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ARMENIAN NATIONAL AGRARIAN UNIVERSITY

SPECIAL ISSUE

Materials of the 1st International
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ARMENIA

April
2025

ANAU FOUNDATION

Guest Editor Message

It is our great pleasure to introduce this Special Issue of the ANAU Scientific Journal of "AgriScience and Technology", dedicated to the 1st International Green Agriculture Conference Armenia (IGACA) 2025, held in Yerevan on April 2-3.

This Special Issue brings together some of the scientific contributions presented at the conference, organized under four thematic areas: Sustainable and Climate-Smart Agriculture, Circular Economy and Sustainable Resource Management, Innovative Technologies in Agriculture, and Knowledge Transfer and Exchange. Collectively, these articles highlight the progress, challenges, and opportunities of advancing green agriculture in Armenia and the wider region.

The breadth of topics covered – from climate-smart practices and soil and water management, to innovative technologies and circular solutions – illustrates the transformative potential of green agriculture. These contributions provide valuable insights not only for researchers and practitioners, but also for policymakers shaping Armenia's agricultural transition.

Green agriculture offers us a path forward: a way to produce more with less, restore soil health, enhance biodiversity, and ensure that future generations inherit a fertile and thriving land. By adopting climate-smart technologies, regenerative practices, and precision agriculture, we can build a system that is not only economically viable, but also ecologically sound.

At the same time, this Special Issue is not a conclusion but a starting point. It underlines the urgent need for further research, stronger knowledge exchange, and continued innovation to strengthen Armenia's agricultural resilience in the face of climate change and resource constraints.

We extend our sincere thanks to all authors, reviewers, and contributors who made this publication possible, and to the Armenian National Agrarian University and EU-GAIA for their support in organizing the conference that gave rise to this collection.

We hope this Special Issue will serve as both a scientific resource and an inspiration for future work, encouraging new collaborations and practical solutions in the journey toward sustainable and resilient agriculture.

Sincerely,
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A Comparison of Climate Smart Food Systems in Armenia, Georgia, and Moldova: Policy Implications for Armenia

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ABSTRACT

In May 2020, the European Commission introduced the Farm to Fork (F2F) strategy (European Commission, 2020), a bold initiative aimed at overhauling Europe's food systems with a strong focus on sustainability and long-term environmental, human, and planetary health goals - in line with the objectives of the EU Green Deal (European Commission, 2021). The profound impacts of industrial food systems on climate change, biodiversity, and public health are often overlooked. Globally, food systems account for nearly one-third of greenhouse gas emissions (Crippa et al. 2021), are the primary causes of biodiversity loss (Boakes, et al., 2024), and play a substantial role in health conditions such as cardiovascular diseases, cancer, and type 2 diabetes. To build on these efforts, the EU Strategic Dialogue on Agriculture recently introduced a document of recommendations called "A Shared Prospect for Farming and Food in Europe."(European Commission, 2024). The initiative aims to reform the EU Common Agricultural Policy (CAP), create Just Transition and Nature Restoration Funds, and advocate for more sustainable diets – new directions for advancing the Farm to Fork agenda that will shape European policy in the future.

Food systems are critical for ensuring food security, supporting sustainable development, and addressing the challenges posed by climate change. This paper explores lessons learned from three GUMA project countries: Armenia, Georgia, and Moldova. A qualitative analysis was conducted using data gathered from diverse sources, including official statistical agencies, international donor organization frameworks, and sectorial data. In addition, for Armenia specifically, the study incorporates insights from surveys of key actors across state, academic, and private sectors. All three countries face challenges related to rising temperatures leading to heat stress and droughts, soil health and degradation, and the prevalence of smaller farm sizes. Additional issues include low levels of organic production, limited access to markets and finance, underdeveloped or no agricultural extension services, significant post-harvest food loss and waste, food insecurity, and insufficient adoption of healthy and sustainable diets. Furthermore, these challenges are worsening because of the lack of governmental or international incentives to promote climate-friendly and sustainable farming programs and gaps in governance and strategic planning. The study highlights key lessons from climate-smart food systems in Armenia, Georgia, and Moldova, offering comparative insights and actionable recommendations to guide policy development and advance sustainable agricultural practices in Armenia.

Introduction

In May 2020, the European Commission introduced the Farm to Fork (F2F) strategy (IBID), a bold initiative aimed at overhauling Europe's food systems with a strong focus on sustainability and long-term environmental, human, and planetary health goals - in line with the objectives of the EU Green Deal (IBID). The profound impacts of industrial food systems on climate change, biodiversity, and public health are often overlooked. Globally, food systems account for nearly one-third of greenhouse gas emissions (IBID), significantly contribute to biodiversity loss (IBID), and are closely linked to major health issues including heart disease, cancer, and type 2 diabetes.

Reinforcing these objectives, the EU Strategic Dialogue on Agriculture recently presented a new set of proposal under the title "A Shared Prospect for Farming and Food in Europe" (IBID). The initiative aims to reform the EU Common Agricultural Policy (CAP), create Just.

Materials and methods

Agriculture, which accounts for 69% of the country's land area (ARMSTAT, 2025) and employs 22% of the total workforce (ARMSTAT, 2023), as a vital part of Armenia's cultural heritage and economy, standing as the third-largest sector in terms of Gross Domestic Product GDP contribution. Its key agricultural commodities include fruits (apricots, peaches, grapes), vegetables (potatoes, tomatoes, cucumbers), cereals (wheat, barley), and herbs. Armenia is also known for wine and brandy production, leveraging its ancient viticulture traditions. Livestock farming (cattle, sheep, pigs) is integral to agriculture, providing meat, dairy, and wool.

Table. Key Agricultural Indicators for Armenia, Georgia and Moldova

Indicator	Armenia	Georgia	Moldova
Agriculture GDP (%)	18	9	12
Arable Land (%)	44	39	52
Average farm Size (hectares)	2.5	1.2	3.0
Smallholder farming (%)	94	99.8	97.7
Top Exports	Fruits, Vegetables, Wine, Grans	Citrus, Grapes, Tea, Vegetables, Wine	Wheat, Sunflower seeds, Grapes, fruits

In its Nationally Determined Contribution (NDC) 2021-2030 (NDC, 2021), Armenia committed to implementing economy-wide climate mitigation measures to achieve per capita net emissions of 2.07 tCO_2eq by the year 2050. Agriculture, the second most significant contributor to GHG emissions (18.5%) after energy (66.7%) (UNDP, 2020), is recognised as an important component within the NDC. There is a focus on several agriculture mitigation strategies, including improved nitrogen fertilizer application practices, the promotion of organic farming methods to decrease reliance on synthetic inputs and enhance soil health, improved irrigation strategies to reduce water loss, and the adoption of digital tools and innovative technologies to improve farm management and resource use efficiency.

Furthermore, the NDC also emphasises the importance of integrating climate change adaptation into national planning, specifically focusing on agriculture, which is particularly vulnerable to its impacts.

Armenian agriculture is a key contributor to and is also impacted by climate change. Armenia has experienced a rise in average temperatures, which affects crop yields and water availability. Changing rainfall patterns, increased frequency of droughts, and deforestation contribute to soil erosion and fertility loss, exacerbating the impacts of climate change (GEFF, 2025). Furthermore, melting glaciers in the Armenian Highlands and reductions in water tables have reduced long-term water availability for crop irrigation (WB, 2021).

Common Challenges in Armenia, Georgia, and Moldova

Whilst Armenia, Georgia, and Moldova are geographically and culturally distinct, they share common challenges across their respective food systems. Several of these challenges have been briefly outlined below:

1. Increasing temperatures leading to heat stress and droughts: The ability to feed growing populations with healthy and nutritious foods and ensure long-term food security is being compromised by the impacts of a changing climate. All three countries are experiencing increasing average temperatures, leading to heat stress for crops and livestock and a consequent drop in yields (IMFFA 2021, WB 2020, UNFCC 2024). Erratic rainfall patterns and more frequent and severe droughts also affect water availability and crop yields, compounded by inefficient and unsuitable ageing irrigation systems. Salination of soils in irrigated issues also occurs (FAO 2021). Managing water resources sustainably remains one of the critical challenges across all three countries, alongside adopting climate-resilient organic and agroecological agricultural practices.

2. Soil health and degradation: Soil erosion and degradation, particularly in hilly areas, are significant issues across all three countries. This typically stems from practices such as excessive grazing, high-input farming, and deforestation. In Armenia, for example, unsustainable livestock practices on the Alpine grasslands have resulted in soil degradation and the loss of critical alpine grasslands (WB 2023). In Georgia, 35% of the country's agricultural land is degraded (NSOG, 2025): in Moldova an estimated 2 million hectares have been affected by degradation (Tamara, 2015).

3. Smaller farm sizes compared with Europe: In Armenia, Georgia, and Moldova, the average farm size is small compared to the rest of Europe, reflecting the agrarian structures established during land reforms following the collapse of the Soviet Union in the 1990s. Today, average farm sizes vary from 1.37 hectares in Armenia (Millns, 2013) to 2.5 hectares in Moldova (WB, 2025). In many cases, agricultural land, which was previously managed by large state-owned farms (kolkhozes and sovkhozes), was redistributed to individual households. Efforts to consolidate landholdings across all three countries have been limited, and there is resistance from rural communities due to concerns over losing their primary means of livelihood. Governments and international organizations are exploring ways to improve the sustainability and efficiency of these smaller farming operations, such as encouraging cooperative farming, improving access to credit, and, in some instances, promoting land consolidation programs.

4. Low levels of organic agriculture production and difficultie accessing markets: While organic agricultural production is growing across the three countries, Moldova has the most developed organic sector, with organic farming covering approximately 1.5% of agricultural land (FiBL 2024). Armenia and Georgia's specific statistics are more difficult to obtain, but estimates suggest that organic agriculture covers less than 1% of land. High certification costs and low consumer purchasing power and awareness are key market challenges that prevent farmers and consumers from producing and purchasing organic foods.

5. Poor access to markets and finance Given the small size of many farms in each country, it can be difficult for farmers to access markets (FAO, 2019, WB, 2025). Cooperation between farmers is still relatively limited, although there is some emerging interest in developing farming cooperatives to improve their negotiating position, particularly with larger buyers. Organic and other environmental certification schemes (e.g., ECOGLOBE (ECOGLOBE 2025), Caucascert (Caucascert 2022), Certificat Eco (Certificate, 2025)) which have the potential to improve access to markets and the value of products, face challenges (e.g., can be expensive) and are nascent in these countries and farmers often struggle to meet the quality and safety standards required to access the larger and export markets.

Furthermore, access to finance is a common challenge. Banks and financial institutions often view farming as a high-risk activity, particularly for smallholder farmers with little access to other forms of collateral. A lack of financial training or systems to support farmers with financial advice compounds these challenges. Even when loan or finance programs are available, they do not tend to focus on climate change mitigation and adaptation—their prime focus is often on productivity improvements.

6. Agriculture and climate education, training, and farmer extension programs: Agricultural education/training and extension programs are critical for improving agricultural productivity, reducing GHG emissions, and supporting rural development. Whilst there is a growing focus and investment in agricultural development across all countries, more informal agrarian development services, particularly regarding farmer training for climate-smart agriculture, are underdeveloped and inaccessible for the smaller farms. Limited resources also hinder the effectiveness and expansion of extension services. Whilst there is some support from international organisations and donors (e.g., USAID, EU, UNDP, World Bank, etc), there are opportunities to increase support for climate-smart agriculture, agroecology, and organic agriculture. Whilst organic and climate-smart-related agriculture research is nascent in the three countries, there are opportunities to include more of these elements within the curricula of research and academic institutions.

7. Post-harvest food loss and waste: Post-harvest food loss and waste (FLW) present significant challenges in Armenia, Georgia, and Moldova. Precise, up-to-date statistics for each country are very limited. Despite this limited data, regional trends suggest that these losses contribute to a lack of proper post-harvest facilities, poor market access (particularly for fresh produce), and limited knowledge of best practices (FAO 2024). The absence of cold storage and processing facilities can also hamper produce quality and shelf life and reduce the amount of food available for the export market (IFAD 2023, Food Systems Summit 2021). Farmers also lack awareness of proper post-harvest handling techniques, leading to physical damage to crops.

