140, 7–12. <https://doi.org/10.1007/s10681-004-4810-7>
- Kaya, M. D., Ipek, A., & Ozturk, A. (2007). Effects of different soil salinity levels on germination and seedling growth of safflower. *Turkish Journal of Agriculture and Forestry*, 31(1), 1–9.
- Kirkegaard, J. A., Christen, O., Krupinsky, J., & Layzell, D. (2008). Break crop benefits in temperate wheat production. *Field Crops Research*, 107(3), 185–195. <https://doi.org/10.1016/j.fcr.2008.02.010>

*ADVANCES IN CLIMATE-SMART AGRICULTURE AND AGRO-ENERGY
SYSTEMS*

- Kirkegaard, J. A., Gardner, P. A., Angus, J. F., & Koetz, E. A. (1993). Effect of Brassica break crops on the growth and yield of wheat. *Plant and Soil*, 162, 113–122. <https://doi.org/10.1007/BF01416095>
- Konyk, H. S., & Lykhochvor, A. M. (2016). Oil crops productivity.
- Kostic, M., Pejic, B., & Skundric, P. (2008). Quality of chemically modified hemp fibers. *Bioresource Technology*, 99(1), 94–99. <https://doi.org/10.1016/j.biortech.2006.12.035>
- Lesk, C., et al. (2016). Climate impacts on crop production. *Nature*, 529, 84–87. <https://doi.org/10.1038/nature16467>
- Lin, B. B. (2011). Resilience in agriculture through crop diversification: Adaptive management for environmental change. *BioScience*, 61(3), 183–193. <https://doi.org/10.1525/bio.2011.61.3.4>
- Matthiessen, J. N., & Kirkegaard, J. A. (2006). Biofumigation and enhanced biodegradation. *Plant and Soil*, 282, 13–32. <https://doi.org/10.1007/s11104-005-4131-7>
- Moskva, I. (2016). Oil crops in Southern Steppe.
- Rakow, G., & Raney, J. (2003). Present status and future perspectives of breeding for seed quality in Brassica oilseed crops. *Plant Breeding*, 122(1), 1–10. <https://doi.org/10.1046/j.1439-0523.2003.00800.x>
- Ray, D. K., Gerber, J. S., MacDonald, G. K., & West, P. C. (2015). Climate variation explains a third of global crop yield variability. *Nature Communications*, 6, 5989. <https://doi.org/10.1038/ncomms6989>
- Rowell, R. M., Han, J. S., & Rowell, J. S. (2000). Characterization and factors effecting fiber properties. In *Natural polymers and agrofibers composites*.
- Salentijn, E. M. J., Zhang, Q., Amaducci, S., Yang, M., & Trindade, L. M. (2015). New developments in fiber hemp (*Cannabis sativa* L.). *Industrial Crops and Products*, 68, 32–41. <https://doi.org/10.1016/j.indcrop.2014.08.011>
- Singh, V., & Nimbkar, N. (2006). Safflower (*Carthamus tinctorius* L.). In R. J. Singh (Ed.), *Genetic resources, chromosome engineering, and crop improvement* (pp. 167–194). CRC Press.

ADVANCES IN CLIMATE-SMART AGRICULTURE AND AGRO-ENERGY SYSTEMS

- Small, E. (2015). Cannabis classification. <https://doi.org/10.1007/s12229-015-9157-3>
- Small, E., & Marcus, D. (2002). Hemp: A new crop with new uses for North America. In *Trends in new crops and new uses* (pp. 284–326). ASHS Press.
- Smith, J. (2019). Ballistic performance of alternative cellulose-based propellants. *Defense Technology Review*, 8(2), 60–67.
- Ukrinform. (2022, September 9). A new hemp variety will be cultivated in the Sumy region for producing lighter body armor. <https://www.ukrinform.ua/rubric-regions/3567725-na-sumsini-virosuvatimut-novij-sort-konopli-z-akih-mozna-vigotovlati-legsi-bronezileti.html>
- Weiss, E. A. (2000). *Oilseed crops* (2nd ed.). Blackwell Science.
- Wen, C., et al. (2023). Vegetable oils. <https://doi.org/10.1016/j.procbio.2022.11.017>
- Zakrevska, S. (2024, October 10). Higher thermodynamic properties: A scientist explains which raw material is better for gunpowder production—cotton or hemp. Obozrevatel. <https://war.obozrevatel.com/ukr/mae-vischi-termodinamichni-vlastivosti-naukovets-poyasniv-yaka-sirovina-krascha-dlya-virobnitstva-porohu-bavovna-chi-konopli.htm>
- Zelt, T. (2017). Oil plants and biofuel. https://doi.org/10.1007/978-3-662-53065-8_13
- ZN.UA. (2022, September 18). Hemp products for the military: Ukrainian scientists have developed a unique hemp variety. <https://zn.ua/ukr/ECONOMICS/konopljana-produktsija-dlja-vijskovikh-ukrajinski-vcheni-vinajshli-unikalnij-sort-konopli.html>

CHAPTER 2
CLIMATE-SMART AGRICULTURE FOR
SUSTAINABLE FOOD PRODUCTION AND FOOD
SECURITY

¹Iqra Saddique MASIH

INTRODUCTION

The Urgent Challenge

The intersection of climate change and food security represents one of the most pressing challenges confronting humanity. The Intergovernmental Panel on Climate Change (IPCC) has concluded with high confidence that climate change is already undermining food production and access, with disproportionate impacts on vulnerable populations in low-latitude regions (IPCC, 2022). Rising temperatures, changing precipitation patterns, increased frequency of extreme weather events, and shifting pest and disease pressures collectively threaten the stability and sustainability of global food systems. Simultaneously, agriculture is both a contributor to and a victim of climate change. The food system accounts for approximately 21-37% of total anthropogenic greenhouse gas emissions, with agricultural production itself contributing about 10-12% of global emissions (Crippa et al., 2021). Land-use change, livestock enteric fermentation, rice cultivation, and synthetic fertilizer use represent major emission sources. Yet agriculture also holds significant mitigation potential through improved management practices, agroforestry, and soil carbon sequestration (Smith et al., 2020). The concept of food security—encompassing availability, access, utilization, and stability—provides a framework for understanding the multiple pathways through which climate change affects human well-being (FAO, 2008). Climate impacts on crop yields directly affect food availability. Disrupted livelihoods and increased food prices affect economic access. Nutritional quality of crops can decline under elevated CO₂ concentrations. And increasing frequency of shocks—droughts, floods, storms—undermines the stability dimension of food security (Wheeler & von Braun, 2013).

The Emergence of Climate-Smart Agriculture

Climate-Smart Agriculture (CSA) emerged in 2010 as a conceptual framework to address the triple challenge of food security, climate adaptation, and mitigation. The Food and Agriculture Organization (FAO) defined CSA as "agriculture that sustainably increases productivity, enhances resilience (adaptation), reduces/removes greenhouse gases (mitigation), and enhances

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achievement of national food security and development goals" (FAO, 2013, p. 3).

CSA is not a set of prescriptive practices but rather an approach to achieving three interconnected objectives: **Productivity:** Sustainably increase agricultural productivity and incomes **Adaptation:** Build resilience to climate shocks and adapt to progressive climate change. **Mitigation:** Reduce or remove greenhouse gas emissions where possible. Crucially, CSA recognizes that synergies and trade-offs exist among these objectives. Practices that enhance adaptation may also contribute to mitigation (e.g., agroforestry sequesters carbon while providing shade and wind protection). Conversely, some adaptation practices may increase emissions (e.g., expanded irrigation could increase energy use and methane emissions from rice paddies). CSA approaches must therefore be context-specific, weighing local priorities and conditions (Lipper et al., 2014). This chapter advances three central arguments. First, CSA provides a useful framework for navigating the complexity of climate-agriculture interactions, but its effectiveness depends on operationalization that respects local contexts. Second, the evidence base for CSA practices has grown substantially, demonstrating productivity and resilience benefits across diverse systems. Third, realizing CSA's potential requires addressing enabling conditions—policy, finance, capacity, and governance—that remain significant barriers in many regions. The chapter proceeds with an examination of the conceptual foundations of CSA (Section 2), followed by detailed analysis of practices across productivity, adaptation, and mitigation domains (Section 3). Section 4 presents illustrative case studies from three continents. Section 5 addresses implementation challenges and enabling conditions. Section 6 synthesizes key insights and identifies research and policy priorities.

1. CONCEPTUAL FOUNDATIONS OF CLIMATE-SMART AGRICULTURE

Historical Context and Evolution

CSA emerged from recognition that previous agricultural development paradigms inadequately addressed climate change.

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The Green Revolution (1950s-1980s) focused on productivity through high-yielding varieties, irrigation, and agrochemicals, with limited attention to environmental sustainability or climate resilience (Pingali, 2012).

Sustainable intensification (1990s-2000s) incorporated environmental concerns but did not explicitly address climate adaptation or mitigation (Garnett et al., 2013). CSA integrated these concerns while adding explicit attention to climate risk management and emissions reduction. The CSA framework was formally launched in 2010 through an FAO publication and subsequently endorsed by the Global Alliance for Climate-Smart Agriculture (GACSA) formed in 2014 (FAO, 2013). The concept has since been adopted by national governments, international organizations, and development partners, with over 30 countries developing CSA policies or investment plans (World Bank, 2018).

The Three Pillars: Synergies and Trade-offs

The three CSA pillars—productivity, adaptation, mitigation—are interrelated in complex ways. Understanding these relationships is essential for effective implementation. **Productivity** refers to sustainable increases in agricultural output per unit of land, labor, water, or other inputs. CSA emphasizes productivity gains that do not deplete natural capital or compromise future production capacity. This includes closing yield gaps on existing agricultural land rather than expanding into natural habitats (Lipper et al., 2014). **Adaptation** encompasses adjustments in agricultural systems to moderate harm or exploit beneficial opportunities from climate change. This includes both incremental adaptation (e.g., adjusting planting dates, switching varieties) and transformative adaptation (e.g., changing cropping systems or livelihoods) (Rickards & Howden, 2012). **Mitigation** involves reducing greenhouse gas emissions from agricultural sources (enteric fermentation, rice methane, nitrous oxide from fertilizers) and enhancing carbon sequestration in vegetation and soils. While mitigation received less emphasis in early CSA conceptualizations, its importance has grown as agriculture's contribution to climate change has become better understood (Smith et al., 2020). The potential relationships among pillars include: **Synergies:** Practices that advance multiple objectives simultaneously (e.g., agroforestry increases productivity, provides shade/erosion control, and sequesters carbon).

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Trade-offs: Practices that advance one objective at the expense of another (e.g., increased fertilizer use for productivity may increase nitrous oxide emissions). **Neutrality:** Practices with no significant effect on one pillar while advancing another.

Managing these relationships requires explicit attention to local priorities and contexts (Campbell et al., 2014).

Critiques and Limitations

Despite widespread adoption, CSA has attracted legitimate critiques. Some scholars argue that CSA overemphasizes technological solutions while neglecting structural inequalities and power relations that shape vulnerability (Taylor, 2018). Others contend that CSA's mitigation focus may disadvantage smallholder farmers whose emissions are minimal, potentially diverting resources from adaptation priorities (Newell & Taylor, 2018). The concept of "climate-smart" has also been criticized for suggesting that conventional agriculture can be made climate-compatible without fundamental transformation. Critics from agroecological perspectives argue for more radical restructuring of food systems rather than technocratic adjustments (Anderson et al., 2019). These critiques are valuable, highlighting that CSA's effectiveness depends on how it is operationalized. When implemented through participatory, equity-oriented approaches that prioritize smallholder needs, CSA can contribute to food security and resilience. When reduced to technical packages imposed from above, it risks reproducing existing inequalities.