8. Food insecurity: While food insecurity varies across Armenia, Georgia, and Moldova and is rising in Moldova, it remains a significant challenge, especially in more rural areas (WFP 2023, FAO 2023). Food insecurity is influenced by factors such as political instability, economic challenges, the impacts of climate change, and regional conflicts. In Georgia and Moldova, migration as a result of from regional disputes (e.g., the war in Ukraine) has added pressure on these countries' food systems. Reduced agricultural output due to climate change can lead to higher food costs, creating barriers for low-income families to access affordable, nutritious diets. All three countries depend on imported foods and key agricultural inputs (e.g., fertilisers), which makes them particularly vulnerable to global market fluctuations and supply chain disruptions.

9. Healthy and sustainable diets: Obesity and other diet-related health issues are rising in all three countries due to increased consumption of highly processed and high-calorie foods. There has been a corresponding reduction in the consumption of healthier and lower-carbon foods, including fruits, vegetables, and whole grains. As a result, micronutrient deficiencies have been rising, including anaemia and vitamin deficiencies, particularly among women and children. Generally, agro biodiversity (crop diversity) has dropped in each country, particularly as more traditional diets (using lentils, beans, nuts, seasonal fruits/vegetables, etc) have lost favour. While governments rarely interfere with peoples' diets, making healthy and sustainable food affordable could increase nutrition security, improve public health, and reduce the climate impacts of food systems.

10. A lack of government or international incentives for promoting climate-friendly and sustainable farming programs: (e.g., subsidies for organic farming or water-saving irrigation) are limited or poorly implemented. International aid often focuses on short-term projects rather than systemic reforms.

11. Governance and strategy: Improving communication, coordination, and synergy between and across ministries can boost progress towards achieving climate-smart food and farming goals. This means looking at food as a whole system, from how food is grown to how it is consumed, engaging all actors (including civil society organisations, farmers, citizens, academics, businesses, etc) with a stake in this process. Scientists and policymakers increasingly agree that making food systems sustainable is not just about new technology; we need systemic changes in food production and consumption. Whilst ministries vary between each of the three countries, they all tend to operate in silos. The Ministries of Agriculture, Environment, Climate, Health, and Labour often develop policies related to food and farming in isolation to align their policies and work together to find practical solutions for shared objectives. Food, agriculture, and climate-related strategies can often be fragmented at best and at worst, they can conflict with one another.

Results and discussions

Examples of Climate Smart Agricultural Policy in Georgia

Agriculture is significant in Georgia's economy, contributing about 7% to the national GDP. 45%, 48% and 7% of Georgia's agricultural production come from animal husbandry, horticulture and farming services. Roughly, 99% of agricultural holdings are small family-run farms, usually operating on about one hectare of land.

While Georgia has no specific GHG emissions reduction targets for agriculture, its climate action plan (Nationally Determined Contribution) supports ‘low carbon development approaches of the agriculture sector through encouraging the climate-smart agriculture and agritourism’ (NDC 2021). The Agricultural and Rural Development Strategy for Georgia 2021-2027 (GRDN 2021) is the principal strategic document that guides agricultural development in Georgia. It serves as a roadmap for achieving sustainable economic growth, with key objectives focused on increasing self-sufficiency levels, improving food security, and increasing food exports while protecting the environment.

Acknowledging the significance of horticulture and aiming to lessen dependency on fruit and vegetable imports, the Georgian government initiated the “Plant the Future” program in 2025 (RDA 2025). The scheme encourages the cultivation of high-value crops such as nuts, berries, and fruit trees, and farmers receive grants to cover the costs of seedlings, irrigation, and infrastructure. The scheme particularly encourages farmers to think about how they can adapt to climate change and specifically funds projects that reduce water usage and instal anti-hail initiatives, for example.

A programme to support organic agricultural production, reducing the reliance on fossil fuel-based fertilisers and pesticides, has also been a key priority of the Georgia government over the last five years. For example, in 2022, Georgia launched an Organic Production Support Programme. This initiative aims to boost the production of organic products by providing financial support to potential beneficiaries willing to transition to organic farming practices. Furthermore, the scheme addresses high certification costs, limited access to processing and storage facilities, outdated infrastructure, and knowledge gaps among some farmers.

Examples of Climate Smart Agricultural Policy in Moldova

The agri-food sector in Moldova plays a significant role in the country’s economy. It accounts for around 12% of Moldova’s Gross Domestic Product and employs over 21% of its labour force. Moldova’s main agricultural products, 45% of which are exported, include fruits, nuts, grapes, cereals and livestock (Statista 2023). Most farmers (97.7%) are small-scale, with farm sizes ranging between 0.85 and 10 hectares. The contributions of smallholders and family farms are vital to the sector, as they generate 63% of the country’s total agricultural production (REU 2022).

Agriculture is the second most significant contributor to GHG emissions after energy (11.3% and 51.5%, respectively). The country’s climate action plan (Nationally Determined Contribution 2022) commits to actively promoting climate-resilient agricultural practices through a wide range of practices, including fertilizer application optimisation, crop diversification, better irrigation, and improvement to soil health. The National Strategy for Agriculture and Rural Development 2023-2030 is the principal piece of legislation.

Given the country’s vulnerabilities to climate change impacts, including significant droughts and floods that have affected crop production over the last few years, a National Climate Change Adaptation Programme (UNFCC 2024) was approved in 2023. The programme aims to integrate adaptation measures across various sectors, significantly focusing on agriculture. Key agricultural strategies, for example, include promoting agrobiodiversity and developing drought-resistant crop varieties. These include traditional Moldovan grape varieties, which are noted for their resistance to cold temperatures and drought conditions, making them valuable crops for viticulture in the region.

Furthermore, the Moldovan government places much emphasis on agricultural extension services. It recently established the Agricultural and Rural Advisory Centre, whose mission is to develop consulting services tailored to farmers’ needs, facilitating their access to technical, economic, financial, and managerial information, as well as training programs and rural development initiatives. The Centre, for example, runs training programs for farmers focussed on adopting conservation agriculture techniques, micro-irrigation systems, and anti-hail and anti-frost systems. The Centre collaborates with local communities to develop action plans addressing climate change adaptation at the community level. These plans include assessments of climate vulnerabilities and outline specific adaptation actions, contributing to broader climate mitigation efforts.

Examples of Climate Smart Agricultural Practices and Polices in Armenia

The 2020-2030 vision for Armenian agriculture focuses on sustainable development, innovation, and high-value production that respects natural resources, supports biodiversity, and promotes eco-friendly farming. The aim is to create healthy, ecologically clean products while enhancing the well-being of rural communities. The government is committed to a coordinated approach that emphasizes resource efficiency and partnerships to address key challenges in agriculture and rural areas. The primary goals are to increase agricultural productivity, strengthen food security, adopt modern technologies, and improve income for everyone involved in agriculture: especially smallholder farmers, producer groups, processors, and exporters.

The Government has identified several critical measures to enhance climate resilience and reduce risks in agriculture. These include establishing a national agricultural insurance system, developing and implementing effective anti-hail mechanisms, and promoting climate-resilient technologies such as drought-resistant crop varieties, modern agricultural practices, and localized smart technologies adapted to changing climatic conditions.

The strategy also includes practices that boost biodiversity, soil health, and efficient use of resources, such as crop rotation and organic farming. As a result, new certification procedure introduced in 2024 now requires local certifying organizations to accept national certification standards, which will simplify organic certification and help Armenian products reach broader markets (GoA 2020).

The “GREEN Armenia” Policy Dialogue with European Union, initiated in 2022, highlights the importance of further discussions for technical and infrastructure development to facilitate a successful green transition. Advancing the agriculture sector necessitates additional investments in human capital across various segments and levels of the agricultural market. This involves a comprehensive reform of the educational and vocational training systems to actively involve youth, enhance farmer skills, and train the next generation of Armenian agronomists, agricultural technologists, and entrepreneurs. Additional efforts are required to attract qualified specialists. The primary objective of the GREEN Armenia platform is to consolidate and streamline policies and investment initiatives with the aim of facilitating Armenia’s transition to a green economy (GoA 2022).

Climate-Smart Agriculture practices have begun to take root in Armenia, notably through the EU Green Agriculture Initiative in Armenia (EU GAIA), implemented by the Austrian Development Agency, the best “Green and Climate smart agriculture technologies” and “Good agricultural practices” were identified and implemented. There were selected and introduced particularly those technologies and practices that are best suited for the local context that conserve natural resources, reduce GHG emissions, and improve soil quality for healthy food production without depleting natural resources (FAO 2023).

Armenia has set ambitious climate goals, aiming for per capita net emissions of 2.07 tCO2eq by 2050 through economy-wide mitigation measures detailed in its 2021–2030 Nationally Determined Contributions. The Nationally Determined Contributions (NDC) highlight agricultural emissions—such as methane from livestock digestion and nitrous oxide from fertilizer applications—as key areas for mitigation. Complementing this, the National Action Programme for Climate Change Adaptation (2021-2024) aligns sector policies with adaptation efforts, particularly for agriculture, as part of the National Adaptation Plan (NAP). Recent policy actions also reflect Armenia’s commitment to sustainable food systems, such as signing the COP28 UAE Declarations on resilient food systems and climate action in December 2023. Despite these prospects, Armenia’s agricultural and food systems currently lack updated greenhouse gas (GHG) emissions data. The latest estimate from 2019 attributes 18.8% of GHG emissions to agriculture, largely from cattle-related methane emissions and nitrogen fertilizer practices, with nitrous oxide emissions predominantly linked to manage soil activities (MoE 2023).

The green technologies and good agricultural practices that demonstrate the best sustainable approaches in agriculture address the following main directions: Improved soil management (ISM), improved crop production (ICP), organic Agriculture and post-harvest processing. The establishment of demonstration sites and agribusiness support projects were the main approaches to promote the adoption of green technologies and good agricultural practices at the farm level. In total 16 demo sites were established at beneficiaries’ farms. To strengthen the technical capacities of demo sites agricultural production machinery and small agricultural equipment, as well as some smart infrastructural inputs were provided to project beneficiaries (AMPERA 2024).

The current agricultural State Support Programs (SSPs) in Armenia are designed to enhance the sector’s competitiveness, sustainability, and export orientation. According to the Ministry of Economy, the primary objectives of state support for the agricultural sector include:

- *Food Security:* As a landlocked country with limited agricultural land, Armenia is particularly vulnerable to food shortages, especially during droughts or other natural disasters. Government involvement is essential in maintaining a secure and dependable food supply chain.
- *Economic Development:* Agriculture is a significant contributor to Armenia’s economy, accounting

for approximately 9% of GDP and providing employment for about 30% of the workforce. By supporting the agricultural sector, the government aims to create new jobs, boost incomes in rural areas, and reduce poverty.

- *Climate-Smart Agriculture and Resilience to Climate Change:* Although climate-smart agriculture and resilience to climate change are reflected in Armenia's agricultural development strategy and some SSP descriptions, their emphasis within the programs remains inconsistent. These elements appear sporadically and are not fully aligned with the country's current economic needs or the growing risks posed by climate change.

- *Environmental Protection:* Agriculture has a significant environmental impact. By promoting sustainable agricultural practices, the government seeks to protect natural resources and ensure the long-term viability of the sector.

Organic farming is recognized as an important driver of export growth. The country strategy sets an ambitious goal of achieving more than 5% eco-certified agricultural production by 2029. Increasing stakeholder awareness of global best practices and strengthening collaboration with the Ministry of Environment on conservation issues are essential to achieving these targets. By focusing on sustainable development, Armenia aims to enhance the resilience and competitiveness of its agricultural sector while advancing its green transition and aligning more closely with EU standards. As a consequence of strategy action plan new certification procedure introduced in 2024 now requires local certifying organizations to accept national certification standards, which will simplify organic certification and help Armenian products reach broader markets.