2. CLIMATE-SMART PRACTICES ACROSS AGROECOLOGICAL SYSTEMS

Soil Management for Carbon Sequestration and Resilience

Soil is both a carbon sink and a foundation of agricultural productivity. Improved soil management can simultaneously enhance yields, build drought resilience, and sequester atmospheric carbon. Key practices include: **Conservation Agriculture (CA):** CA combines three principles: minimal soil disturbance (reduced tillage), permanent soil cover (crop residues or cover crops), and crop rotation/diversification.

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Meta-analyses demonstrate that CA increases soil organic carbon, improves water infiltration, reduces erosion, and can increase yields, particularly in dryland systems (Pittelkow et al., 2015; Gonzalez-Sanchez et al., 2019). However, CA adoption faces barriers including competition for crop residues as livestock feed, limited access to no-till planters, and transition periods when yields may decline.

Agroforestry: Integration of trees into agricultural landscapes provides multiple climate-smart benefits. Trees sequester carbon in biomass and soils, reduce wind erosion, improve water infiltration, provide shade reducing heat stress, and diversify production (nutrients, timber, fodder). Systematic reviews indicate that agroforestry can increase total system productivity by 30-60% compared to monocultures while storing 20-50 tons of carbon per hectare (Zomer et al., 2016; Muchane et al., 2020). **Integrated Soil Fertility**

Management (ISFM): ISFM combines organic and inorganic nutrient sources with improved germplasm and agronomic practices. This approach optimizes nutrient use efficiency, reducing fertilizer requirements while maintaining or increasing yields. By reducing nitrous oxide emissions from excess fertilizer while building soil organic matter, ISFM advances both adaptation and mitigation (Vanlauwe et al., 2015).

Water-Smart Agriculture

Water scarcity is intensifying across many agricultural regions due to climate change. Water-smart practices enhance water use efficiency, capture and store rainfall, and reduce vulnerability to drought. **Rainwater Harvesting:** Techniques including in-field micro-catchments, contour bunds, and farm ponds capture rainfall that would otherwise run off. Studies from semi-arid Africa demonstrate that rainwater harvesting can increase crop yields by 30-300% depending on rainfall patterns, while reducing crop failure risk (Rockström et al., 2010; Bouman et al., 2019). **Drip Irrigation and Precision Water Management:** Micro-irrigation delivers water directly to plant roots, reducing evaporation losses and increasing water productivity. Solar-powered drip irrigation has proven particularly effective for smallholders, enabling vegetable production during dry seasons with high market values (Burney et al., 2010).

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However, capital costs and maintenance requirements remain barriers. **Alternate Wetting and Drying (AWD) for Rice:** Conventional flooded rice systems produce substantial methane emissions. AWD involves periodic draining of rice paddies, reducing methane emissions by 30-70% while maintaining or increasing yields and reducing water use by 15-30% (Lampayan et al., 2015; Sander et al., 2020).

Climate-Resilient Crops and Varieties

Genetic improvement and diversity management provide crucial adaptation options. **Stress-Tolerant Varieties:** Development of crop varieties with tolerance to drought, heat, submergence, and salinity has accelerated through conventional breeding and marker-assisted selection. The Sub1 gene conferring submergence tolerance in rice, for example, has been incorporated into varieties grown on millions of hectares in South Asia, reducing yield losses from flooding by 30-80% (Mackill et al., 2012; Dar et al., 2017). **Crop Diversification:** Diversifying cropping systems—including intercropping, rotations, and variety mixtures—spreads risk across species with different climate sensitivities. Diverse systems also provide ecological services including pest regulation and nutrient cycling (Lin, 2011; Beillouin et al., 2019). **Neglected and Underutilized Species:** Many traditional crops possess climate resilience traits absent from major staples. Fonio (*Digitaria exilis*), millets, sorghum, cassava, and cowpea exhibit heat and drought tolerance that merit greater research and promotion (Mayes et al., 2012; Mabhaudhi et al., 2019).

Livestock Management for Reduced Emissions and Enhanced Resilience

Livestock production contributes approximately 14.5% of anthropogenic greenhouse gas emissions, primarily from enteric methane (ruminants), manure management, and feed production (Gerber et al., 2013). Climate-smart livestock management includes: **Improved Feed and Nutrition:** Higher-quality forages and feed additives (lipids, tannins, nitrates) can reduce enteric methane emissions by 10-30% while improving animal productivity (Hristov et al., 2013; Knapp et al., 2014).

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Manure Management: Covered lagoons, biogas digesters, and composting reduce methane emissions while producing renewable energy and improved fertilizers (Chadwick et al., 2011). **Pasture Management:** Rotational grazing, silvopastoral systems (integrating trees, forage, and livestock), and restoration of degraded pastures increase soil carbon sequestration and reduce emission intensity per unit of meat or milk (Thornton & Herrero, 2015; Broom, 2017).

Integrated Pest and Disease Management

Climate change alters pest and disease distributions, creating new challenges for crop protection. Climate-smart pest management emphasizes: **Early Warning Systems:** Weather-based forecasting and monitoring enable timely interventions before pest populations reach damaging levels (Pautasso et al., 2012). **Biological Control:** Conservation of natural enemies, augmentative releases of beneficial organisms, and biopesticides reduce reliance on synthetic pesticides (Heeb et al., 2019). **Resistant Varieties:** Deployment of host-plant resistance reduces vulnerability to emerging pest and disease pressures (Garrett et al., 2014).

3. CASE STUDIES: CLIMATE-SMART AGRICULTURE IN PRACTICE

Conservation Agriculture in Zambia

Context: Smallholder farmers in Zambia's Eastern Province face variable rainfall, declining soil fertility, and limited access to inputs. Maize, the staple crop, is vulnerable to drought during critical growth stages. **Intervention:** From 2010-2020, the Conservation Agriculture Scaling Up (CASU) project promoted CA among smallholders. The project provided training, facilitated farmer-to-farmer learning through demonstration plots, and supported access to jab planters and cover crop seeds (FAO, 2020). **Results:** By 2020, over 150,000 smallholder households had adopted CA principles. Evaluation studies documented: Maize yields 30-50% higher than conventional tillage during normal rainfall years, Yield advantage increased to 50-100% during drought years. Reduced labor requirements for land preparation (particularly for women).

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Improved soil organic carbon and water infiltration. Reduced crop failure risk, enhancing household food security (Ngwira et al., 2012; Thierfelder et al., 2016). **Challenges:** CA adoption was not universal. Farmers without access to jab planters, those with high livestock numbers requiring crop residues for feed, and those in very high-rainfall areas experienced less benefit. Ongoing support for extension and input access remains critical (Andersson & D'Souza, 2014).

Climate-Smart Outcomes: Productivity: Increased yield and income, Adaptation: Reduced drought vulnerability, improved soil water holding capacity, Mitigation: Increased soil carbon sequestration (estimated 0.5-1.0 t CO₂e/ha/year)

Alternate Wetting and Drying in Vietnam

Context: The Mekong Delta produces over half of Vietnam's rice but faces sea-level rise, saltwater intrusion, and freshwater scarcity. Traditional continuously flooded rice generates high methane emissions and uses excessive water. **Intervention:** From 2010-2018, the Vietnam Ministry of Agriculture partnered with the International Rice Research Institute (IRRI) to promote Alternate Wetting and Drying (AWD). Farmers received training on using simple field tubes to monitor water levels, irrigating only when water fell below 15 cm below the soil surface. Over 100,000 farmers participated in demonstration programs (IRRI, 2018). **Results:** Independent evaluations documented: Water savings of 15-30% without yield reduction, Methane emission reductions of 30-50% compared to flooded rice, Reduced pumping costs (less fuel/electricity), Some evidence of reduced arsenic uptake in grain (Sander et al., 2020; Carrijo et al., 2017). **Challenges:** AWD requires coordinated water management at irrigation scheme levels, which proved difficult in systems with poorly maintained infrastructure. Some farmers reported increased weed pressure, requiring additional management. However, participatory approaches and farmer-to-farmer learning helped address these issues (Yamaguchi et al., 2021). **Climate-Smart Outcomes:** Productivity: Maintained yields with reduced input costs, Adaptation: Reduced water use, increased resilience to water scarcity, Mitigation: Substantial methane emission reductions

Silvopastoral Systems in Costa Rica

Context: Livestock production in Central America has historically contributed to deforestation, land degradation, and greenhouse gas emissions. However, climate change threatens pasture productivity through increased temperatures and prolonged dry seasons.

Intervention: The Costa Rican government's Payment for Environmental Services (PES) program, combined with technical assistance from CATIE (Tropical Agricultural Research and Higher Education Center), promoted silvopastoral systems integrating trees, shrubs, and improved pastures. Farmers received payments for tree establishment and maintenance (Pagiola et al., 2007). **Results:** Longitudinal studies documented: Milk production increased 15-25% due to shade reducing heat stress and improved forage quality. Tree carbon sequestration of 10-20 t CO₂e/ha/year. Improved biodiversity (bird and mammal species richness). Reduced erosion and improved water quality (Murgueitio et al., 2011; World Bank, 2019)

Challenges: Initial establishment costs and the 2-3 year period before tree benefits fully materialized required patient capital. Some farmers expressed concerns about tree competition with pastures, though research demonstrated net positive effects with appropriate species and densities.

Climate-Smart Outcomes: Productivity: Increased milk yield and income, Adaptation: Reduced heat stress, improved dry season forage availability, Mitigation: Substantial carbon sequestration

4. ENABLING CONDITIONS FOR CLIMATE-SMART AGRICULTURE

Policy and Institutional Frameworks

CSA implementation requires supportive policy environments. Key policy instruments include: **National CSA Strategies:** Over 30 countries have developed CSA policies or investment plans, integrating climate considerations into agricultural sector planning. Examples include Zambia's National CSA Strategy, India's National Mission on Sustainable Agriculture, and Colombia's Climate-Smart Livestock Strategy (World Bank, 2018; CGIAR, 2019).

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Agricultural Extension Services: Climate information services, weather forecasting, and agronomic advisory services enable farmers to make climate-informed decisions. Participatory extension approaches—farmer field schools, demonstration plots, farmer-to-farmer learning—prove more effective than top-down models (Waddington et al., 2014; Partey et al., 2018). **Land Tenure Security:** Farmers are more likely to invest in long-term improvements (trees, soil conservation) when they have secure land rights. Strengthening customary and formal tenure systems supports CSA adoption (Lawry et al., 2017). **Alignment with National Climate Commitments:** Integrating CSA into Nationally Determined Contributions (NDCs) under the Paris Agreement signals political commitment and enables access to climate finance (Richards et al., 2015).

Climate Finance and Incentives

Financial barriers significantly constrain CSA adoption. Addressing these requires diverse mechanisms: **Public Climate Finance:** The Green Climate Fund, Global Environment Facility, and bilateral donors provide resources for CSA. However, only approximately 2-3% of climate finance reaches smallholder farmers, with most directed toward large-scale mitigation projects (IPCC, 2022). **Results-Based Payments:** Carbon credit programs for soil carbon sequestration, reduced emissions from livestock, and avoided deforestation provide performance-based incentives. The Verified Carbon Standard (VCS) and Gold Standard certify agricultural carbon projects (Schmitt & Taylor, 2021). **Risk Management Instruments:** Weather-indexed insurance, contingent credit, and social protection programs help farmers manage climate risk, enabling investment in CSA practices with upfront costs but long-term benefits (Barnett et al., 2008; Jensen et al., 2017). **Subsidy Reform:** Repurposing agricultural subsidies that incentivize unsustainable practices (e.g., fossil fuel-based fertilizers, irrigation electricity) toward CSA practices could generate multiple benefits (Searchinger et al., 2020).

Capacity Building and Knowledge Systems

CSA adoption requires technical knowledge and skills: **Farmer Education:** Participatory learning approaches—farmer field schools, demonstration plots, farmer-to-farmer networks—build local capacity for CSA implementation. These approaches respect local knowledge while introducing new practices (Davis et al., 2012; Tambo et al., 2019). **Climate Information Services:** Access to seasonal forecasts, early warnings, and weather data enables climate-informed decision-making. Mobile phone-based services have expanded reach in Africa and South Asia (Partey et al., 2018; Hansen et al., 2019). **Research-Extension Linkages:** Agricultural research institutions must generate locally-relevant knowledge and translate it into accessible formats for extension providers. Participatory action research involving farmers as co-researchers proves particularly effective (Van de Fliert & Braun, 2002). **Gender-Responsive Approaches:** Women farmers face particular constraints in accessing information, credit, and land. CSA programming must explicitly address gender barriers and engage women as decision-makers (Jost et al., 2016; Huyer et al., 2020).

Inclusive Governance and Participation

Who decides which CSA practices to promote, for whom, and with what resources? These governance questions shape outcomes: **Multi-Stakeholder Platforms:** Platforms bringing together farmers, extension providers, researchers, policymakers, private sector, and civil society enable inclusive priority-setting and adaptive management. National CSA coordination bodies in Kenya, Tanzania, and Zambia represent examples (Kakabadse et al., 2021). **Social Accountability Mechanisms:** Participatory monitoring, community scorecards, and grievance mechanisms enable farmers to hold service providers accountable for CSA support delivery (Joshi, 2014). **Representation of Marginalized Groups:** CSA governance must include smallholders, women, youth, pastoralists, and indigenous peoples, whose perspectives and priorities may differ from those of technical experts or commercial farmers (Taylor, 2018; Anderson et al., 2019).

5. IMPLEMENTATION CHALLENGES AND RESEARCH PRIORITIES

Persistent Barriers

Despite progress, significant barriers constrain CSA adoption at scale:

Financial Constraints: Upfront costs for many CSA practices (trees, irrigation equipment, no-till planters) exceed smallholder capital availability. Credit access remains limited, particularly for women and tenant farmers (Partey et al., 2018). **Knowledge Gaps:** Location-specific information on optimal CSA practices is often unavailable to farmers and extension providers. Climate information services remain underfunded and poorly tailored to farmer decision-making (Singh et al., 2018). **Policy Incoherence:** Agricultural, environment, energy, and land use policies often work at cross-purposes. Subsidies for flood irrigation or synthetic fertilizers, for example, may discourage water-efficient or organic alternatives (Searchinger et al., 2020). **Trade-offs and Conflicts:** CSA practices may generate winners and losers. Land use changes for agroforestry or restoration may conflict with grazing rights. Water conservation measures may affect downstream users (Campbell et al., 2014).

Research Priorities

Advancing CSA requires continued research investment: **Context-Specific Evidence:** More research is needed on CSA performance across diverse agroecological, socioeconomic, and policy contexts. Meta-analyses and systematic reviews should disaggregate results by context (Sumberg et al., 2021). **Trade-off Analysis:** Methods for identifying, quantifying, and managing trade-offs among CSA pillars require further development. Decision-support tools for farmers and policymakers need testing (Klapwijk et al., 2014). **Scaling Pathways:** Understanding what enables or constrains CSA adoption at scale—beyond project contexts—requires comparative political economy and institutional analysis (Schut et al., 2020). **Social Dimensions:** Research on gender, equity, and social inclusion in CSA adoption and outcomes remains underdeveloped. Participatory and action research approaches can address these gaps (Jost et al., 2016; Huyer et al., 2020).

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Digital Technologies: The potential of mobile applications, remote sensing, and decision-support tools for CSA requires rigorous evaluation of effectiveness and equity implications (Tsan et al., 2019).

The Role of Agroecology and Alternative Paradigms

CSA is not the only framework for addressing climate-agriculture interactions. Agroecology—which emphasizes ecological principles, biodiversity, local knowledge, and food sovereignty—offers complementary but distinct approaches (Gliessman, 2016; Wezel et al., 2014). Productive dialogue between CSA and agroecology communities can generate integrated approaches that combine: CSA's emphasis on evidence-based practices and climate finance mechanisms, Agroecology's attention to ecological principles, social justice, and participatory governance. Polarization between these camps serves neither smallholder farmers nor the urgent climate challenge (Anderson et al., 2019; Sumberg et al., 2021).

CONCLUSION

Climate-Smart Agriculture provides a valuable framework for navigating the complex interactions among food production, climate adaptation, and mitigation. The evidence base has grown substantially, demonstrating that context-specific combinations of practices—conservation agriculture, agroforestry, water-smart technologies, improved germplasm, and integrated soil fertility management—can simultaneously enhance productivity, build resilience, and reduce emissions intensity. However, CSA's transformative potential depends critically on enabling conditions that remain inadequate in many regions. Policy frameworks must integrate climate considerations into agricultural planning. Finance mechanisms must reach smallholder farmers, women, and marginalized groups. Capacity building must respect local knowledge while introducing new practices. Governance must be inclusive, accountable, and adaptive. The case studies from Zambia, Vietnam, and Costa Rica illustrate that CSA works when implemented through participatory, context-sensitive approaches. They also demonstrate that barriers are primarily institutional and financial rather than technical or biophysical.

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Overcoming these barriers requires political will, sustained investment, and commitment to equity.

The urgency of climate action in agriculture cannot be overstated. Each year of delay locks in emissions-intensive infrastructure, degrades adaptive capacity, and increases vulnerability for millions of food-insecure households. CSA is not a panacea, but it represents a pragmatic, evidence-informed pathway toward more resilient and sustainable food systems. For researchers, the priority is generating context-specific evidence and understanding scaling pathways. For policymakers, the priority is creating enabling conditions—policy coherence, finance access, capacity building. For development practitioners, the priority is participatory, equity-oriented implementation. For all actors, the priority is action.

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REFERENCES

- Anderson, S., Sumberg, J., & Thompson, J. (2019). Agroecology and climate-smart agriculture: A comparative analysis of concepts and practice. *Food Policy*, 88, 101764.
- Andersson, J. A., & D'Souza, S. (2014). From adoption claims to understanding farmers and contexts: A literature review of conservation agriculture (CA) adoption among smallholder farmers in southern Africa. *Agriculture, Ecosystems & Environment*, 187, 116-132.
- Barnett, B. J., Barrett, C. B., & Skees, J. R. (2008). Poverty traps and index-based risk transfer products. *World Development*, 36(10), 1766-1785.
- Beillouin, D., Ben-Ari, T., & Makowski, D. (2019). Evidence map of crop diversification effects at field and global scales. *Nature Communications*, 10(1), 1-12.
- Bouman, B., Humphreys, E., Tuong, T. P., & Barker, R. (2019). Rice and water. *Advances in Agronomy*, 92, 187-237.
- Broom, D. M. (2017). *Sustainable, efficient livestock production with high biodiversity and good welfare for animals*. CABI.
- Burney, J., Woltering, L., Burke, M., Naylor, R., & Pasternak, D. (2010). Solar-powered drip irrigation enhances food security in the Sudano-Sahel. *Proceedings of the National Academy of Sciences*, 107(5), 1848-1853.
- Campbell, B. M., Thornton, P., Zougmore, R., van Asten, P., & Lipper, L. (2014). Sustainable intensification: What is its role in climate smart agriculture? *Current Opinion in Environmental Sustainability*, 8, 39-43.
- Carrizo, D. R., Lundy, M. E., & Linquist, B. A. (2017). Rice yields and water use under alternate wetting and drying irrigation: A meta-analysis. *Field Crops Research*, 203, 173-180.
- CGIAR. (2019). *Guidance on climate-smart agriculture for national policy and planning*. CGIAR Research Program on Climate Change, Agriculture and Food Security.
- Chadwick, D., Sommer, S., Thorman, R., Fanguero, D., Cardenas, L., Amon, B., & Misselbrook, T. (2011). Manure management: Implications for greenhouse gas emissions. *Animal Feed Science and Technology*, 166, 514-531.

ADVANCES IN CLIMATE-SMART AGRICULTURE AND AGRO-ENERGY SYSTEMS

- Crippa, M., Solazzo, E., Guizzardi, D., Monforti-Ferrario, F., Tubiello, F. N., & Leip, A. (2021). Food systems are responsible for a third of global anthropogenic GHG emissions. *Nature Food*, 2(3), 198-209.
- Dar, M. H., Chakravorty, R., Waza, S. A., Sharma, M., Zaidi, N. W., Singh, A. N., ... & Ismail, A. M. (2017). Transforming rice cultivation in flood prone coastal Odisha to ensure food and economic security. *Food Security*, 9(4), 711-722.
- Davis, K., Nkonya, E., Kato, E., Mekonnen, D. A., Odendo, M., Miiro, R., & Nkuba, J. (2012). Impact of farmer field schools on agricultural productivity and poverty in East Africa. *World Development*, 40(2), 402-413.
- FAO. (2008). *An introduction to the basic concepts of food security*. Food and Agriculture Organization of the United Nations.
- FAO. (2013). *Climate-smart agriculture: Sourcebook*. Food and Agriculture Organization of the United Nations.
- FAO. (2020). *Conservation agriculture scaling up project: Final evaluation report*. Food and Agriculture Organization of the United Nations.
- Garnett, T., Appleby, M. C., Balmford, A., Bateman, I. J., Benton, T. G., Bloomer, P., ... & Godfray, H. C. J. (2013). Sustainable intensification in agriculture: Premises and policies. *Science*, 341(6141), 33-34.
- Garrett, K. A., Forbes, G. A., Savary, S., Skelsey, P., Sparks, A. H., Valdivia, C., ... & Willocquet, L. (2014). Complexity in climate-change impacts: An analytical framework for effects mediated by plant disease. *Plant Pathology*, 63(3), 445-454.
- Gerber, P. J., Steinfeld, H., Henderson, B., Mottet, A., Opio, C., Dijkman, J., ... & Tempio, G. (2013). *Tackling climate change through livestock: A global assessment of emissions and mitigation opportunities*. Food and Agriculture Organization.
- Gliessman, S. R. (2016). Transforming food systems to sustainability with agroecology. *Journal of Sustainable Agriculture*, 40(3), 187-189.
- Gonzalez-Sanchez, E. J., Veroz-Gonzalez, O., Blanco-Roldan, G. L., Marquez-Garcia, F., & Carbonell-Bojollo, R. (2019). A renewed view of conservation agriculture and its evolution over the last decade in Spain. *Soil and Tillage Research*, 193, 1-12.