Armenia's green transition also gained momentum with the country's membership in the International Union for the Protection of New Varieties of Plants in 2024. Armenia became the 79th member of the International Union for the Protection of New Varieties of Plants (UPOV), which offers a unique legal framework for plant variety protection. By introducing plant breeders' rights, Armenia opens up opportunities for sector growth and societal benefits, including enhanced breeding practices, access to improved plant varieties, foreign varieties and technologies, increased genetic diversity, and expanded seed and plant material exports. Additionally, this aligns with political commitments, including the CEPA agreement.

Armenia has introduced legislative measures to reduce pollution from mineral fertilizers. As part of its commitments under the Comprehensive and Enhanced Partnership Agreement (CEPA), the country is aligning its laws with EU standards and international guidelines (EU 2018). In terms of water quality and resource management, this includes adherence to five key EU directives: the Water Framework Directive, the Floods Directive, the Urban Waste Water Treatment Directive, the Drinking Water Directive, and the Nitrates Directive. According to Article 32 of the Armenian Water Code: "The Water Resources Management and Protection Authority is responsible for establishing criteria to identify nitrate-sensitive water resource areas and developing strategies to reduce and prevent nitrate pollution caused by agricultural activities."

To address nitrate pollution from agricultural activities, the Armenian government issued Prime Minister's Decision N 1099-A on September 27, 2022. This decision focuses on amendments to the Water Code and the National Water Program of Armenia. The Ministry of Environment of the Republic of Armenia issued a new decree on June 18, 2024. The decree, aligned with Armenia's revised Water Code, sets out criteria for designating nitrate-sensitive areas and outlines actions to limit nitrate pollution. To address the impact of agricultural activities on nitrate pollution, the decree imposes restrictions on the use of nitrogen fertilizers and the storage of livestock manure, considering factors such as soil type, slope, climatic conditions, rainfall, irrigation practices, and agricultural activities. The goal is to strike a balance between the nitrogen requirements of crops and the amount of nitrogen that leaches into soil and water, thereby preventing pollution. The specific measures, tailored to the characteristics of each river basin, will be determined as part of the River Basin Management Plans (Government Decision of RA, 2024).

A crucial regulatory framework on reducing the environmental impact of food systems in the Republic of Armenia is the 'Forestry Code of the Republic of Armenia.' This code establishes the competencies of authorized state administration bodies in the field of sustainable forest management and control, and plays a key role in ensuring that forest practices contribute to environmental protection and climate goals. The Forestry Code, which states the responsibilities of authorized state administration bodies, includes 42 key points, two of which, No. 27 and No. 40, are specifically devoted to agroforestry. These points are essential in regulating and supporting various aspects of agroforestry, such as the restoration and afforestation of forests, the management of seed systems, and the promotion of sustainable forest practices (Forestry Code of RA 2024).

The agritech sector in Armenia shows great potential for growth and transformation. Agriculture remains a key pillar of the nation's economy, and the development of agritech is seen as a way to modernize traditional farming practices, boost productivity, and enhance sustainability in response to challenges such as climate change, water scarcity, and a rapidly changing global marketplace.

Conclusion

Policy opportunities for climate-smart agriculture and food systems in Armenia.

Overall, the green transition within Armenia's agricultural and food sectors is crucial for ensuring the country's long-term sustainability and resilience. The consequences of not achieving a green transition in Armenia's agricultural and food processing sectors are significant, posing risks to the environment, economy, and long-term food security. Given Armenia's dependence on agriculture to meet food demands, any disruption in agricultural production threatens the country's food security.

There are significant opportunities to address these challenges in the food system in Armenia, Georgia, and Moldova. In Armenia specifically, drawing on lessons from Georgia and Moldova, we identified the following:

1. Modernizing irrigation systems: Improving Armenia's irrigation systems (e.g., drip and precision irrigation systems) is key to increased agricultural productivity and climate resilience, particularly given how Armenia is increasingly subject to droughts and water scarcity. Providing financial assistance and tax incentives for purchasing and installing modern irrigation equipment and planting a greater diversity of drought-resistant crops is also key. The protected cropping (greenhouse) sector is also an economically promising area for expansion in Armenia with export growth potential – supporting water and energy-efficient greenhouses using renewable energy technologies holds promise with dual benefits for climate and the economy.

2. Promotion of climate-smart practices such as organic agriculture, agroecological practices, and agroforestry: Armenia has a significant opportunity to significantly expand organic farming and agroecological practices due to its rich agricultural and food heritage, fertile soils, and increasing demand, particularly from urban customers, for organic products. Using digital tools such as precision agriculture, remote sensing, and more accurate monitoring systems (e.g., weather, pests, and diseases) can also reduce the reliance on fossil fuels and pesticides whilst reducing costs and risks. The Armenian government could develop policies to support the further subsidisation and expansion of organic production, and organic certification and provide more technical training (formal and informal) for farmers.

3. Crop diversification programs and strategies: Given the benefits of crop diversification in terms of drought resilience, enhancing soil fertility, and improving biodiversity, there are significant opportunities to scale up production and research in a wider variety of traditional, wild, or underutilised crops. However, farmers often lack awareness or technical knowledge about the benefits and methods of diversification. Policies and funding can also favour monoculture cropping systems rather than supporting crop diversification and mixed or intercropping systems.

4. Supporting on-farm renewable energy technologies (on-farm solar and biogas): Solar energy is one of Armenian farmers' most promising renewable energy sources, given the country's favourable geographic location and abundant sunshine. Solar could particularly help power horticulture and greenhouse production but also be used to power irrigation pumps and cold stores. Furthermore, biogas has significant potential in Armenia, particularly in the agricultural sector. The country has abundant agricultural waste from the livestock and dairy sectors, such as straw, crop residues, and animal manure. This can be converted into biogas, fertilizers, or solid biomass for heating and electricity generation.

5. Growth in climate-smart food processing: Armenia's food processing sector is also experiencing rapid growth. While this can come with challenges (more highly processed foods with high levels of fats, sugars, and salts), it also offers significant export market growth, driven by healthy and environmentally friendly 'green products', using, for example, organic ingredients and manufacturing technologies using low-carbon sources of energy.

6. Tackling post-harvest food waste: Overall, there needs to be more analysis and monitoring to quantify food losses across the supply chain and identify hotspots for intervention. In general, financial support through subsidies, grants, and loans is needed to help farmers and cooperatives build on-site storage and infrastructure that enables timely delivery of food to important markets. Low-carbon cold storage infrastructure solutions must ensure fresh produce is delivered to markets before it perishes. There are also opportunities to support the development of processing units for drying, canning, or freezing surplus to extend life.

7. Agriculture extension services: Given Armenia's vulnerability to climate change and the need for the

transition to climate-smart technologies and techniques, there is an opportunity to provide agricultural extension services that can focus on educating farmers about climate-smart farming practices, such as drought-resistant crops, water conservation techniques, and alternative pest management systems. There are also opportunities to foster partnerships with the private sector, academic partners, and farmer cooperatives, supporting farmers in accessing better markets, inputs, and financial services (e.g. micro-finance).

8. Digitalization for better governance, transparency and enforcement: Achieving sustainable and effective governance in the agri-food sector requires updating and harmonising national laws, policies, and regulations to align with best practices and standards. Integrating digitisation into this process can significantly enhance efficiency and transparency by creating centralized electronic platforms for legal documentation, compliance tracking, and reporting. Advanced digital tools can also support real-time monitoring and enforcement, ensuring consistent application of standards and reducing gaps in compliance. Furthermore, digitized systems promote accessibility, enabling stakeholders to access updated regulations and submit necessary documentation online, fostering greater accountability and participation.

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Declarations of interest

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Enhancing Sustainable Agriculture through Innovative Soil Science Technologies

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ABSTRACT

Modern agriculture demands sustainable solutions to increase productivity while preserving environmental health. This study investigates the effectiveness of water-soluble combined fertilizers (WCF) in improving the growth, yield, and quality of winter wheat (Bezostaya 100) and potato (Marfona) under low-fertility soil conditions in Armenia. The WCF contains macro- and micronutrients, amino acids, and chelating agents, tailored to meet the nutritional needs of crops from germination to maturity. The experimental design included seed soaking and foliar application at key growth stages. Results revealed that WCF significantly increased field germination rates, enhanced root and shoot biomass, and improved crop yields compared to both control and conventional fertilizer treatments. A significant enhancement in wheat grain yield was observed, reaching up to 42.9% more than the control treatment. In the case of potatoes, production increased by 44.5%, accompanied by improved levels of dry matter and starch, and a noticeable decrease in nitrate concentration. These findings demonstrate that WCF can serve as a valuable component in sustainable nutrient management, enhancing crop performance and economic efficiency. The combination of seed priming and foliar feeding ensures nutrient availability throughout critical growth stages. This study supports the broader application of WCF in environmentally responsible agriculture and encourages further research into its benefits across diverse crops and soil types.

Introduction

Modern agriculture is facing unprecedented challenges due to the need for increased food production, resource conservation, and environmental protection. Green agriculture, a concept centered around sustainable practices, has gained prominence in addressing these challenges. This article delves into the significance of new technologies in soil science and their role in revolutionizing green agriculture (Naghdi, et al., 2022).

Soil, as the foundation of agriculture, plays a crucial role in plant growth and ecosystem health. With the global population projected to reach 9 billion by 2050, the demand for food will soar, necessitating a substantial increase in agricultural productivity. However, conventional farming practices have often led to soil degradation, loss of biodiversity, and excessive use of chemicals, impacting long-term sustainability. The integration of new technologies in soil science offers promising solutions to mitigate these issues (Yeritsyan, 2024).

One such technology is precision agriculture, which employs various tools like satellite imagery, sensors, and data analytics to assess soil health and optimize resource use. These innovations aid in precisely targeting irrigation, fertilization, and pesticide application, minimizing waste and environmental harm. Additionally, the use of drones and remote sensing helps monitor crop health and detect potential soil degradation, allowing farmers to take timely corrective measures (Trukhachev, 2024).

Advancements in soil sensors have revolutionized real-time monitoring of soil parameters such as moisture content, nutrient levels, and pH. These sensors provide farmers with valuable insights, enabling them to make informed decisions about irrigation and fertilization, ultimately reducing water and nutrient wastage. Moreover, the advent of low-cost sensors has democratized access to these technologies, benefiting small-scale farmers as well (Yeritsyan, 2024).

Cover crops and agroforestry are other eco-friendly practices gaining traction in green agriculture. These techniques improve soil structure, enhance water retention, and foster nutrient cycling, contributing to long-term soil health. Combined with innovative soil-science-driven technologies, they create a synergistic approach that optimizes yields while preserving the environment (Beglaryan, 2025).

Soil microbiology, a fascinating field within soil science, has uncovered the intricate relationships between microorganisms and plant growth. Microbial activity plays a key role in improving nutrient efficiency, controlling plant diseases, and maintaining good soil structure. Incorporating microbial-based biofertilizers and soil conditioners into agricultural practices not only reduces reliance on synthetic inputs but also promotes soil biodiversity (Gasparyan, 2023; Gasparyan, 2025; Jhangiryan, 2023; Jhangiryan, 2024; Larionov, 2024).

Furthermore, the concept of 'smart soils' is emerging, involving the modification of soil properties through the addition of organic amendments or engineered materials. These changes improve the soil's ability to hold moisture, capture carbon, and provide a steady supply of nutrients. By tailoring soil characteristics to specific crops and regions, smart soils contribute to increased resilience and productivity (Markad, 2024).

In conclusion, the integration of green agriculture and innovative soil science technologies holds immense promise for sustainable food production. The adoption of precision agriculture, soil sensors, and soil microbiology-based interventions is reshaping farming practices, optimizing resource use, and reducing environmental impact. As the world faces mounting agricultural challenges, harnessing these advancements will be essential for ensuring food security without compromising the planet's health. Through collaborative efforts between researchers, policymakers, and farmers, this paradigm shift in agriculture can pave the way for a greener and more resilient future.