ADVANCES IN CLIMATE-SMART AGRICULTURE AND AGRO-ENERGY SYSTEMS

- Hansen, J. W., Vaughan, C., Kagabo, D. M., Dinku, T., Carr, E. R., Körner, J., & Zougmore, R. (2019). Climate services for smallholder farmers: A review of evidence and practice. *Climate Services*, 16, 100129.
- Heeb, L., Jenner, E., & Cock, M. J. (2019). Climate-smart pest management: Building resilience of farms and landscapes to changing pest threats. *Journal of Pest Science*, 92(3), 951-969.
- Hristov, A. N., Oh, J., Lee, C., Meinen, R., Montes, F., Ott, T., ... & Oosting, S. (2013). *Mitigation of greenhouse gas emissions in livestock production: A review of technical options for non-CO2 emissions*. FAO.
- Huyer, S., Twyman, J., Koningstein, M., Ashby, J., & Vermeulen, S. (2020). Supporting women farmers in a changing climate: Five policy lessons. *CCAFS Policy Brief*, 10, 1-6.
- IPCC. (2022). *Climate change 2022: Impacts, adaptation and vulnerability*. Cambridge University Press.
- IRRI. (2018). *Alternate wetting and drying irrigation in rice: A practical guide*. International Rice Research Institute.
- Jensen, N. D., Mude, A. G., & Barrett, C. B. (2017). How basis risk and spatiotemporal adverse selection influence demand for index insurance: Evidence from northern Kenya. *Food Policy*, 74, 199-219.
- Joshi, D. (2014). Social accountability in the context of climate-smart agriculture. *Climate and Development*, 6(4), 357-364.
- Jost, C., Kyazze, F., Naab, J., Neelormi, S., Kinyangi, J., Zougmore, R., ... & Kristjanson, P. (2016). Understanding gender dimensions of agriculture and climate change in smallholder farming communities. *Climate and Development*, 8(2), 133-144.
- Kakabadse, N., Mwila, M., & Phiri, D. (2021). Multi-stakeholder platforms for climate-smart agriculture in Africa. *Climate Policy*, 21(5), 621-635.
- Klapwijk, C. J., van Wijk, M. T., Rosenstock, T. S., van Asten, P. J., Thornton, P. K., & Giller, K. E. (2014). Analysis of trade-offs in agricultural systems: Current status and way forward. *Current Opinion in Environmental Sustainability*, 6, 110-115.
- Knapp, J. R., Laur, G. L., Vadas, P. A., Weiss, W. P., & Tricarico, J. M. (2014). Invited review: Enteric methane in dairy cattle production—Quantifying

*ADVANCES IN CLIMATE-SMART AGRICULTURE AND AGRO-ENERGY
SYSTEMS*

- the opportunities and impact of reducing emissions. *Journal of Dairy Science*, 97(6), 3231-3261.
- Lampayan, R. M., Rejesus, R. M., Singleton, G. R., & Bouman, B. A. (2015). Adoption and economics of alternate wetting and drying water management for irrigated lowland rice. *Field Crops Research*, 170, 95-108.
- Lawry, S., Samii, C., Hall, R., Leopold, A., Hornby, D., & Mtero, F. (2017). The impact of land property rights interventions on investment and agricultural productivity in developing countries: A systematic review. *Journal of Development Effectiveness*, 9(1), 61-81.
- Lin, B. B. (2011). Resilience in agriculture through crop diversification: Adaptive management for environmental change. *BioScience*, 61(3), 183-193.
- Lipper, L., Thornton, P., Campbell, B. M., Baedeker, T., Braimoh, A., Bwalya, M., ... & Hottle, R. (2014). Climate-smart agriculture for food security. *Nature Climate Change*, 4(12), 1068-1072.
- Mabhaudhi, T., Chimonyo, V. G., & Modi, A. T. (2019). Status of underutilised crops in South Africa: Opportunities for developing resilience. *Agriculture & Food Security*, 8(1), 1-11.
- Mackill, D. J., Ismail, A. M., Singh, U. S., Labios, R. V., & Paris, T. R. (2012). Development and rapid adoption of submergence-tolerant (Sub1) rice varieties. *Advances in Agronomy*, 115, 299-352.
- Mayes, S., Massawe, F. J., Alderson, P. G., Roberts, J. A., Azam-Ali, S. N., & Hermann, M. (2012). The potential for underutilized crops to improve security of food production. *Journal of Experimental Botany*, 63(3), 1075-1079.
- Muchane, M. N., Sileshi, G. W., Gripenberg, S., Kuyah, S., Carsan, S., & Jonsson, M. (2020). Agroforestry boosts soil health in the humid and sub-humid tropics: A meta-analysis. *Agriculture, Ecosystems & Environment*, 295, 106899.
- Murgueitio, E., Calle, Z., Uribe, F., Calle, A., & Solorio, B. (2011). Native trees and shrubs for the productive rehabilitation of tropical cattle ranching lands. *Forest Ecology and Management*, 261(10), 1654-1663.

*ADVANCES IN CLIMATE-SMART AGRICULTURE AND AGRO-ENERGY
SYSTEMS*

- Newell, P., & Taylor, O. (2018). Contested landscapes: The global political economy of climate-smart agriculture. *Journal of Peasant Studies*, 45(1), 108-129.
- Ngwira, A. R., Aune, J. B., & Mkwinda, S. (2012). On-farm evaluation of yield and economic benefit of short term maize legume intercropping systems under conservation agriculture in Malawi. *Field Crops Research*, 132, 149-157.
- Pagiola, S., Ramírez, E., Gobbi, J., de Haan, C., Ibrahim, M., Murgueitio, E., & Ruíz, J. P. (2007). Paying for the environmental services of silvopastoral practices in Nicaragua. *Ecological Economics*, 64(2), 374-385.
- Partey, S. T., Zougmore, R. B., Ouédraogo, M., & Campbell, B. M. (2018). Developing climate-smart agriculture to face climate variability in West Africa: Challenges and lessons learnt. *Journal of Cleaner Production*, 172, 3457-3464.
- Pautasso, M., Döring, T. F., Garbelotto, M., Pellis, L., & Jeger, M. J. (2012). Impacts of climate change on plant diseases—opinions and trends. *European Journal of Plant Pathology*, 133(1), 295-313.
- Pingali, P. L. (2012). Green revolution: Impacts, limits, and the path ahead. *Proceedings of the National Academy of Sciences*, 109(31), 12302-12308.
- Pittelkow, C. M., Liang, X., Linquist, B. A., Van Groenigen, K. J., Lee, J., Lundy, M. E., ... & van Kessel, C. (2015). Productivity limits and potentials of the principles of conservation agriculture. *Nature*, 517(7534), 365-368.
- Richards, M., Bruun, T. B., Campbell, B. M., Gregersen, L. E., Halsnæs, K., & Olhoff, A. (2015). How countries plan to address agricultural adaptation and mitigation: An analysis of Intended Nationally Determined Contributions. *CCAFS Policy Brief*, 8, 1-6.
- Rickards, L., & Howden, S. M. (2012). Transformational adaptation: Agriculture and climate change. *Crop and Pasture Science*, 63(3), 240-250.

*ADVANCES IN CLIMATE-SMART AGRICULTURE AND AGRO-ENERGY
SYSTEMS*

- Rockström, J., Karlberg, L., Wani, S. P., Barron, J., Hatibu, N., Oweis, T., ... & Qiang, Z. (2010). Managing water in rainfed agriculture—The need for a paradigm shift. *Agricultural Water Management*, 97(4), 543-550.
- Sander, B. O., Wassmann, R., & Siopongco, J. D. (2020). Alternate wetting and drying in rice: A climate-smart practice. *Climate Smart Agriculture Brief*, 12, 1-8.
- Schmitt, E., & Taylor, M. (2021). Carbon credits for smallholder agriculture: Opportunities and challenges. *Climate Policy*, 21(4), 512-527.
- Schut, M., van Asten, P., Okafor, C., Hicintuka, C., Mapatano, S., Nabahungu, N. L., ... & Vanlauwe, B. (2020). Commodity system assessment studies on scaling of climate-smart agriculture in eastern and southern Africa. *Agricultural Systems*, 185, 102948.
- Searchinger, T., Waite, R., Hanson, C., & Ranganathan, J. (2020). *Creating a sustainable food future: A menu of solutions to feed nearly 10 billion people by 2050*. World Resources Institute.
- Singh, C., Daron, J., Bazaz, A., & Ziervogel, G. (2018). The utility of weather and climate information for adaptation decision-making: Current uses and future prospects in Africa and India. *Climate and Development*, 10(6), 517-525.
- Smith, P., Calvin, K., Nkem, J., Campbell, D., Cherubini, F., Grassi, G., ... & Arneeth, A. (2020). Which practices co-deliver food security, climate change mitigation and adaptation, and combat land degradation and desertification? *Global Change Biology*, 26(3), 1532-1575.
- Sumberg, J., Chamberlin, J., & Giller, K. E. (2021). Climate-smart agriculture: A critical review. *Global Food Security*, 29, 100535.
- Tambo, J. A., Uzayisenga, B., & Mugambi, I. (2019). Farmer field schools for climate-smart agriculture: Evidence from Rwanda. *Journal of Agricultural Education and Extension*, 25(4), 321-337.
- Taylor, M. (2018). Climate-smart agriculture: What is it good for? *Journal of Peasant Studies*, 45(1), 89-107.
- Thierfelder, C., Matemba-Mutasa, R., & Bunderson, W. T. (2016). Evaluating conservation agriculture for small-scale farmers in Malawi. *Experimental Agriculture*, 52(4), 551-571.

*ADVANCES IN CLIMATE-SMART AGRICULTURE AND AGRO-ENERGY
SYSTEMS*

- Thornton, P. K., & Herrero, M. (2015). Adapting to climate change in the mixed crop and livestock farming systems in sub-Saharan Africa. *Nature Climate Change*, 5(9), 830-836.
- Tsan, M., Totapally, S., Hailu, M., & Addom, B. K. (2019). *The digital divide in agricultural extension: A review of mobile applications and their impact*. World Bank.
- Van de Fliert, E., & Braun, A. R. (2002). Conceptualizing integrative, farmer participatory research for sustainable agriculture: From opportunities to impact. *Agriculture and Human Values*, 19(1), 25-38.
- Vanlauwe, B., Descheemaeker, K., Giller, K. E., Huising, J., Merckx, R., Nziguheba, G., ... & Zingore, S. (2015). Integrated soil fertility management in sub-Saharan Africa: Unravelling local adaptation. *Soil*, 1(1), 491-508.
- Waddington, H., Snilstveit, B., Hombrados, J., Vojtkova, M., Phillips, D., Davies, P., & White, H. (2014). Farmer field schools for improving farming practices and farmer outcomes: A systematic review. *Campbell Systematic Reviews*, 10(1), 1-335.
- Wezel, A., Casagrande, M., Celette, F., Vian, J. F., Ferrer, A., & Peigné, J. (2014). Agroecological practices for sustainable agriculture: A review. *Agronomy for Sustainable Development*, 34(1), 1-20.
- Wheeler, T., & von Braun, J. (2013). Climate change impacts on global food security. *Science*, 341(6145), 508-513.
- World Bank. (2018). *Climate-smart agriculture: Investment guide*. World Bank Group.
- World Bank. (2019). *Bringing the ecosystem services approach to agriculture: Costa Rica's silvopastoral systems*. World Bank Group.
- Yamaguchi, T., Tuan, L. M., Minamikawa, K., & Yokoyama, S. (2021). Alternate wetting and drying (AWD) in the Mekong Delta: Farmer adoption and constraints. *Paddy and Water Environment*, 19(3), 437-448.
- Zomer, R. J., Neufeldt, H., Xu, J., Ahrends, A., Bossio, D., Trabucco, A., ... & Wang, M. (2016). Global tree cover and biomass carbon on agricultural land: The contribution of agroforestry to global and national carbon budgets. *Scientific Reports*, 6(1), 1-12.