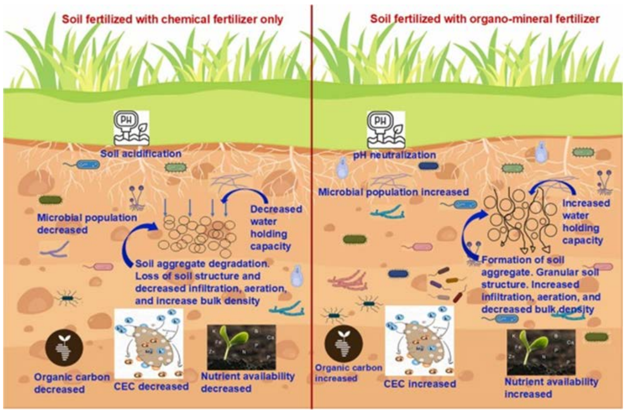

Figure. Overall effect of OMF on soil properties.

Materials and methods

The study aimed to evaluate the effect of a newly developed water-soluble combined fertilizer (WCF) on seed quality, plant growth, and yield in cereal and vegetable crops, specifically winter wheat (Bezostaya 100) and potato (Marfona). The experiments were conducted under field conditions with soils of low fertility, particularly deficient in available nitrogen and phosphorus.

For winter wheat, the experimental design included the following treatments:

1. Control (no fertilization),
2. Background application: $N_{30}P_{90}K_{60} + N_{75}$,

3.Background + water-soluble combined fertilizer (seed soaking before sowing),

4.Background + water-soluble combined fertilizer (seed soaking + foliar feeding during the tillering stage)

For potatoes, the experiment was conducted on mountain brown forest soils, characterized by low levels of available nitrogen, phosphorus, and potassium. The treatment scheme included:

1. Control (no fertilization),

2.Background application: $N_{60}P_{90}K_{90} + N_{60}$,

3.Background + water-soluble combined fertilizer (tuber soaking before planting),

4.Background + water-soluble combined fertilizer (tuber soaking + three foliar applications during the growing season)

Numerous observations and measurements were conducted during the experiments, which revealed the effect of the complex fertilizer on seed germination, plant growth, yield, and the nutritional and planting quality of the crops (grain). An assessment of field germination rates and germination energy under the influence of complex fertilizer was conducted by marking four 0.25 m² sampling areas within various zones of each experimental field on day three of sprouting. The number of germinated seeds in these plots was counted, and on the 7th day of germination, the total number of germinated seeds was recorded. Based on this data, and considering the planted seed density (500 viable seeds per 1 m²), the seed germination rate and germination energy were calculated (Arinuskina, 1962; Dospekhov, 1973).

Description of the applied organomineral fertilizer: The complex fertilizer is a multifaceted compound, the composition of which has been developed based on the fertility status of soils in Armenia and the nutrient requirements of crops starting from the seed germination phase. The fertilizer dissolves well in water and contains macro elements (nitrogen in the form of NH_2^- and NO_3^- ions, phosphorus, potassium, sulfur, iron) and micronutrients (*B, Zn, Mn, Mo, Cu, Co*), amino acids, and complex-forming agents. The fertilizer is applied as a water solution, with a concentration of 0.35-0.40%, through foliar feeding and drip irrigation, 2-3 times during the vegetative stage. It can be combined with insecticides and fungicides that do not contain copper.

The research was conducted at the laboratory of "Soil Science, Agrochemistry and Amelioration Scientific Center after H. Petrosyan" Branch of Armenian National Agrarian University Foundation.

Results and discussions

The use of fertilizers plays a crucial role in the sustainable agricultural practices in the Republic of Armenia, due to the relatively low fertility of the available soils. Our studies have shown that, in addition to the primary mineral fertilizers, the application of fertilizers containing macro and micronutrients, as well as bioactive substances, is significant for increasing the yields of winter wheat and potatoes. These fertilizers are most effective when applied through seed soaking and foliar feeding during the vegetative stage, resulting in noticeable economic efficiency. The synthesized water-soluble complex fertilizer has contributed to an increase in the field germination rate and germination energy of autumn wheat seeds, enhanced root system development, and improved yield (Table 1).

Table 1. Effect of Fertilizers on the Growth and Yield of Autumn Wheat (Bezostaya 100)

Variants	Field germination of seeds, %	Seed germination energy, %	Fresh weight of shoot biomass, 6 plants, 20 days after treatment, g	Grain yield, c/ha
Control (no fertilization)	78.6-84.9	71.4-79.1	1.13	31.2-35.4
Background application: $N_{30}P_{90}K_{60} + N_{75}$	79.0-84.5	71.6-79.5	1.35	40.1-43.2
Background + water-soluble combined fertilizer (seed soaking before sowing)	87.5-91.5	88.5-95.1	2.41	44.9-50.6
Background + water-soluble combined fertilizer (seed soaking + foliar feeding during the tillering stage)	-	-	-	49.3-55.1

Table 2. Effect of Fertilizers on Potato Yield and Tuber Quality Indicators

Variants	Straw yield, c/ha	Dry matter, %	Starch, %	Nitrate content, mg/kg	Leaf infestation by Colorado potato beetle, %
Control (no fertilization)	249-255	18,6	13,8	51,0	15,0
Background application: $N_{30}P_{90}K_{60} + N_{60}$	293-300	18,7	14,5	52,0	16,0
Background + water-soluble combined fertilizer (tuber soaking before planting)	305-312	19,4	14,9	50,0	14,0
Background + water-soluble combined fertilizer (tuber soaking + three foliar applications during the growing season)	328-361	21,8	17,7	27,0	0

In experiments with winter wheat, the field germination of seeds was highest when applying the combined water-soluble combined fertilizers (WCF), ranging from 78.6% to 84.9%, while the control and background treatments showed germination rates of 74.1% to 80.2%. WCF also resulted in increased yield, which, compared to the control, was on average 15.2 c/ha (42.9%), and compared to the background, it was 7.3 c/ha (16.8%). Water-soluble combined fertilizers (WCF) improved both the chemical composition and the seed quality. For example, seed germination in laboratory conditions ranged from 95.5% to 98.6%, and germination energy was between 87.6% and 90.5%, while in the control, these indicators were 85.1% to 87.6% and 61.6% to 74.6%, respectively. In the $N_{30}P_{90}K_{60}+N_{75}$ variant, germination ranged from 84.5% to 90.3%, and germination energy from 68.7% to 78.4% (Table 1, Diagram).

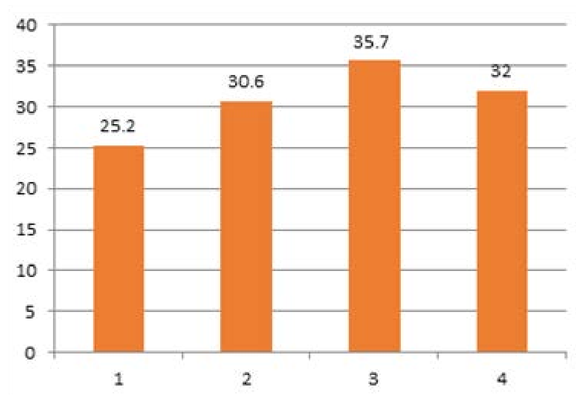

Diagram. The effect of water-soluble combined fertilizers on the yield of wheat, c/ha *Variants:*1.Control (no fertilization), 2.Background application: $N_{30}P_{90}K_{60} + N_{75}$, 3.Background+water-soluble combined fertilizer (seed soaking before sowing), 4.Background+water-soluble combined fertilizer (seed soaking + foliar feeding during the tillering stage).

The soil analysis revealed a humus content of 3.12%, a neutral pH of 7.3, and available nutrient concentrations measured at 3.14 mg of mobile nitrogen (N), 1.58 mg of phosphorus pentoxide (P_2O_5), and 47.8 mg of potassium oxide (K_2O) per 100 grams of soil sample.

Similar effects of the water-soluble combined fertilizer (WCF) were observed in the potato experiment. Tuber yields following WCF treatment varied between 328 and 361 centners per hectare, whereas the background treatment resulted in yields ranging from 293 to 300 c/ha, and the control plots produced between 249 and 255 c/ha. The content of dry matter and starch in the tubers increased significantly, while the nitrate content decreased. The spread of the Colorado potato beetle was completely prevented, which we attribute to the noticeable hardening of the leaves during foliar feeding with the fertilizer (Table 2). At the molecular level, the genetic mechanism behind certain beneficial traits in potatoes was studied using the RFLP molecular marker (Restriction Fragment Length Polymorphism). Restriction enzymes EcoRI, ScaI, and PvuI were employed to perform DNA cleavage. Mapping revealed that the gene regulating starch content is located in a recognizable site of the EcoRI restriction enzyme.

Conclusion

The conducted research demonstrates the significant positive impact of water-soluble combined fertilizers (WCF) on the germination, growth, and productivity of both winter wheat and potatoes. The application of WCF, through seed soaking and foliar feeding during key vegetative stages, led to enhanced field germination rates, improved plant vigor, increased dry matter and starch content, and reduced nitrate accumulation. Notably, the resistance to pests such as the Colorado potato beetle improved, which may be attributed to changes in leaf structure following foliar treatment. These findings highlight the potential of integrated nutrient management strategies involving macro- and micronutrients, amino acids, and bioactive compounds to sustainably boost crop yields and improve produce quality.

WCF should be adopted as part of integrated nutrient management, especially in low-fertility soils, to improve seed quality and crop productivity.

It is recommended to apply WCF through seed/tuber soaking before planting and repeated foliar applications (2–3 times) during the growing season to achieve optimal results.

Local production and accessibility of such fertilizers should be encouraged to support smallholder and large-scale farmers in achieving sustainable agricultural outcomes.

Further research should be conducted across different soil types and crop varieties, including molecular studies, to optimize fertilizer compositions and understand the genetic mechanisms behind observed agronomic improvements.

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Exploring the Mechanical Composition of the Armenian Indigenous Grape Varieties "Mormor" and "Chragi Yerkser"

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ABSTRACT

This research explores the mechanical composition of Mormor and Chragi Yerkser, rare and unexplored grape varieties indigenous to Armenia. By meticulously examining physical attributes, the research aims to uncover their unique characteristics and potential implications. Investigating these varieties not only enhances knowledge about their cultivation and potential use but also contributes to biodiversity by preserving and promoting lesser-known Armenian grape varieties. This supports the diversity within Armenia's viticultural landscape and fosters resilience in grape production. The findings are intended to facilitate knowledge exchange among growers and researchers, while ultimately supporting the diversification, sustainability, and competitiveness of Armenia's wine industry by integrating Mormor and Chragi Yerkser as valuable genetic resources into differentiated product lines.

Introduction

Armenia's diverse climate and varied terroir play a pivotal role in shaping its profound viticultural legacy, leading to a broad spectrum of grapevine genetic diversity. This biodiversity extends beyond natural adaptations, capturing centuries of deliberate and skilled cultivation by Armenian vintners. Numerous studies have identified Armenia as an essential center for both wild and cultivated grape varieties, with many local varieties uniquely adapted to their environments (Margaryan, et al. 2025; Margaryan, et al., 2021; Margaryan, et al., 2019). The melding of native grape varieties with the unique terroir creates a valuable genetic bank that holds significant, untapped potential for advancing viticulture and winemaking practices.

The exploration of these genetic resources is vital for the development and expansion of Armenia's wine industry. The study of indigenous grape varieties, such as Mormor and Chragi Yerkser from Armenia, offers valuable insights into the unique aspects of local oenology. These grape varieties, which are neglected and relatively unknown, possess unique characteristics shaped by Armenia's distinct climatic and geological environments. Grapes are the primary raw material in winemaking, and the quality of the final product is closely linked to the quality of the fruit used (Ribereau-Gayon, 2006). A key factor in assessing grape quality is the mechanical composition of the berry - specifically, the ratio of bunches, skins, pulp, juice, and seeds. This composition is determined through mechanical analysis and is influenced by grape variety, environmental conditions, soil and climatic conditions, and the degree of ripeness (Sutugina, et al., 2018; Grigoryan, et al., 2024). The study of mechanical composition is a part of uvology, which focuses on the structural components and mechanical properties of grapes and berries and is considered a specialized section of ampelography. Such analysis not only reveals the characteristic structure of a grape variety but also plays a critical role in determining its technological potential. It enables to identify specific varieties, evaluate their optimal use - whether for fresh consumption, winemaking, or raisin production - and determine their stage of technical maturity (Prostoserdov, 1935; Zaushintsena & Zerenkova, 2012; Grigoryan, et al., 2024). These attributes, though influenced by vintage variability, are critical for determining wine yield and quality (Chen, 2018; Rogiers, 2022).