CHAPTER 3
**CLIMATE-SMART LIVESTOCK PRODUCTION:
HARNESSING CROP RESIDUES AND AGRO-
INDUSTRIAL BY-PRODUCTS FOR METHANE
MITIGATION AND CARBON EMISSION
REDUCTION WITHIN SUSTAINABLE
AGRICULTURAL SYSTEMS**

¹Emmanuel Ugochukwu ANASO

¹Federal University of Agriculture, Department of Animal Science, Faculty of Agriculture, Nigeria, dranasocub@gmail.com, ORCID ID: 0009-0001-6886-8557

INTRODUCTION

Livestock production is a vital component of global agriculture, contributing substantially to food security, nutrition, income generation, and rural livelihoods. However, the sector is also associated with significant environmental impacts, particularly the emission of greenhouse gases (GHGs) such as methane (CH₄), nitrous oxide (N₂O), and carbon dioxide (CO₂). Among these, methane is of particular concern due to its high global warming potential, which is approximately 28–34 times greater than CO₂ over a 100-year period (IPCC, 2021; Anaso and Olafadehan, 2025). Enteric fermentation in ruminant animals is the largest agricultural source of methane emissions globally.

At the same time, agricultural systems generate large volumes of crop residues and agro-industrial by-products annually. These include cereal straws, maize stover, rice husks, cassava peels, oilseed cakes, molasses, brewers' spent grain, and fruit processing wastes. In many developing countries, these materials are either underutilized or disposed of through environmentally harmful practices such as open burning or uncontrolled decomposition, both of which contribute to greenhouse gas emissions and air pollution. Open burning of crop residues releases CO₂, CH₄, nitrous oxide, and particulate matter, thereby exacerbating climate change and posing serious public health risks (Anaso and Anaso, 2025).

The concept of climate-smart agriculture (CSA) has emerged as a framework for addressing the interconnected challenges of food security, climate change adaptation, and mitigation. Within this framework, livestock systems are increasingly being re-evaluated for opportunities to reduce emission intensity while maintaining productivity. One promising strategy is the integration of crop residues and agro-industrial by-products into animal feeding systems. These resources, when properly processed and strategically incorporated into diets, can enhance feed efficiency, reduce reliance on conventional feedstuffs, and modify rumen microbial fermentation in ways that reduce methane emissions.

The mitigation potential of these feed resources is driven by several mechanisms. First, improved digestibility through physical, chemical, or biological treatment enhances nutrient utilization, thereby reducing methane emissions per unit of animal product.

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Second, many agro-industrial by-products contain secondary plant metabolites such as tannins, saponins, and phenolic compounds that inhibit methanogenic archaea or protozoa in the rumen. Third, dietary shifts toward more balanced carbohydrate and lipid profiles can alter fermentation pathways, favoring propionate production over acetate and reducing hydrogen availability for methanogenesis.

Beyond enteric methane emissions, the utilization of crop residues and agro-industrial by-products contributes to carbon reduction across the agricultural value chain. Diverting residues from open burning prevents direct CO₂ emissions, while reducing dependence on feed crops such as maize and soybean lowers indirect emissions associated with land use change, fertilizer application, and energy-intensive production processes (Anaso and Alagbe, 2025ba-c).

Despite these advantages, several constraints hinder widespread adoption. These include low nutritional quality, high lignocellulosic content, presence of anti-nutritional factors, seasonal variability, and inadequate processing infrastructure. Addressing these limitations requires technological innovation, policy support, and capacity building to ensure effective integration into livestock feeding systems.

1. METHANE EMISSIONS IN LIVESTOCK SYSTEMS

Methane emissions in livestock systems primarily originate from enteric fermentation in ruminants such as cattle, sheep, and goats. During digestion, microbial populations in the rumen break down fibrous feed components, producing volatile fatty acids (VFAs), carbon dioxide, and hydrogen. Methanogenic archaea utilize hydrogen and carbon dioxide to produce methane, which is subsequently eructated by the animal.

The efficiency of this process is influenced by diet composition, feed digestibility, and rumen microbial ecology. High-fiber, low-quality diets typically increase methane production per unit of feed consumed due to slower fermentation rates and higher hydrogen accumulation. Conversely, diets rich in readily fermentable carbohydrates or lipids tend to reduce methane output by altering fermentation pathways and suppressing methanogenic populations.

Manure management systems also contribute to methane emissions, particularly under anaerobic storage conditions. However, enteric fermentation remains the dominant source in ruminant production systems.

2. CROP RESIDUES AND AGRO-INDUSTRIAL BY-PRODUCTS AS FEED RESOURCES

Crop residues such as rice straw, wheat straw, maize stover, and sorghum stubble are abundant lignocellulosic materials with low crude protein and high fiber content. Agro-industrial by-products include oilseed cakes (soybean, groundnut, palm kernel), brewers' spent grain, cassava peels, molasses, and fruit processing wastes.

These materials are often underutilized despite their large availability. When properly processed and formulated into diets, they can partially or fully replace conventional feed ingredients, reducing feed costs and environmental pressure on arable land used for feed production (Anaso et al., 2024b, 2026b).

Processing methods such as urea treatment, ensiling, fermentation, and fungal biodegradation significantly improve their nutritional value by increasing digestibility, reducing fiber complexity, and detoxifying anti-nutritional factors.

Mechanisms of Methane Mitigation

The inclusion of crop residues and agro-industrial by-products in livestock feeding systems reduces methane emissions through a series of interrelated nutritional, microbiological, and biochemical mechanisms that collectively influence rumen fermentation dynamics and whole-animal efficiency (Anaso, 2025a-e). These mechanisms do not operate in isolation; rather, they interact within the rumen ecosystem to shift metabolic pathways away from methanogenesis and toward more energy-efficient end products.

Modification of rumen fermentation pathways

One of the primary mechanisms involves the alteration of rumen fermentation end-products. In typical high-fiber diets, acetate production dominates, a process that generates substantial amounts of hydrogen (H₂), which methanogenic archaea utilize to produce methane.

However, when crop residues are supplemented or replaced with more fermentable agro-industrial by-products such as molasses or fruit pulp wastes the fermentation profile shifts toward increased propionate production. Propionate formation acts as a competitive hydrogen sink, effectively diverting hydrogen away from methanogenesis. This biochemical redirection reduces the substrate availability required by methanogens, thereby lowering methane output per unit of feed fermented.

Improved feed digestibility and reduced rumen retention time

Processing of crop residues (e.g., urea treatment, ensiling, fungal degradation) and inclusion of nutrient-dense by-products enhances overall diet digestibility. Improved fiber breakdown leads to more efficient nutrient extraction and faster passage rate through the rumen. A reduced retention time limits the duration available for microbial fermentation and hydrogen accumulation, thereby decreasing total methane production (Anaso and Alagbe, 2025). Additionally, improved digestibility increases animal productivity, which reduces methane emissions intensity when expressed per unit of meat or milk produced.

Suppression of methanogenic archaea and rumen protozoa

Many agro-industrial by-products contain bioactive secondary metabolites such as tannins, saponins, flavonoids, and essential oils. These compounds exert direct and indirect inhibitory effects on rumen methanogens. Tannins can bind to microbial enzymes and cell wall proteins, reducing microbial activity, while saponins are known to disrupt protozoal cell membranes. Since rumen protozoa maintain symbiotic relationships with methanogens by supplying hydrogen, their suppression leads to a cascading reduction in methane production. Consequently, diets rich in such by-products can significantly alter rumen microbial ecology in favor of less methanogenic communities.

Reduction in fiber fermentation intensity and hydrogen release

Crop residues are typically high in structural carbohydrates such as cellulose and hemicellulose, which undergo slow fermentation and generate substantial hydrogen. However, when these residues are partially replaced or strategically combined with more digestible agro-industrial by-products, overall fiber fermentation intensity is moderated. This reduces cumulative hydrogen production in the rumen, thereby limiting the substrate pool available for methane formation. Furthermore, improved fiber-to-concentrate balance enhances fermentation efficiency and reduces the proportion of energy lost as methane.

Lipid-mediated inhibition of methanogenesis

Certain agro-industrial by-products, particularly oilseed cakes (e.g., palm kernel cake, cottonseed cake, and groundnut cake), contain residual lipids that play a critical role in methane mitigation. Lipids reduce methane emissions through multiple pathways: they inhibit the growth of methanogens, reduce protozoal populations, and act as alternative hydrogen sinks through biohydrogenation processes. Additionally, fats physically coat feed particles, limiting microbial access and reducing the extent of fiber degradation, which further decreases methane production.

Shifts in microbial population structure and diversity

Dietary inclusion of diverse crop residues and by-products alters the composition and functional capacity of the rumen microbiome. These dietary interventions promote the proliferation of bacterial species associated with propionate production while reducing populations of fibrolytic bacteria that strongly contribute to hydrogen release. Over time, this microbial restructuring leads to a more stable and less methanogenic rumen environment. Metagenomic studies have shown that such dietary shifts can also reduce the abundance of methanogenesis-related genes, further confirming their long-term mitigation potential.

Enhanced energy efficiency and reduced emission intensity

Although not a direct microbial mechanism, improved feed conversion efficiency resulting from the inclusion of processed residues and by-products significantly reduces methane emissions intensity. When animals convert feed more efficiently into body mass or milk, less feed is required per unit of output, thereby reducing cumulative methane emissions over the production cycle. This productivity-linked reduction is particularly important in climate-smart livestock systems, where emissions are evaluated on a per-product basis rather than absolute terms.

Collectively, these interconnected mechanisms demonstrate that the strategic inclusion of crop residues and agro-industrial by-products influences methane emissions through multiple biological and nutritional pathways. By simultaneously altering rumen fermentation patterns, suppressing methanogenic microbes, improving feed efficiency, and modifying microbial ecology, these feed resources provide a scientifically grounded approach to mitigating enteric methane emissions in ruminant production systems.

2.1 Improved Feed Digestibility

Enhanced digestibility is a fundamental determinant of methane emissions in ruminant livestock systems because it directly governs the efficiency and pathway of rumen fermentation. When feed ingredients particularly crop residues and agro-industrial by-products undergo physical, chemical, or biological treatment that improves their digestibility, there is a corresponding reduction in the time and extent of microbial fermentation within the rumen. This reduction in fermentation duration has significant implications for hydrogen (H₂) dynamics and, consequently, methane (CH₄) formation (Anaso et al., 2025a-g).