A deeper understanding of the mechanical composition of Armenia's indigenous grape varieties can support their strategic use across various industrial sectors while contributing to the development of distinctive products, progress in science and advancement of national efforts in agricultural sustainability and crop diversification.

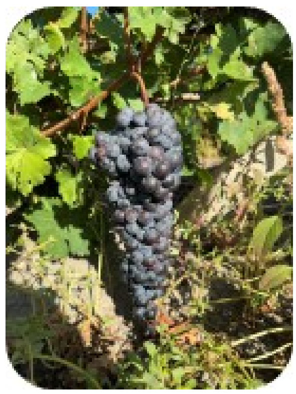
Materials and methods

The mechanical composition of the Mormor and Chragi Yerkser grape varieties was systematically investigated during the 2023-2024 growing seasons in the Armavir region. The vineyards were established with a planting density of 3x1.5 m, using a trunkless fan training system. Standard viticultural practices, including irrigation and conventional cultivation methods, were employed during the cultivation of the vineyard.

According to ampelographic records, Mormor, also known locally as "Ampaguyn Khaghogh" and "Mokhraguyn Milagh" is a rarely spread indigenous variety of grape primarily used for both table consumption and wine production. According to the records it is typically found as single vines within the older vineyards of the Yeghegnadzor region. Currently, there is a lack of data regarding its resistance to diseases and adverse climatic conditions. (Melyan, et al., 2019). Considering the ampelographic characteristics Mormor is of interest for use in both fresh consumption and in the production of wine.

In the ampelographic records Chragi Yerkser is classified as a dual-purpose, late-maturing grape variety. It is found in limited quantities, either as single vines or vine-groups, within the ancient vineyards of the Meghri district. According to the records this grape variety exhibits partial resistance to common fungal diseases such as mildew and oidium but remains susceptible to damage from the European grapevine moth (Lobesia botrana Den. e. Schiff). Its resistance to cold temperatures is notably weak. (Melyan, et al., 2019; Lucchi & Scaramozzino, 2018). Considering the ampelographic characteristics Chragi Yerkser is of interest for use in both fresh consumption and in the production of wine.

The mechanical composition of the grape bunches was analyzed using the Prostoserdov methodology, which involved measuring the mass of the bunches, individual berries, and the number of berries per bunch (Prostoserdov, 1935). Additionally, the number and mass of seeds, as well as the masses of the berry skins and stems, were determined (Grigoryan, et al., 2024). The measurements were made in laboratory conditions. The collected data facilitated analysis of the bunch structure and composition of these indigenous grape varieties, highlighting their unique phenotypic characteristics and potential oenological significance.

Picture. Mormor on the left, Chragi Yerkser on the right.

Results and discussion

The results of analysis of the mechanical composition of the Armenian indigenous rare grape varieties Mormor and Chragi Yerkser, presented in Table 1, reveal notable bunch morphology. Chragi Yerkser exhibits significantly longer and heavier bunches, with an average length of 312.6 mm, width of 114.55 mm, and bunch mass of 649.80 g. Mormor presents a shorter bunch length of 163.0 mm, width of 125.17 mm, and lower average mass of 295.98 g.

In terms of berry count and mass, Chragi Yerkser contains 235 berries per bunch with a total berry mass of 630.0 g, Mormor holds 131 berries weighing 285.36 g. Chragi Yerkser has a dense bunch structure, with the stem and skin masses registering 18.02 g and 90.30 g. In the case of Mormor, the mass is 10.02 g for the stem and 41.24 g for the skin, respectively. Furthermore, seed mass is 38.92 g in Chragi Yerkser and 14.08 g in Mormor.

The structural characterization of grape bunches was assessed based on parameters such as average bunch mass, number and size of berries, the proportion of berries within the bunch, and the bunch structure index. The structural index, defined as berry-to-bunch mass ratio serves as an indicator of how efficiently the bunch is used. According to Chausov, a higher structural index correlates with better bunch use efficiency and higher potential yield (Chausov, 2015).

Bunch structure analysis is presented in Table 2. The berry to bunch ratio for both varieties was as follows: 96.41% for Mormor and 96.95% for Chragi Yerkser, suggesting high fruit density. However, Chragi Yerkser had a slightly lower stem proportion of 2.77% compared to Mormor's 3.38%.

The structural index, which reflects the effective use of the bunch, was considerably higher for Chragi Yerkser (34.97) compared to Mormor (28.48). This suggests that Mormor has strong potential for use in winemaking, as it may offer higher relative yield per unit mass.

The berries index, which reflects the quantity of berries in 100g bunch, was considerably higher for Mormor (44.20) compared to Chragi Yerkser (36.19).

Table 1. Mechanical composition of the studied grape varieties*

Grape variety	Bunch length, mm	Bunch width, mm	Bunch mass, g	Number of berries in the bunch, n	Berries mass, g	Stem mass, g	Skin mass, g	Seed mass, g	Hard residue mass, g	Berries pulp + juice, g
Mormor	163.00	125.17	295.98	131	285.36	10.02	41.24	14.08	65.33	230.65
Chragi Yerkser	312.60	114.55	649.80	235	630.00	18.02	90.30	38.92	147.24	502.56

Table 2. Bunch structure of the studied grape varieties*

Grape variety	Average bunch mass, g	Number of berries in the bunch, n	Berries mass, g	Berries ratio to the bunch, %	Stem mass, g	Stem ratio to the bunch, %	Bunch structure index	Berries index
Mormor	295.98	131	285.36	96.41	10.02	3.38	28.48	44.20
Chragi Yerkser	649.80	235	630.00	96.95	18.02	2.77	34.97	36.19

*Composed by the authors.

Table 3. Berry composition of the studied grape varieties*

Grape variety	Mass, g		Number of seeds in 100 berries, n	Mass of 100 berries, g			Berry composition index
	100 berries	100 seeds		Seed	Skin	Pulp + juice	
Mormor	231.37	7.58	142	10.76	31.52	189.09	6.00
Chragi Yerkser	335.50	5.93	279	16.55	38.40	280.55	7.31

Table 4. Bunch composition indicators*

Grape variety	Percentage composition of individual parts in the bunch, %					Bunch composition index
	Stem	Skin	Seed	Hard residue	Pulp + juice	
Mormor	3.38	13.93	4.76	22.07	77.93	3.53
Chragi Yerkser	2.77	13.90	5.99	22.66	77.34	3.41

*Composed by the authors.

The fewer the number of berries in a 100g bunch, the larger they are.

Analysis of berry composition presented in Table 3 revealed that Chragi Yerkser berries were large and heavy. The mass of 100 berries was 335.50 g for Chragi Yerkser. It also contained a great number of seeds - 279 seeds per 100 berries, with a correspondingly higher seed mass of 16.55 g. Additionally, the skin and pulp + juice mass per 100 berries were high in Chragi Yerkser, respectively 38.40 g and 280.55 g. Of particular importance is the berry composition index, which is determined by the ratio of berry pulp + juice to skin mass, a marker of internal composition balance. In Chragi Yerkser it was 7.31.

For Mormor, the mass of 100 berries was 231.37 g; the number of seeds was 142 with a seed mass of 10.76 g. Additionally, the skin and pulp + juice mass per 100 berries were respectively 31.52 g and 189.09 g. The berry composition index for Mormor variety was 6.00, highlighting its juicy berry structure.

The ratio of berries to stem in the bunch is also important for grape processing. The structure of the grape is characterized by the composition of its components: stem, skin, seeds, pulp, juice and their percentage distribution, which varies depending on the grape variety, degree of ripeness, ecological factors, and natural climatic conditions.

Table 4 presents the proportional composition of bunch components.

According to the results of the research, the stem content in the bunches of Mormor was 3.38%. The skin of the Mormor variety made up 13.93% of the bunch. The content of seeds in the berries was 4.76%. The pulp + juice fraction in Mormor was 77.93%. The bunch composition index reflects the ratio of pulp + juice to skeletal mass. The higher the pulp + juice content, the greater the ratio of juice and pulp to skeletal mass, the higher the bunch composition index, and consequently, the greater the yield (Troshin, 2017). The bunch composition index for Mormor was 3.53. This suggests that Mormor allocates a greater proportion of its mass to juice-bearing and structural tissues, which are critical for wine yield.

The stem content in the bunches of Chragi Yerkser was 2.77% and the skin was 13.90%. The content of seeds in the berries was 5.99%. The pulp + juice fraction in Chragi

Yerkser was 77.34%. The bunch composition index was 3.41.

The results indicate that Mormor and Chragi Yerkser, due to their high juice volumes, are particularly well-suited for applications where maximizing yield per bunch is essential. Both varieties demonstrate a high bunch composition index and an efficient structural mass distribution, highlighting their potential value in wine production, where optimizing juice extraction relative to bunch mass is one of the key factors. Moreover, the enhanced efficiency observed in both varieties may contribute to lower production costs and greater sustainability in winemaking, positioning them as a particularly advantageous variety for modern viticultural practices.

Further research is recommended to evaluate how these mechanical traits influence processing performance, sensory characteristics of derived products, and adaptation to varying agro-climatic conditions.

Conclusion

This research presents the first detailed assessment of the mechanical composition of two rare and less common indigenous Armenian grape varieties: Mormor and Chragi Yerkser, revealing distinct morphological and compositional characteristics. Ampelographic descriptions continue to play a fundamental role in identifying grape varieties, with uvological analysis forming an essential initial stage in researching and documenting lesser-known cultivars.

Chragi Yerkser exhibited high values for bunch size, berry count, and absolute juice mass. Both Mormor and Chragi Yerkser demonstrated elevated bunch composition indices - 3.53 and 3.41, respectively - indicating an efficient internal structure with a higher proportion of pulp and juice relative to total bunch mass. This structural efficiency suggests that these varieties could offer a potential and notable advantages for wine production, including increased juice yield per unit of raw material and potentially reduced processing costs.

The mechanical analysis of Mormor and Chragi Yerkser enriches the current understanding of these underexplored varieties and underscores their potential for oenological applications. These findings emphasize the importance of considering not only total yield but also internal structural composition when evaluating grape varieties for technical and industrial use.

Ultimately, Mormor and Chragi Yerkser represent valuable genetic resources that can enrich and support the development of Armenian viticulture. Their unique mechanical properties support their integration into differentiated product lines, contributing to the diversification, sustainability, and competitiveness of the local vine and wine industry. Future research should prioritize expanded geographical sampling and pilot-scale vinification trials to fully unlock their potential uses, particularly the oenological potential of these indigenous varieties.

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Measuring the Climate Resilience of Smallholder Farmers in Lori Province

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ABSTRACT

Armenia's main risks from climate change are increasing temperatures and variability in precipitation. The agricultural sector will be heavily impacted by these climate risks. Climate projections estimate the agricultural sector will experience changes in growing season, exacerbated soil degradation, and erosion due to extreme and unpredictable weather, unfavorable growing conditions, increased water demand, and reduction in yields. This research study aimed to 1) develop a tool to measure the climate resilience of smallholder Armenian farmers in Lori Province, 2) use the tool to measure climate resilience of smallholder farmers throughout Lori, and 3) use key findings to provide farmers with climate-smart recommendations to increase climate resilience specifically relating to soil health, food security, financial stability, and livelihoods. Recent research reveals that smallholder farmers in Lori Province are largely unprepared to cope with escalating impacts of the climate crisis. Despite their vulnerability, rural women farmers demonstrate a relatively higher level of climate resilience and show greater openness to adopting innovative and climate adaptive agricultural practices. The study determined the easiest, most cost-effective solutions to increase climate resilience for smallholder farmers through interviews with farmers using a set of 24 environmental, economic, and social indicators. Solutions include the following: reduced tillage practices, introduction of cover crops, use of higher quality seeds, implementation of water management practices, increased access to financial opportunities including external markets, and increased access to training and knowledge particularly around soil health.