In the rumen, microbial digestion of feed carbohydrates results in the production of volatile fatty acids (VFAs), carbon dioxide (CO₂), and hydrogen (H₂). Hydrogen is a critical intermediate in the rumen ecosystem and serves as the primary substrate for methanogenic archaea, which convert CO₂ and H₂ into methane. Therefore, the quantity of methane produced is strongly dependent on the amount of hydrogen generated during fermentation and the time available for its accumulation and utilization by methanogens.

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When feed digestibility is enhanced through processes such as urea treatment of straw, ensiling, microbial pre-digestion, or enzymatic breakdown the structural integrity of fibrous components like cellulose and hemicellulose is partially disrupted. This increases the rate at which rumen microorganisms can access and degrade feed particles (Anaso et al., 2025b). As a result, fermentation becomes more efficient and faster, reducing the overall retention time of feed particles in the rumen.

A shorter rumen retention time means that substrates are fermented more rapidly and completely, leaving less opportunity for excessive hydrogen accumulation. In poorly digestible diets, slow fermentation allows hydrogen to build up in the rumen environment, creating favorable conditions for methanogenic archaea to thrive and convert this hydrogen into methane. In contrast, improved digestibility leads to a more synchronized fermentation process, where hydrogen is more efficiently redirected into alternative metabolic pathways, such as propionate formation, rather than being channeled into methanogenesis (Anaso and Alagbe, 2025c).

Furthermore, enhanced digestibility improves the overall energy capture efficiency of the animal. More of the dietary energy is converted into absorbable nutrients rather than being lost as gaseous emissions. This improves feed conversion efficiency (FCE), meaning that less feed is required to produce a given unit of milk or meat. From an environmental perspective, this reduces methane emissions intensity (CH_4 per unit of product), which is a key metric in climate-smart livestock systems.

Improved digestibility also influences rumen microbial ecology. Faster and more efficient fermentation tends to favor microbial populations that are less associated with hydrogen production and methane formation, while reducing the dominance of slow-growing fibrolytic bacteria that generate large quantities of hydrogen during prolonged fiber degradation. This shift in microbial population structure contributes further to reduced methanogenic activity (Olafadehan et al., 2021,2023).

In addition, enhanced feed breakdown reduces the physical bulk of digesta in the rumen, which can improve passage rate and reduce the window of time available for methanogens to utilize hydrogen.

This kinetic limitation on hydrogen use is a critical but often underappreciated pathway through which improved digestibility reduces methane emissions.

2.2 Fermentation Shifts

Dietary carbohydrates play a central role in shaping rumen fermentation patterns, and consequently, they have a profound influence on volatile fatty acid (VFA) profiles and methane production in ruminant livestock. The type, rate of degradation, and fermentability of carbohydrates determine the metabolic pathways favored by rumen microorganisms, thereby influencing the balance between acetate, propionate, and butyrate production.

In the rumen ecosystem, carbohydrates are fermented by a diverse microbial population comprising bacteria, protozoa, fungi, and archaea. The end products of this fermentation process are primarily VFAs; acetate, propionate, and butyrate which serve as major energy sources for the host animal. However, the formation of these VFAs is associated with different hydrogen (H₂) dynamics, which are directly linked to methane synthesis by methanogenic archaea.

When diets are rich in structural carbohydrates such as cellulose and hemicellulose (typically found in low-quality forages and crop residues), fermentation tends to favor acetate production. Acetate formation is accompanied by the release of metabolic hydrogen as a by-product. This hydrogen is subsequently utilized by methanogenic archaea to reduce carbon dioxide into methane (CH₄), making high-acetate fermentation pathways strongly associated with increased methane emissions.

In contrast, when dietary carbohydrates shift toward more readily fermentable substrates such as starches, sugars, and certain agro-industrial by-products, the rumen fermentation profile shifts toward increased propionate production. Propionate formation is a hydrogen-consuming process, meaning it acts as a metabolic sink for reducing equivalents within the rumen. Instead of releasing hydrogen, propionate synthesis incorporates hydrogen into its biochemical pathway, thereby reducing the amount of free hydrogen available for methanogenesis.

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This shift in VFA proportions is therefore critical: higher propionate production directly competes with methane formation for hydrogen, effectively diverting metabolic flow away from methanogenic pathways. As a result, the overall production of methane is reduced, both in absolute terms and per unit of feed fermented.

The mechanisms underlying this shift are closely linked to changes in microbial population dynamics. Diets that promote propionate production tend to favor the proliferation of amylolytic and succinate-producing bacteria, such as *Prevotella* and *Selenomonas* species, which are efficient propionate producers. At the same time, there is often a relative reduction in fibrolytic bacteria that are associated with acetate production and hydrogen generation. This microbial restructuring contributes to a more energetically efficient fermentation process with reduced methane output.

Additionally, rapidly fermentable carbohydrates can lower rumen pH slightly, which may further suppress methanogenic archaea and protozoa, although extreme reductions in pH can negatively affect fiber digestion and overall rumen health. Therefore, the relationship between carbohydrate type and methane production is highly dependent on achieving a balanced fermentation environment.

From an energetic standpoint, propionate is particularly advantageous because it serves as a major glucogenic precursor in ruminants. Unlike acetate, which is primarily used for lipogenesis, propionate is absorbed through the rumen wall and converted into glucose in the liver. This improves metabolic efficiency and supports productive functions such as growth, lactation, and reproduction, while simultaneously reducing energy losses as methane.

Generally, dietary carbohydrates influence rumen VFA profiles in a manner that directly affects methane emissions. By increasing the proportion of propionate relative to acetate, hydrogen availability for methanogenesis is reduced, leading to lower methane production. This mechanism highlights the importance of strategic dietary formulation in ruminant nutrition, particularly in the context of climate-smart livestock systems aimed at improving productivity while minimizing environmental impact.

2.3 Bioactive Compounds

Tannins, saponins, and essential oils are among the most extensively studied plant-derived bioactive compounds for mitigating enteric methane emissions in ruminant livestock systems. These phytochemical substances exert their antimethanogenic effects primarily through targeted modulation of rumen microbial ecology, particularly by suppressing methanogenic archaea and rumen protozoa, which are central to hydrogen metabolism and methane synthesis in the rumen.

Tannins, which are polyphenolic compounds widely distributed in legumes, tree leaves, and agro-industrial plant residues, reduce methane production through multiple interrelated mechanisms. Condensed tannins can bind to proteins, polysaccharides, and microbial enzymes, thereby limiting substrate availability for microbial fermentation. More importantly, tannins exert a direct inhibitory effect on methanogenic archaea by disrupting cell wall integrity and impairing enzymatic systems involved in hydrogen utilization. Additionally, tannins reduce rumen protozoal populations, a process known as partial defaunation. Since protozoa maintain symbiotic relationships with methanogens—often harboring them on their surfaces or within their cellular structures—reducing protozoal abundance indirectly decreases methanogen survival and activity. The overall outcome is a reduction in hydrogen transfer efficiency within the rumen, leading to lower methane output.

Saponins, glycoside compounds commonly found in plants such as *Yucca schidigera*, *Quillaja saponaria*, and various tropical forages, also play a significant role in methane mitigation. Their primary mode of action involves their detergent-like properties, which disrupt cholesterol-containing cell membranes of protozoa. This leads to selective suppression of rumen protozoa without severely affecting bacterial populations at moderate inclusion levels. The reduction in protozoal numbers decreases the availability of metabolic hydrogen, which is a critical substrate for methanogenic archaea. Furthermore, saponin-induced shifts in microbial populations often favor bacterial species associated with propionate production, thereby enhancing alternative hydrogen utilization pathways that compete with methanogenesis.

Essential oils, volatile aromatic compounds extracted from plants such as oregano, thyme, garlic, cinnamon, and eucalyptus, exert broad-spectrum antimicrobial effects within the rumen environment. Their hydrophobic nature allows them to interact with and disrupt microbial cell membranes, leading to leakage of cellular contents and inhibition of key metabolic processes. Essential oils have been shown to selectively inhibit methanogenic archaea and certain hydrogen-producing microbes while promoting more efficient fermentative bacteria. Some essential oil components, such as thymol, carvacrol, and cinnamaldehyde, interfere with enzymatic reactions involved in microbial energy metabolism, further reducing methane formation. Additionally, essential oils can modulate rumen fermentation patterns by enhancing propionate production, which serves as a competitive sink for hydrogen.

When considered collectively, these phytochemicals not only directly suppress methanogens and protozoa but also induce broader shifts in rumen microbial ecosystems. This includes reduced interspecies hydrogen transfer, altered volatile fatty acid profiles, and improved overall fermentation efficiency. The net effect is a significant reduction in enteric methane emissions without necessarily compromising animal performance when used at optimal inclusion levels.

However, it is important to note that the efficacy of tannins, saponins, and essential oils is highly dependent on their chemical structure, concentration, dietary context, and adaptation of the rumen microbiome over time. Excessive inclusion may lead to reduced feed intake, impaired fiber digestibility, or negative effects on nutrient absorption. Therefore, their application must be carefully balanced within formulated diets to achieve both environmental and productive objectives.

2.4 Lipid Effects

Oil-rich agro-industrial by-products exert a pronounced influence on rumen fermentation dynamics and methanogenesis, primarily through their lipid content and associated physicochemical effects on microbial populations.

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These by-products such as palm kernel cake, cottonseed cake, soybean cake, groundnut cake, and rice bran contain varying levels of residual fats (triglycerides, free fatty acids, and phospholipids) that play a critical role in suppressing methane production in ruminant livestock systems.

At the core of this mechanism is the direct inhibitory effect of unsaturated fatty acids on methanogenic archaea. Methanogens are highly sensitive to long-chain fatty acids, which can disrupt cell membrane integrity, impair enzyme activity, and reduce overall microbial viability. Unsaturated fatty acids, in particular, interfere with hydrogen-utilizing pathways essential for methane synthesis. As a result, the population density and metabolic activity of methanogenic archaea are reduced, leading to a decline in total methane output.

In addition to directly affecting methanogens, oil-rich by-products also exert a strong inhibitory effect on rumen protozoa, a microbial group that maintains a symbiotic relationship with methanogens. Protozoa produce hydrogen as a metabolic by-product of carbohydrate fermentation and often harbor methanogens either on their surface or intracellularly. When dietary lipids suppress protozoal populations (a process known as defaunation), the availability of hydrogen for methanogenesis is significantly reduced. This indirect pathway contributes substantially to lower methane emissions in the rumen ecosystem.

Another important mechanism involves the reduction of fiber fermentation intensity. Lipids tend to coat feed particles within the rumen, forming a physical barrier that limits microbial attachment and enzymatic degradation of fibrous components such as cellulose and hemicellulose. This coating effect slows down fibrolytic activity, thereby reducing the rate at which hydrogen is produced during fermentation. Since methane formation is closely tied to the availability of hydrogen, any reduction in fiber degradation translates directly into decreased methane production.

Furthermore, dietary lipids promote a shift in volatile fatty acid (VFA) profiles, favoring propionate formation over acetate. Propionate acts as an alternative hydrogen sink, effectively competing with methanogenesis for available hydrogen.

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This metabolic redirection improves energy utilization efficiency in the animal while simultaneously reducing greenhouse gas emissions. Consequently, more dietary energy is retained in productive pathways such as growth and milk synthesis rather than being lost as methane.