Introduction

Climate resilience is defined as the ability to prepare, adapt, and recover from climate risks like floods, heatwaves, and droughts (Center for Climate and Energy Solutions (C2ES), 2019). Going beyond mitigation and adaptation, climate resilience is the ability to not only withstand but recover from climate risks. Armenia's main risks from the climate crisis are increasing temperatures and variability in precipitation (Morin & Bucher, 2021). By 2090, temperatures in Armenia are expected to increase by 35-40% more than the global average (Morin & Bucher, 2021). Projected shifts in precipitation patterns across Armenia will vary by region and elevation. Nonetheless, a general decline in average monthly precipitation is anticipated, alongside more frequent extreme rainfall events. These trends, combined with the retreat of the Caucasus glaciers and inadequate water management, are expected to result in more frequent droughts. Armenia's current adaptive capacity is classified as moderate. According to the ND-GAIN Index (2025), the country ranks 50th out of 118 nations, indicating a relatively favorable position to face climate challenges, though significant improvements are still needed. In terms of disaster risk, Armenia ranks 113 out of 191 countries in the INFORM Risk Index, placing it at medium risk to humanitarian disasters and crises with a high risk from earthquakes, droughts and epidemics (INFORM, 2025).

The projected increase in severity of the climate crisis in combination with Armenia's low national adaptive capacity will heavily impact the sector. Climate projections estimate Armenia's agriculture sector will experience changes in growing season, exacerbated soil degradation, and erosion due to extreme and unpredictable weather, unfavorable growing conditions, increased water demand, and reduction in yields for high-value crops like grains and vegetables (Ahouissoussi, et al., 2014; World Bank, 2025). The climate crisis will have the largest impact on the agriculture sector by reducing water availability (Ahouissoussi, et al., 2014). Yields for all crops except tomatoes, wheat, and watermelon grown in mountainous regions are expected to decline (Ahouissoussi, et al., 2014). A reduction in water availability will directly impact crop yields, food and water security, and farmer livelihoods.

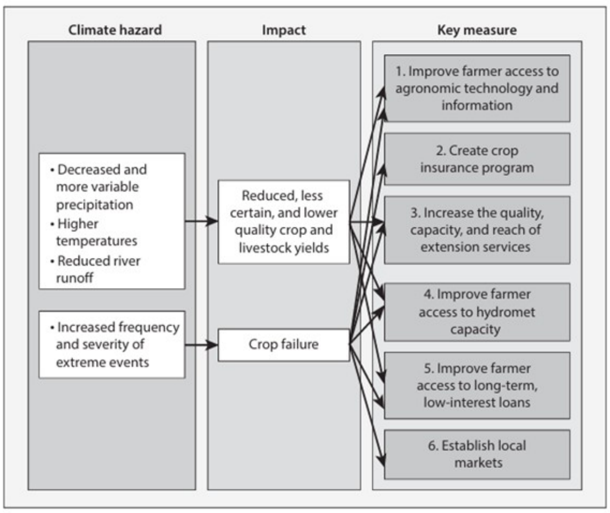

Figure 1. Armenia›s climate change risks and recommended adaptation measures at the national level for the agriculture sector *(Ahouissoussi, et al., 2014)*.

The agriculture sector remains a cornerstone of Armenia's economy, employing 22% of the labor force. However, its economic contribution is limited, accounting for just 10.37% of the national GDP, and it remains the least remunerated sector in terms of wages. (Statista, 2025; FAO, 2020). The majority of Armenia's farmers live and work in rural communities, with 45% of those employed in rural Armenia engaged in agriculture, compared to 3% in urban Armenia. Much of rural Armenia is poor, with a 22.8% poverty rate as of 2022 (ARMSTAT, 2022; ARMSTAT, 2023). The informal sector is overrepresented in the agricultural labor force, with 70% of the informal sector engaged in agriculture. Women and children will be most heavily impacted by the climate crisis (i.e. changes in growing season, droughts, floods), as well as members of Armenia's population within the lowest level of poverty - smallholder farmers (World Bank, 2025). Challenges for smallholder women farmers include extreme weather, water insecurity, land abandonment, limited access to financing, unequal labor distribution, limited access to knowledge and training, high risk inherent in subsistence farming, national security risks, and outmigration (FAO, 2020; Huyer, et al., 2021). 99% of all farms in Armenia are family farms, with close to 90% of all Armenian farmers owning or cultivating on less than 2 hectares of land (FAO, 2020). On average, these two hectares are split between three different land plots averaging 0.41 hectares in size (FAO, 2020). Plots are disjointed in location and are often up to 15 kilometers away from each other (FAO, 2020). This land fragmentation makes it difficult for smallholder farmers to have high enough production volumes to sell their goods at larger markets, thus contributing to consistent poverty rates. Rural women farmers lack access to financial security, resources, education, and training, making them the most susceptible demographic to the climate crisis as well as the least prepared to adapt (Kristjanson, et al., 2017; FAO, 2020).

The Ministry of the Economy's national strategy for the agriculture sector for 2020-2030 focuses on economic development, profitability, and market competitiveness but includes climate adaptation foci like water management and irrigation, reduced vulnerability from drought and hail, increased efficiency and optimization, disease management, knowledge sharing, training on modern agriculture technologies, youth engagement, and encouragement of organic practices (Ministry of the Economy, 2020). Targeted goals to increase climate resilience like restoration of degraded farmland, reduction of desertification, and improvement in adaptive capacity to floods, frost, and heatwaves are missing from the national strategy for agriculture. This strategic gap is exacerbated by existing knowledge gaps nationally relating to climate resilience at the regional and farmer level. While the agriculture sector's climate mitigation and adaptation capacity has been examined on the national level, an understanding of climate resilience at the regional and farmer level is still lacking. The focus of this research study was to bridge the knowledge gap as it relates to smallholder farmer climate resilience specifically in Lori Province by identifying which climate risks farmers are the least prepared for and where capacity-building at the regional and farmer level is most needed to increase climate resilience. The goals of the study were 1) develop a tool to measure the climate resilience of smallholder farmers in Lori Province, 2) use the tool to measure climate resilience of smallholder farmers throughout Lori, and 3) use key findings to provide farmers with climate-smart recommendations to increase climate resilience.

The intended outcomes of the research study are to increase climate farmer climate resilience and align national and regional strategic goals, policies, investments, and agricultural initiatives with identified needs on-the-ground.

Materials and methods

A "Farmer Climate Resilience Toolkit" was developed to measure the climate resilience of smallholder farmers in Lori. The toolkit uses 24 environmental, economic, and social indicators, interview questionnaire, and a scoring rubric to identify climate resilience at the farm level. The following methodology was used to develop the toolkit:

1. Identify relevant climate risks to smallholder farmers in Lori Province.
2. Identify a set of indicators to measure farmer resilience to identified climate risks.
3. Develop a "Farmer Climate Resilience Assessment" (FCRA) to interview farmers and document their current climate resilience.
4. Develop a "Farmer Climate Resilience Score" (FCRS) to measure and compare the climate resilience of smallholder farmers.

The full Farmer Climate Resilience Toolkit including the Farmer Climate Resilience Assessment, Farmer Climate Resilience Scoring tool, and interview questionnaire can be found, downloaded, and used at the Climate Hub Armenia website (https://www.climatehubarmenia.com/resilience-toolkit).

Identify Climate Risks

This research study used the IPCC AR6 definition of "risk" as a combination of hazards, exposure, and vulnerability to identify relevant climate risks to smallholder farmers in Lori (Figure 2) (Reisinger, 2021). The identified climate hazards were hail, flooding, drought, frost, and extreme temperatures (Ahouissoussi, et al., 2014; Morin & Bucher, 2021).

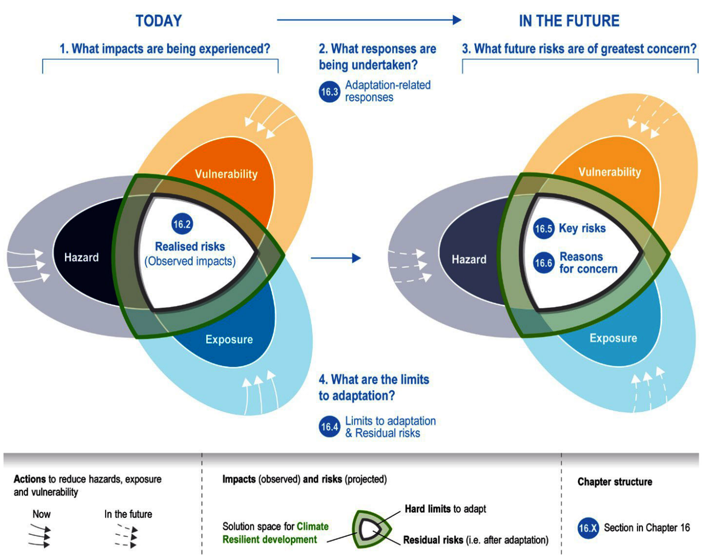

Figure 2. Illustration of risk as a combination of hazards, exposure, and vulnerability. The green areas at the center of the propeller diagrams indicate the ability for solutions to reduce risk, up to certain adaptation limits, leaving the white residual risk (or observed impacts) in the center. The shading of the right-hand-side propeller diagram compared with the non-shaded one on the left reflects some degree of uncertainty about future risks *(O'Neill, et al., 2022)*.

Identify Indicators to Measure Climate Resilience

Verstand et al.’s farm-level indicators for resilience to climate change stressors, Dubby›s “Resilience Design in Smallholder Farming Systems Measurement Toolkit”, and Pasa Sustainable Agriculture›s “Soil Health Benchmark Study” for 2021 were used as primary examples to select a set of indicators to measure a farmer climate resilience and for overall assessment design (Verstsand, et al., 2021; Dubby, 2019; Egan & Nawa, 2021). Twenty-four (24) total environmental, economic, and social indicators were chosen to assesss farmer climate resilience. Fourteen (14) environmental indicators were selected within the subsectors of soil health, soil cover, soil erosion, soil fertility, water conservation, biodiversity, and weather protection, two (2) economic indicators, and eight (8) social indicators (Verstsand, et al., 2021).

Indicators were chosen based on the following criteria (Figure 4):

1. Research-backed connection to an increase in climate resilience. All indicators have a direct connection to climate resilience. This means that when farmers show improvements in any of the selected indicators, there is a clear reduction in a farmer›s vulnerability to climate risks backed by research studies.
2. Relevance to identified climate risks in Lori Province.
3. Feasibility and ease of measurement within the research parameters.

The first section of the FCRA includes instructions for in-field soil sampling and soil testing. Due to research limitations, soil sampling and testing was not done but is recommended for future research studies to gain a more holistic understanding of a farmer’s climate resilience.

Develop Farmer Climate Resilience Assessment (FCRA)

The chosen indicators were used to develop Farmer Climate Resilience Assessment to interview farmers and document their current climate resilience. A set of interview questions were designed for each indicator for data collection. This FCRA is designed to understand a smallholder farmer›s baseline climate resilience at the time of the interview and is designed to be repeated once a year. Repeating the FCRA once a year will allow researchers and farmers to compare results year over year, track progress or lack thereof in increasing climate resilience, and help provide farmers with personalized recommendations on how to increase resilience based on farm-level data. The FCRA questions were written in English and translated into Armenian. In instances where direct translations from English to Armenian were unavailable, multiple or alternative modes of questioning were included to ensure full understanding by the interviewee in Armenian. The full FCRA and interview quesionnaire can be found at https://www.climatehubarmenia.com/resilience-toolkit.