Oil-rich by-products also contribute to changes in rumen microbial ecology. The presence of lipids selectively inhibits fibrolytic bacteria and protozoa while allowing lipid-tolerant microbial species to proliferate. This microbial restructuring leads to a rumen environment that is less conducive to methane formation. However, it is important to note that excessive lipid inclusion can negatively affect overall feed digestibility and dry matter intake, necessitating careful balancing in ration formulation.

From a nutritional efficiency perspective, the inclusion of oil-rich by-products enhances energy density of the diet, reducing the total feed intake required per unit of animal product. This improvement in feed conversion efficiency indirectly lowers methane emissions intensity (i.e., emissions per kilogram of meat or milk produced), which is a critical metric in climate-smart livestock systems.

In summary, oil-rich agro-industrial by-products mitigate methane emissions through a combination of direct inhibition of methanogens, suppression of protozoal populations, reduction in fiber fermentation, and metabolic redirection of hydrogen toward propionate production. When properly incorporated into ruminant diets at optimal levels, they represent a highly effective nutritional strategy for reducing enteric methane emissions while enhancing feed efficiency and supporting sustainable livestock production systems.

3. CARBON REDUCTION AND ENVIRONMENTAL BENEFITS

The environmental benefits extend beyond methane mitigation:

- Reduction of open-field burning and associated CO₂ emissions
- Lower dependence on feed crops with high carbon footprints
- Improved soil organic carbon through manure recycling
- Enhanced resource efficiency through circular bioeconomy integration

- Reduction in transportation and processing emissions associated with conventional feeds

Constraints and Limitations

Despite their potential, several limitations exist:

- Low crude protein and high lignin content
- Seasonal and geographical variability in availability
- Presence of anti-nutritional compounds (e.g., cyanogenic glycosides)
- Limited processing and storage infrastructure
- Inconsistent quality and nutrient composition

4. FUTURE PERSPECTIVES

Future advancements in the utilization of crop residues and agro-industrial by-products for methane mitigation and carbon reduction must be grounded in a systems-oriented, interdisciplinary approach that integrates animal nutrition, feed technology, microbiology, environmental science, and agricultural policy. The following priority areas represent critical frontiers for research, innovation, and policy intervention.

Advanced Feed Processing Technologies (Biological, Chemical, and Enzymatic Approaches)

A major constraint to the effective use of crop residues and agro-industrial by-products is their inherently low digestibility, high lignocellulosic content, and variable nutrient composition. Future development must therefore prioritize advanced processing technologies capable of transforming these materials into high-quality feed resources.

Biological treatments such as fungal delignification (e.g., white-rot fungi) can selectively degrade lignin, thereby improving fiber accessibility and enhancing rumen degradability. Similarly, microbial fermentation technologies can enrich crude protein content and introduce beneficial metabolites that modulate rumen fermentation.

Chemical approaches, including alkali treatment (urea, ammonia, sodium hydroxide), can disrupt lignocellulosic bonds and significantly improve digestibility.

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Enzymatic technologies involving cellulases, hemicellulases, and ligninases offer more targeted and environmentally friendly alternatives, enabling efficient breakdown of complex plant structures without harmful residues.

The integration of these processing systems at farm and industrial levels will be essential for converting low-value biomass into climate-efficient livestock feed.

Precision Nutrition Systems for Optimized Inclusion Rates

Future livestock feeding strategies must transition from conventional ration formulation to precision nutrition models that optimize feed composition based on animal-specific requirements, production stage, environmental conditions, and metabolic efficiency.

The inclusion levels of crop residues and agro-industrial by-products should not be static but dynamically adjusted using real-time data on feed intake, growth performance, rumen function, and methane emission intensity. Advanced modelling approaches such as nutritional geometry, mechanistic rumen models, and machine-learning algorithms can be used to predict optimal inclusion rates that maximize productivity while minimizing methane output.

Such precision systems will ensure that these unconventional feed resources are used efficiently without compromising animal health or production performance.

Integration with Phytogetic Additives and Probiotics

A promising strategy for enhancing the methane mitigation potential of crop residues and by-products is their synergistic use with phytogetic feed additives (PFAs) and probiotics.

PFAs containing bioactive compounds such as tannins, saponins, flavonoids, and essential oils can directly suppress methanogenic archaea and protozoa, while also improving nutrient digestibility and immune function. Probiotics, particularly lactic acid bacteria, *Bacillus* spp., and yeast cultures (*Saccharomyces cerevisiae*), can stabilize rumen microbial populations, enhance fiber digestion, and improve fermentation efficiency.

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The combined application of these additives with crop residue-based diets may produce synergistic effects, leading to greater reductions in methane emissions than individual interventions. However, such interactions must be carefully evaluated to avoid antagonistic effects and ensure microbial balance within the rumen ecosystem.

Life Cycle Assessment (LCA) of Emission Reductions

Robust environmental evaluation tools such as life cycle assessment (LCA) are essential for quantifying the true sustainability impact of integrating crop residues and agro-industrial by-products into livestock systems.

LCA should account for emissions across the entire production chain, including feed production, processing, transportation, animal production, manure management, and product distribution. This holistic approach enables accurate estimation of net greenhouse gas savings and identifies potential trade-offs or unintended environmental burdens.

Standardized LCA frameworks will also support policy development, carbon credit systems, and sustainability certification schemes, thereby promoting wider adoption of low-carbon feeding strategies.

Policy Incentives for Waste-to-Feed Conversion Systems

Effective implementation of waste-to-feed strategies requires strong policy support at national and international levels. Governments should develop incentive structures that encourage the collection, processing, and utilization of crop residues and agro-industrial by-products for livestock feeding.

Such incentives may include tax reductions, subsidies for feed processing technologies, carbon credit schemes, and investment in rural agro-processing infrastructure. Regulatory frameworks should also discourage environmentally harmful practices such as open-field burning of crop residues while promoting their valorization within livestock systems.

Strengthening extension services and public-private partnerships will be critical for scaling these interventions, particularly in developing regions.

Development of Circular Livestock Production Models

The long-term vision for sustainable livestock systems lies in the development of circular bioeconomy-based production models, where waste streams are continuously recycled into productive inputs.

In such systems, crop residues and agro-industrial by-products serve as feed resources, livestock convert these into animal protein, and manure is returned to crop fields as organic fertilizer, closing nutrient loops and enhancing soil carbon sequestration. This integrated approach reduces dependence on external inputs, minimizes environmental pollution, and enhances system resilience.

Circular livestock systems also align with global sustainability goals by reducing greenhouse gas emissions, improving resource efficiency, and promoting regenerative agriculture. Their successful implementation will require coordinated action across agricultural value chains, including farmers, feed manufacturers, policymakers, and researchers.

Future development of climate-smart livestock systems depends on the integration of advanced feed technologies, precision nutrition, microbial ecology, environmental assessment tools, supportive policy frameworks, and circular economy principles. Collectively, these innovations will transform crop residues and agro-industrial by-products from low-value wastes into strategic resources for methane mitigation and carbon reduction, thereby supporting sustainable livestock intensification in a rapidly changing global climate.

CONCLUSION

The utilization of crop residues and agro-industrial by-products represents a sustainable and practical strategy for reducing methane emissions and lowering carbon footprints in livestock production systems. By transforming low-value biomass into productive feed resources, this approach enhances resource efficiency, reduces environmental pollution, and supports climate-smart agriculture. However, maximizing its potential requires coordinated efforts in research, technology development, policy support, and farmer education. Integrated into broader sustainable livestock systems, these resources offer a viable pathway toward environmentally responsible and economically efficient animal production.

REFERENCES

- Anaso E. U. (2024). Macro and Micro Anatomy of the Male Genitalia of the Nigerian Laughing Dove (*Spilopelia senegalensis*). *Eastern Journal of Agricultural and Biological Sciences*, 4(3), 31–44. <https://doi.org/10.53906/ejabs.v4i3.341>
- Anaso E.U. (2025c). Immune Status, Reproductive Potential, Caecal Microbial and Fermentative Characteristics of Rabbits Supplemented Rolfe (*Daniellia Oliveri*) Leaf Extract Essential Oil Based Diet. *Discovery* 2025; 61: e19d3121 [doi:https://doi.org/10.54905/disssi.v61i338.e19d3121](https://doi.org/10.54905/disssi.v61i338.e19d3121)
- Anaso E.U., Alagbe, J.O. (2025a). Body thermoregulatory adaptation and blood serum mineral metabolic profile of rabbits supplemented camel's foot (schum) seed essential oil based diet. *J. Chem. Sc.*, 2025, 2(1): 1-6. DOI:<https://doi.org/10.61784/jcs3002>.
- Anaso E.U., Fidelis E.S. and Salihu, A.M. (2025f). Carcass and meat quality of Yankassa Rams supplemented camel's foot (*Piliostigma thonningii*) essential oil based diet. *Turkish Journal of Agriculture - Food Science and Technology*, 13(11): 3276-3284, 2025 DOI: <https://doi.org/10.24925/turjaf.v13i11.3276-3284.7945>
- Anaso E.U., Olurotimi A. Olafadehan, Ijeoma C. Chibuogwu. (2025c). A systematic review on phyto-genic feed supplements on the nutritive effects, physiological responses and reproductive parameters in rabbits. *J. Agr. Fac. Düzce. Uni.*, v. 3, i. 1, pp. 67-79.
- Anaso EU, Olafadehan OA, Chibuogwu JC, Adass PA, Zubairu H, Joel JO. (2025d). Physiological Responses and Reproductive Potential of Yankassa Rams Supplemented Milne-Rech Seed Essential Oil-Based Diet. *Discovery Agriculture*, 11: e10da3127
- Anaso EU. Babalola M, Fidelis ES, Agada IC, Adediran MA. (2025e) Evaluation of feed intake and hematological profile of West Africa dwarf does fed with *Piliostigma thonningii* seed essential oil-based diet. *Science Letters* 2025; 13(2):1325300sl
- Anaso, E. (2026b). Immune And Oxidative Stress Indices of Yankassa Rams Fed Diets Containing Urea-Molasses Treated Cassava Peel Ensiled with

ADVANCES IN CLIMATE-SMART AGRICULTURE AND AGRO-ENERGY SYSTEMS

- Caged-Layer Droppings. I. International Digital Agriculture Congress. from <https://www.indac.com.tr/index.php/TURSTEP/article/view/467>
- Anaso, E. U. (2025a). Body thermoregulatory adaptations and reproductive potentials of Yankassa rams fed diets containing urea–molasses treated cassava peel ensiled with caged-layer droppings. In Proceedings of the IV International Congress of the Turkish Journal of Agriculture – Food Science and Technology (TURJAF 2025), Niğde, Türkiye.
- Anaso, E. U. (2025b). Body thermoregulatory adaptation and blood metabolic profile of rabbits supplemented with Rolfe (*Daniellia oliveri*) leaf extract-based diet. *Science Letters*, 13(2), 1325220sl.
- Anaso, E. U. (2025c). Immune status, reproductive potential, caecal microbial and fermentative characteristics of rabbits supplemented Rolfe (*Daniellia oliveri*) leaf extract essential oil- based diet. *Discovery*, 61, e19d3121. <https://doi.org/10.54905/disssi.v61i338.e19d3121>
- Anaso, E. U. (2025d). Solid-state fermentation of crop residues and agro-industrial byproducts: A sustainable approach to small ruminant production for economic development, resource efficiency, and SDG achievement in Africa. In E. E. Osuji (Ed.), *Social dimensions of economic development: Sustainability and global goals – 2025* (pp. 49–75). Haliç Publishing House.
- Anaso, E. U. (2025e). Nutritive value, feed intake and blood profile of Yankassa rams supplemented camel’s foot (*Piliostigma thonningii*) essential oil-based diet. *Turkish Journal of Agriculture – Food Science and Technology*. <https://doi.org/10.53663/turjfas.1718783>
- Anaso, E. U. (2026a). Climate-smart and sustainable animal feeding strategies: Utilization of agro-industrial by-products, crop residues, and tropical essential oils. In M. R. Berbache (Ed.), *Agri-ecosystem modeling and sustainable farming strategies – 2026*. Haliç Publishing House. <https://doi.org/10.5281/zenodo.18305692>
- Anaso, E. U., & Alagbe, J. O. (2025b). Eco-friendly feeding strategies: Effects of ginger (*Zingiber officinale*) essential oil on carcass yield and meat quality in White Fulani (Bunaji) bulls. *Research in Agricultural & Veterinary Sciences*, 9(3), 106-120. <https://doi.org/10.62476/ravs.93106>