Develop Farmer Climate Resilience Score (FCRS)

A scoring system was developed to measure and compare the climate resilience of smallholder farmers. Each FCRA indicator has a set of measurement parameters that have been set in the Farmer Climate Resilience Scoring tool (Figure 3). These measurement parameters are equal to 1, 2, 3, or 4 points. 1 point equals Very Low Resilience, 2 equals Low Resilience, 3 equals Medium Resilience, and 4 equals High Resilience. Farmers are interviewed using the developed questionnaire for the FCRA to collect data and then score climate resilience using the scoring tool. The tool is used to generate a final “Farmer Climate Resilience Score” (FCRS). The FCRS the sum of points from all indicators and provides a baseline understanding of a smallholder famer’s climate resilience. Total points and equivalent scores are as follows: 24 total points equals Very Low Resilience, 25-48 total points equals Low Resilience, 49-72 total points equals Medium Resilience, and 73-96 points equals High Resilience (Figure 4). The farmer climate resilience scoring tool additionally breaks down points by environmental, economic, and social indicators, with further breakdowns for all environmental indicators within the subsectors of soil cover, soil erosion, soil fertility, water protection, biodiversity, and weather protection.

Farmer Climate Resilience Indicator List			
Indicator #	Descripction	Measurement	FCRS Points
Environmental Indicators			
1	Months (#) of living cover	6	3
2	Percent (%) of the field with living cover during the RA	100%	
	Yearly percentage (%) of the field with living cover	50%	3
3	Number (#) of different cover crops used	2	3
4	Number (#) of different mulches used	2	3
5	Number (#) of different trees/shrubs on the farm	2	3
6	Percent (%) of the farm with signs of erosion	25%	3
7	Number (#) nitrogen fixing crops	2	3
8	Number (#) of different fertilizers and pesticides used	2	3
9	Number (#) of soil amendments used	2	3
10	Number (#) of different water collection methods used	2	3
11	Percentage (%) of the farm that is irrigated	.	4
12	Number (#) of different crops grown	-	4
13	Number (#) of different pollinator friendly plants, trees, shrubs, etc.	2	3
14	Number (#) of different weather protection methods used	2	3
Economic Indicators			
15	Number (#) of income sources	2	3
16	Farmer dependence on external inputs (#)	1	3
Social Indicators			
17	Percentage (%) of crops covered by insurance	50%	3
18	Number (#) of trainings attended by farmer	2	3
19	Number (#) of social networks farmer is part of	2	3
20	Access to knowledge resources (#)	2	3
21	Gender distribution of labor and pay (# points)	3	3
22	Percent (%) of the land owned outright	50%	3
23	Gender distribution of decision making (# points)	3	3
24	Dependence on third parties for supply chain (%)	50%	3

Figure 3. Full farmer climate resilience indicator list for an example farmer. The indicator list includes the indicator number (#), description, measurement, and total Farmer Climate Resilience Score (FCRS) points for the Farmer Climate Resilience Scoring tool.

Final Farmer Climate Resilience Score (FCRS) Guide		
Total Points	FCRS	Description
24	1	Very Low Resilience
25-48	2	Low Resilience
49-72	3	Medium Resilience
73-96	4	High Resilience

Figure 4. Final Farmer Climate Resilience Score (FCRS) scoring guide for Very Low Resilience *(score = 1)*, Low Resilience *(score = 2)*, Medium Resilience *(score = 3)*, and High Resilience *(score = 4)*

The scoring system was developed for use in Excel and can be found at https://www.climatehubarmenia.com/resilience-toolkit.

Assessment Participant Outreach

Assessment participant outreach was done through local Armenian organizations, cold calling, connections via colleagues, and on-the-ground outreach. Green Lane NGO and Armenia Tree Project provided contacts of farmers in Lori Province via phone number. The phone numbers listed in the USAID report *Assessment of the Potential of the Armenian Greenhouse Cluster and Greenhouse Sub-sector Analysis in Armenia* were used to cold call 30 smallholder farmers in Lori Province (USAID, 2007); Netherlands Embassy in Yerevan, Armenia, 2022). Colleagues from the World Food Programme provided direct farmer contacts via phone number. The Margahovit Youth Center made introductions to farmers through in-person meetings. On-the-ground outreach was done in Gargar, Arevatsag, Odzun, Pushkino, and Kurtan by approaching farmers working in their fields directly for permission to complete an FCRA.

Data Collection

From March 2024 to January 2025, 17 total smallholder farmers were interviewed using the FCRA in Lori Province. Eleven of the seventeen interviews were done in person either on the farmer's land or in the farmer's home. Farmers were interviewed in Armenian using an online version of the FCRA (accessible at https://www.climatehubarmenia.com/resilience-toolkit) for data collection, and many of the interviews were recorded using a cellphone for accuracy. In-person assessments lasted between half an hour to three hours total. Six of the seventeen total FCRAs were done online using the online version of the FCRA.

Three focus group discussions (FGDs) were additionally held in Debet with a total of four farmers, Gugark with a total of eight farmers, and Margahovit with a total of twelve farmers. FGDs were done to gain further understanding of the main climate risks present in Lori, the current challenges for smallholder farmers, and to provide simple, cost-effective recommendations to increase climate resilience.

Results and discussions

The developed Farmer Climate Resilient Assessment was used to interview a total of 17 farmers throughout Lori Province. Farmers were interviewed in the following cities and villages: Arevatsag, Debet, Gargar, Gyulagarak, Kurtan, Margahovit, Odzun, Pushkino, and Spitak (Table). Mixed vegetable, wheat, honey and bee, walnut, tea, legume, and berry farmers were interviewed using the FCRA. Sixteen farmers owned less than 2 hectares of land, one farmer owned less than 10 hectares of land, and one farmer owned 40 hectares of land.

The results of 17 interviews with smallholder farmers found that most farmers in Lori Province are not climate resilient. Farmer Climate Resilience Scores for all 17 smallholder farmers were as follows: nine farmers had Low Resilience (score = 2), six farmer had Medium Resilience (score = 3), and one farmer had High Resilience (score = 4) (Figures 5-6).

Table. Farmers Assessed using the Farmer Climate Resilience Assessment (FCRA)*

Village	Total Number of Farmers Assessed	Men	Women
Arevatsag	1	1	
Debet	2	2	
Gargar	1		1
Gyulagarak	1	1	
Kurtan	2	2	
Margahovit	6	4	2
Odzun	2	2	
Pushkino	1	1	
Spitak	1		1

*Composed by the authors.

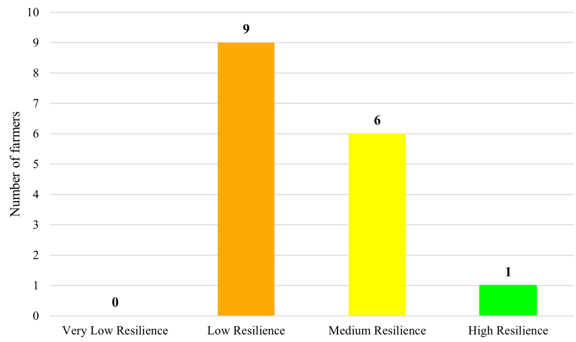

Figure 5. Total Farmer Climate Resilience Scores (FCRS) by number of farmers (#) for Very Low Resilience *(score = 1)*, Low Resilience *(score = 2)*, Medium Resilience *(score = 3)*, and High Resilience *(score = 4)*.

Final Farmer Climate Resilience Scores (FCRS)						
Farmer #	Environmental Score	Economic Score	Social Score	Total Points	Final FCRS	Description
Sample						
1	3	4	3	64	3	Medium Resilience
2	2	2	2	40	2	Low Resilience
3	2	2	2	38	2	Low Resilience
4	2	1	1	32	2	Low Resilience
5	2	2	2	39	2	Low Resilience
6	3	2	3	56	3	Medium Resilience
7	2	2	2	46	2	Low Resilience
8	3	3	4	73	4	High Resilience
9	2	2	2	47	2	Low Resilience
10	2	2	3	50	3	Medium Resilience
11	3	2	3	57	3	Medium Resilience
12	3	4	3	64	3	Medium Resilience
13	2	3	3	48	2	Low Resilience
14	2	3	2	47	2	Low Resilience
15	2	3	3	40	2	Low Resilience
16	3	2	3	59	3	Medium Resilience
17	3	2	2	51	3	Medium Resilience

Figure 6. All Farmer Climate Resilience Scores (FCRS) by each farmer including the environmental score, economic score, social score, total pints, and final FCRS – Very Low Resilience *(score=1)*, Low Resilience *(score=2)*, Medium Resilience *(score=3)*, and High Resilience *(score=4)*.

On the whole, farmers exhibited the following overall environmental, economic, and social gaps resulting in the large number of Low Resilience scores.

<u>Environmental Gaps</u>

- Not enough months of living cover and no cover crops increasing erosion, increasing soil degradation, and reducing soil health
- No trees or shrubs on the farm increasing erosion and soil degradation
- No nitrogen fixing crops increasing soil degradation
- No water collection method or irrigation contributing to water insecurity and reduced yields
- Limited variety in crops grown decreasing soil health
- No pollinator friendly plants, trees, shrubs, increasing possible impacts from pests/disease and decreasing yields
- No weather protection methods equaling high vulnerability to climate risks (ex. hail)

<u>Economic Gaps</u>

- Large dependence on external inputs (i.e. seeds, fertilizer, soil, etc.)

<u>Social Gaps</u>

- No crops covered by crop insurance
- Limited access to trainings, social networks, and knowledge resources
- Poor gender distribution in labor and decision making
- Large dependence on third parties for items in the supply chain

Within the environmental indicators, the indicators that consistently scored the lowest were within the water protection subsector (Figure 3). Fifteen out of seventeen farmers had an average resilience score of 1 (Very Low Resilience) for water protection indicators. Within the economic indicators, no farmers scored higher than a 3 (Medium Resilience) for both Indicators #15 (Number of income sources) and #16 (Farmer dependence on external inputs). Within the social indicators, all farmers had a score of 1 (Very Low Resilience) for indicator #17 (Percentage of crops covered by insurance), as no farmer had access to crop insurance. Most farmers had limited access to trainings, social networks, and knowledge resources and had at least some dependence on third parties to source items in their supply chains. Although rural women farmers are the most vulnerable demographic to climate risks, all women interviewed were found to have higher overall levels of climate resilience and were more willing to try new and innovative farming practices than men due both to necessity and flexibility.

According to the results of the study, the easiest and most cost-effective ways to increase climate resilience among smallholder farmers are the following: encouraging reduced tillage practices, introducing cover crops, increasing access to training and knowledge particularly around soil health, increasing access to financial opportunities, availability of higher quality seeds, implementation of water management practices, and increased access to markets. These identified climate-smart agricultural practices have low financial and educational barriers to entry and have low risk. The recommendation for next steps is to pilot climate-smart agricultural practices in rural Armenia to increase farmer climate resilience.

Research challenges were due to lack of accurate data, logistical hurdles, and language barriers. None of the farmers interviewed kept track of their land use habits or farming practices, making accurate data collection for each indicator difficult. Estimates were used for some indicators when specific data was not available or unknown by the farmer. Logistical hurdles impacted data collection. Due to the remote nature of many of the villages where FCRAs were completed, it was not always feasible to return to a farmer's village if incomplete data was collected. Language barriers between interviewer and interviewee made the assessment process inefficient at times, and occasionally resulted in wrong data collection.

Conclusion

Smallholder rural farmers in Lori Province are extremely vulnerable to the climate crisis. Most farmers lack access to the necessary inputs, resources, financing, training, and education to increase their climate resilience. Increased frequency and intensity of climate risks are already having disproportionate impacts on the agriculture sector. Climate-related events in Armenia have cost more than $1.5 billion in damages and losses over the past 25 years, equaling ~0.6% of GDP in average annual damages and losses from floods, drought, hail, and landslides (World Bank, 2025). The interview and FGDs done using the developed Farmer Climate Resilience Toolkit underscore the need to invest in climate-smart practices throughout rural Armenia. Investing in climate resilience will reduce short-term costs of mitigation, with projections showing that adaptation will increase GDP by 0.5% per year on average as soon as 2030 (World Bank, 2025). Rural farmers understand their vulnerability to climate risks and are open to innovative, climate-smart practices to reduce it. The research done with smallholder farmers in Lori Province should be utilized to implement climate-smart practices throughout Armenia to increase local, regional, and national climate resilience.