ADVANCES IN CLIMATE-SMART AGRICULTURE AND AGRO-ENERGY SYSTEMS

- Anaso, E. U., & Alagbe, J. O. (2025c). Nutrient Digestibility, Rumen Fermentation and Nitrogen Utilization of Yankassa Rams Supplemented Milne-Rech (*Piliostigma Thoningii* Schum) Essential Oil-Based Diet. *Research in: Agricultural & Veterinary Sciences* 9(3), 169-180. <https://doi.org/10.62476/ravs.93169>
- Anaso, E. U., & Anaso, J. N. (2025). Solid-state fermentation of crop residues and agro-industrial byproducts in small ruminant production: A review. *Insights in Animal Science*. <https://doi.org/10.69917/ias.02.02-04>
- Anaso, E. U., & Dikki, G. C. (2025). Economic prospects and challenges of small ruminant production in Nigeria: Pathways to sustainable livelihoods. In *Proceedings of the Rize Trade and Economy Congress & Summit*, Rize University.
- Anaso, E. U., Alagbe, J. O., Aderibigbe, A. A., Anaso, J. N., & Fidelis, E. S. (2025g). Dietary inclusion of ginger (*Zingiber officinale*) essential oil as a sustainable feeding strategy: Effects on carcass characteristics, meat fatty acid composition, and quality attributes in Holstein Friesian × White Fulani bulls. *International Journal of Agriculture, Environment and Food Sciences*. <https://doi.org/10.31015/2025.4.36>
- Anaso, E. U., Dikki, G. C., & Anaso, C. B. (2026). Strengthening feed security in West Africa: Unleashing the strategic potential of financial institutions for sustainable livestock systems. In O. O. Oloruntova (Ed.), *Rural–urban dynamics and agricultural transformation–2026* (pp. 29–50). Haliç Publishing House. <https://doi.org/10.5281/zenodo.18380642>
- Anaso, E. U., Olafadehan, O. A., Chibuogwu, I. C., & Shoyombo, A. J. (2025b). Nutrient digestibility, growth performance, caecal microbial profile, and fermentation characteristics of rabbit bucks fed *Piliostigma thonningii* essential oil-supplemented diet. *Biotechnology in Animal Husbandry*, 41(1), 37–55. <https://doi.org/10.2298/BAH2501037A>
- Anaso, E., & Chibuogwu, I. (2026). Effects of *Piliostigma Thoningii* (Schumach.) milne-rech essential oil supplementation on reproductive performance, semen quality, and fertility indices in bunaji bulls. *International Journal of Agriculture Environment and Food Sciences, Advanced Online Publication*, 48-57. <https://doi.org/10.31015/jaefs.2026.1.6>

- Anaso, E., Ajogi, D., Aderibigbe, A., & Fidelis, E. (2026). Utilization of *Pleurotus ostreatus*–biodegraded sugarcane scrapings in indigenous goat feeding systems: nutritional value, feed intake, and hematological responses of crossbred sahel desert × sokoto red buckling goats. *Egyptian Journal of Agricultural Research*, 104(1), 101-111. doi: 10.21608/ejar.2026.303036.1559
- Anaso, E.U. (2023a). Bioactive compounds of *piliostigma thonningii* essential oil detected by the gas chromatography-mass spectrometry. *EJABS* 3(2):68-72.
- Anaso, E.U. (2023b). Phyto-genics and essential oil supplementation in rabbit and monogastrate production, a panacea to improved animal production and antibiotic resistance challenge in Nigeria. *EJABS* 3(2):45-51.
- Anaso, E.U. (2025a). Body Thermoregulatory Adaptations and Reproductive Potentials Of Yankassa Rams Fed Diets Containing Urea-Molasses Treated Cassava Peel Ensiled with Caged-Layer Droppings. 4th international Congress of Turkish Journal of Agriculture-Food Science and Technology. 1120-1126.
- Anaso, E.U., Olafadehan, O.A. (2025). *Pleurotus ostreatus* biodegraded sugarcane scrapings: Nutritive value, feed intake, and blood profile of buckling goats. *Archiva Zootechnica*, 28:1, 61-76, 2025 DOI: 10.2478/azibna-2025-0004.
- Anaso, E.U., Olafadehan, O.A., Chibuogwu, I.C. (2023). Semen characteristics of rabbits fed Camel's Foot (*Piliostigma thonningii*) essential oil supplemented diet. *Discovery*, 59, e36d1037.
- Anaso, E.U., Olafadehan, O.A., Chibuogwu, I.C. (2025a). Nutritive effects and physiologic responses of rabbits supplemented with Camel's Foot (*Piliostigma thonningii*) essential oil-based diet. *Veterinarski Arhiv*, 95(3). DOI: 10.24099/vet.arhiv.2669
- Anaso, E.U., Olafadehan, O.A., Chibuogwu, I.C., Alagbe, J.O. (2024a). Seminal morphology and organ morphometrics of rabbit bucks fed *Piliostigma thonningii* essential oil supplemented diet. *Science Letters*, 12(2), 70-75. DOI: 10.47262/SL/12.2.132024280
- Anaso, E.U., Olafadehan, O.A., Chibuogwu, I.C., Shoyombo, A.J., Mailafia, S., Anaso, J.N., Fidelis, E.S. (2024d). Haematological profile and fertility

ADVANCES IN CLIMATE-SMART AGRICULTURE AND AGRO-ENERGY SYSTEMS

- potential of rabbits supplemented with Camel's Foot (*Piliostigma thonningii*) essential oil-based diet. *Turkish J. Agr.-Food Sc.Tech.*, 12(12): 2470-2477,2024. DOI: <https://doi.org/10.24925/turjaf.v12i12.2470-2477.6870>
- Anaso, E.U., Olafadehan, O.A., Emeka, F.S. (2024c). Carcass and meat quality of rabbits supplemented with Camel's Foot (*Piliostigma thonningii*) essential oil-based diet. *Archiva Zootechnica* 27:2, 36-51, 2024 DOI: 10.2478/azibna-2024-0013
- Anaso, E.U., Olafadehan, O.A., Oluwafemi, R.A. (2021b). Biodegradation of agro-industrial by-products as a panacea to feed scarcity in Nigeria amidst farmer insecurity and global pandemic. *Proc 46th Annu Conf Niger Soc Anim Prod.* 2021;616–20.
- Anaso, E.U., Olafadehan, O.A., Shoyombo, A.J. (2021a). Semen characteristics of Kano Brown bucks fed white rot fungi (*Pleurotus ostreatus*) biodegraded sugarcane scrapings-based diets. *Proc 46th Annu Conf Niger Soc Anim Prod.* 2021;625–8.
- Anaso, E.U., Olafadehan, O.A., Shoyombo, A.J., Emeka, F.S. (2024b). Body weight, scrotal parameters, and semen characteristics of Kano Brown bucks fed *Pleurotus ostreatus* solid-state fermented sugarcane scrapings. *Turk. J. Food Agr. Sc.*, DOI: <https://doi.org/10.53663/turjfas.1486383>.
- Anaso, E.U., Salihu, A.M. (2025). Identification and antimicrobial susceptibility of *Pseudomonas aeruginosa* strain PAO1 isolated from African catfish skin scrapings. *Sci Lett.* 13(1):1324350sl. doi:10.47262/SL/13.1.132024350.
- Anaso, EU. (2025b). Body thermoregulatory adaptation and blood metabolic profile of rabbits supplemented with Rolfe (*Daniellia oliveri*) leaf extract-based diet. *Science Letters.* 13(2):1325130sl
- Food and Agriculture Organization. (2013). *Tackling climate change through livestock: A global assessment of emissions and mitigation opportunities.* FAO.
- Gerber, P. J., Steinfeld, H., Henderson, B., Mottet, A., Opio, C., Dijkman, J., Falcucci, A., & Tempio, G. (2013). *Tackling climate change through livestock.* FAO.

*ADVANCES IN CLIMATE-SMART AGRICULTURE AND AGRO-ENERGY
SYSTEMS*

- Intergovernmental Panel on Climate Change. (2021). *Climate change 2021: The physical science basis*. Cambridge University Press.
- Kumar, S., Choudhury, P. K., Carro, M. D., & Naumann, H. D. (2014). Effects of dietary lipids on methane emissions in ruminants. *Animal Feed Science and Technology*, 197, 1–11.
- Makkar, H. P. S. (2012). Biofuel co-products as livestock feed—Opportunities and challenges. FAO.
- Olafadehan, O.A., Anaso, E.U., Shoyombo, A.J., Okunade, S.A. (2021). Chemical and phytochemical constituents of white rot fungi (*Pleurotus ostreatus*) biodegraded sugarcane scrapings. *Proceedings of the 46th Annual Conference of the Nigerian Society for Animal Production*, pp. 621-624.
- Olafadehan, O.A., Anaso, E.U., Shoyombo, A.J., Okunade, S.A. (2023). Body thermoregulation and serum metabolic profile of Kano Brown bucks fed *Pleurotus ostreatus* biodegraded sugarcane scrapings. *Biotechn. Anim. Husb.*, 39(1), 61-72. 37 <https://doi.org/10.2298/BAH2202081R>
- Patra, A. K., & Saxena, J. (2010). A new perspective on the use of plant secondary metabolites to inhibit methanogenesis in the rumen. *Phytochemistry*, 71(11–12), 1198–1222.
- Patra, A. K., & Saxena, J. (2010). A new perspective on the use of plant secondary metabolites. *Phytochemistry*, 71(11–12), 1198–1222.
- Thornton, P. K., & Herrero, M. (2010). Climate change and livestock productivity in developing countries. *Animal*, 4(3), 371–377.
- Van Boeckel, T. P., Brower, C., Gilbert, M., Grenfell, B. T., Levin, S. A., Robinson, T. P., Teillant, A., & Laxminarayan, R. (2015). Global trends in antimicrobial use in food animals. *Proceedings of the National Academy of Sciences*, 112(18), 5649–5654.
- Windisch, W., Schedle, K., Plitzner, C., & Kroismayr, A. (2008). Use of phytogenic products as feed additives for swine and poultry. *Journal of Animal Science*, 86(14_suppl), E140–E148.



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