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Declarations of interest

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Farm Waste Management and Climate-Smart Practices in Marginal Environments: Focus on the South Caucasus Region

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ABSTRACT

The South Caucasus region, encompassing Georgia and Armenia, is home to diverse agricultural systems that are increasingly vulnerable to the effects of climate change. These challenges are particularly intensified in marginal environments - areas where soil degradation, water scarcity, and topographical constraints significantly hinder sustainable farming efforts. One critical yet often overlooked aspect of resilience-building in these regions is farm waste management, which plays a direct role in both environmental health and agricultural productivity. This study presents a desk review and analytical synthesis of existing literature, government reports, and international best practices to assess the current state of farm waste management and climate-smart agricultural (CSA) practices across marginal zones. Special attention is given to the Agricultural Waste Management System (AWMS) concept, including the characterization of waste types, available treatment methods, and broader systemic benefits when implemented effectively. The analysis also identifies prevailing poor practices, highlights their environmental and socioeconomic consequences, and proposes policy recommendations tailored to regional needs. Drawing on my practical experience and engagement with stakeholders in the region, the study emphasizes the urgent need for region-specific CSA approaches, integrated waste systems, and stronger institutional frameworks to better support farmers. The article concludes with actionable guidelines for both farmers and policy-makers aiming to reduce climate vulnerabilities and promote sustainable rural development in the South Caucasus.

Introduction

Marginal environments, characterized by degraded soils, limited water and challenging topographies, are highly vulnerable to the compounded effects of climate change and poor agricultural practices. These landscapes are home to farming communities who rely on agriculture not just for income, but as a way of life. In the South Caucasus region, especially in Georgia and Armenia, agriculture continues to play a central role in rural livelihoods and national economies (FAO, 2013). However, the farmers working in marginal zones frequently face a double burden: on the one hand, the accelerating impacts of climate variability, and on the other, structural limitations such as inadequate infrastructure, lack of knowledge-sharing systems, and limited institutional support.

One of the most pressing yet under-addressed issues in these environments is farm waste management. Farm waste, including manure, crop residues, processing by-products, and agrochemical remnants is often mismanaged or simply left untreated. This contributes not only to immediate environmental concerns such as water pollution, unpleasant odors, and soil degradation, but also to broader issues like greenhouse gas (GHG) emissions and long-term loss of soil fertility (FAO, 2024). These challenges, when unaddressed, undermine both the sustainability and productivity of farming systems, leaving communities more exposed to climate risks.

As someone who has worked closely with farmers and local agricultural stakeholders in the region, I have witnessed the resourcefulness of smallholders and their willingness to adapt. In many cases, the problem is not only a lack of awareness, but rather a gap in access to context-specific solutions and supportive policies. Effective farm waste management, integrated into broader CSA strategies, offers a critical pathway to mitigate environmental impacts while improving agricultural resilience.

This study aims to fill a knowledge gap by exploring existing waste management practices in marginal environments and proposing climate-smart, locally adaptable strategies for improvement. Through a synthesis of academic literature, policy reports, and on-the-ground insights, the research highlights both the challenges and opportunities of building resilient, waste-conscious farming systems. Special attention is given to region-specific conditions, as well as to the potential for institutional frameworks and grassroots innovations to drive positive change.

Materials and methods

This paper is built on a qualitative, desk-based review approach that brings together both academic research and practical, field-informed knowledge. Instead of collecting new primary data, I focused on reviewing a wide range of existing materials: spanning scientific literature, policy documents, and development reports, to better understand the current realities of farm waste management and climate-smart agricultural practices in the marginal environments of Georgia and Armenia. The aim was to connect what is already known with what is being experienced on the ground, highlighting gaps, opportunities, and region-specific needs.

Data was collected from the following key sources:

- Peer-reviewed journals covering topics such as agricultural waste systems, climate vulnerability, and sustainable land use (EC, 2022).
- Reports and technical publications by the international organizations, including the Food and Agriculture Organization (FAO), Deutsche Gesellschaft für Internationale Zusammenarbeit (GIZ) and relevant ministries of agriculture and environment in Georgia and Armenia.
- Existing projects and past experience of the U.S. Department of Agriculture (USDA) in Georgia and Armenia (USDA, 2019-2025).
- National-level policy documents, regulations, strategies and action plans pertaining to agricultural development, environmental sustainability, and rural resilience (MEPA, n.d.).
- Grey literature, project evaluations, and case studies from development programs and NGOs actively working in the South Caucasus.

These sources were selected with an emphasis on practical relevance and regional specificity. Each document was reviewed for content related to key themes such as waste categorization (organic, chemical, and mixed), treatment and reuse methods, climate risk exposure, institutional and policy frameworks, and CSA interventions.

The literature was analyzed using a thematic approach to identify recurring patterns, critical gaps, emerging best practices, and region-specific challenges. Particular focus was placed on synthesizing insights that could inform practical recommendations tailored to the unique socio-environmental context of marginal agricultural areas in the South Caucasus.

This method allowed me to integrate both formal scientific knowledge and informal practitioner insights, many of which stem from my own work and dialogue with local farmers, extension agents, and development partners. The result is a comprehensive yet grounded exploration of the intersection between farm waste management and climate adaptation in this under-researched region.

Results and discussions

As the impacts of climate change intensify, particularly in regions already vulnerable due to their marginal environments, farm waste management has become an essential element of sustainable agricultural practices. In the South Caucasus, particularly in Armenia and Georgia, the challenges posed by poor soil fertility, water scarcity, extreme climatic conditions, and economic vulnerabilities are increasingly pressing. Marginal areas in these countries, including the mountainous regions of Adjara, the semi-arid zones of Kakheti in Georgia (REC Caucasus, n.d.), and areas like Aragatsotn and Vayots Dzor in Armenia, are at the forefront of these challenges. These regions are experiencing severe land degradation, soil erosion, limited rainfall, and water stress, which all exacerbate the vulnerability of farming systems. These areas are heavily reliant on agriculture for their livelihoods, yet face the compounded pressures of climate change and environmental degradation (Metreveli & Iosebidze, 2022).

Farm waste, which includes both biodegradable and non-biodegradable materials, presents a significant opportunity for improving environmental and agricultural sustainability. In the South Caucasus, however, much of this waste is poorly managed. Livestock manure, crop residues, agrochemical waste, and slurry often end up being discarded improperly, contributing to pollution, methane emissions, and soil contamination. If effectively managed, however, this farm waste can be transformed into valuable resources that not only reduce the negative environmental impacts but also enhance agricultural productivity and resilience. A more efficient and sustainable approach to farm waste management, such as composting, anaerobic digestion, and biochar production, can help turn agricultural by-products into organic fertilizers, soil amendments, and even renewable energy sources, thus supporting the long-term sustainability of farming in these marginal environments (Tskhakaia, 2024).

In Armenia, most farms lack structured waste management practices, and manure is often disposed of informally by spreading it on nearby fields, limiting opportunities for biogas production and raising environmental concerns (FAO, 2019). Similarly, in Georgia, composting of livestock waste is not widely practiced, with much of the manure left unmanaged on pastures, especially in small-scale farming systems (FAO, 2024). This informal handling of farm waste in both countries restricts nutrient recovery, contributes to greenhouse gas emissions, and poses risks to public health and environmental sustainability.

The significance of managing farm waste becomes particularly clear in the context of the challenges faced by smallholder farmers in Armenia and Georgia. These farmers, who dominate the agricultural sector in both countries, are often dealing with limited infrastructure, a lack of technical knowledge, and economic constraints (FAO, 2013). Many of them continue to rely on traditional, unsustainable practices such as open dumping, burning of crop residues, and improper storage of manure. These practices not only lead to environmental degradation but also limit the potential of the land. For example, the open burning of crop residues releases harmful greenhouse gases and particulate matter, contributing to air pollution and the acceleration of climate change. Similarly, the improper storage of livestock manure results in the leaching of nitrates into water bodies, threatening water quality and ecosystem health.

Table 1. Summarizes key categories of farm waste in the South Caucasus, common sources, associated environmental risks, and their potential for reuse*

Type of Waste	Common Sources	Environmental Risks	Reuse Potential
Livestock Manure	Dairy, beef, pig farms	Water contamination, methane emissions	Compost, biogas production
Crop Residues	Wheat, vineyards, maize	Air pollution (from burning), soil erosion	Compost, mulching, soil amendment
Agrochemical Waste	Fertilizer, pesticide use	Soil toxicity, plastic packaging litter	Recyclable containers, regulated disposal
Slurry and Wastewater	Livestock and dairy farms	Leaching into groundwater, eutrophication	Irrigation reuse, energy (biogas)

*Key categories of farm waste (*composed by the author based on the agricultural production practices in the South Caucasus*).

Table 2. Common Poor Practices in Farm Waste Management and their Environmental Consequences*

Bad Practice	Consequence
Open dumping near rivers / farmland	Groundwater contamination, soil degradation
Field burning of crop residues	Air pollution (PM2.5), carbon emissions (CO_2)
Improper storage of manure	Nitrate leaching, odor issues, GHG emissions
Mixing organic and hazardous waste	Toxic leachate, disease transmission risks
No dedicated manure storage	Nutrient loss, spread of pathogens
Overuse and mismanagement of irrigation water	Waterlogging, salinization of soils, and depletion of local water sources
Using agrochemicals and pesticides without guidance	Soil and water pollution, harm to beneficial organisms, long-term soil toxicity
No sequencing or separation of farm waste types	Inability to recycle effectively, increased health risks, and inefficient waste utilization
Lack of awareness and training on sustainable waste practices	Continuation of harmful practices, reduced productivity

*Poor practices in Farm Waste Management and their consequences (*composed by the author based on the field observations*).

To address these issues, it is crucial to implement integrated farm waste management systems (AWMS) that take a comprehensive, systematic approach to managing waste throughout the entire agricultural process. The AWMS model focuses on six key functional components: production, collection, storage, treatment, transfer, and utilization (ICBALearning, n.d.). By incorporating these elements into farm management practices, it is possible to create a circular system where waste is minimized, reused, and recycled, thereby reducing its environmental impact while simultaneously enhancing farm productivity and sustainability.

Several farm waste treatment methods are proving effective in the South Caucasus. Composting, for example, is a low-cost and widely applicable method suitable for organic waste such as crop residues and livestock manure. It allows for the transformation of waste into nutrient-rich organic fertilizers that can improve soil fertility and water retention, which is crucial in areas experiencing water scarcity. Anaerobic digestion is another promising method, particularly for livestock manure. This process produces biogas, a renewable energy source that can be used to power farms or households (FAO, 2024). While the scalability of anaerobic digestion is still limited by high initial investment costs, pilot projects in Armenia, such as those supported by GIZ in dairy farms, have demonstrated the potential for this technology to contribute to sustainable energy production. Vermiculture, or worm farming, also offers an option for small-scale composting, yielding high-quality, nutrient-dense outputs that can be used to improve soil health (GIZ, n.d.).

In addition to these treatment methods, recycling and chemical stabilization can help manage hazardous waste, such as pesticide packaging and other agrochemical residues. Establishing systems for the recycling of agrochemical containers and the safe disposal of hazardous materials is critical for reducing the environmental risks associated with these types of waste. However, the lack of proper recycling infrastructure in many regions of the South Caucasus remains a significant barrier to fully addressing these waste streams.

Beyond waste management, climate-smart agricultural practices are also key to building resilience in the South Caucasus' marginal environments. The region's farmers are increasingly facing unpredictable weather patterns, rising temperatures, and shifts in planting seasons, which require adaptive strategies. Climate-smart practices such as conservation tillage, agroforestry, integrated pest management (IPM), water-efficient irrigation techniques, and nutrient management are essential for optimizing the use of available resources and improving overall farm productivity (EC, 2022). These practices, when combined with sustainable waste management, can significantly improve soil health, conserve water, and reduce greenhouse gas emissions.

For example, conservation tillage helps to maintain soil structure and moisture levels, making it particularly valuable in areas prone to drought or water stress. Agroforestry, which involves integrating trees with crops, can provide additional income through timber or fruit production, while also enhancing biodiversity and improving water retention in the soil. Similarly, IPM techniques help farmers manage pests and diseases without relying heavily on chemical pesticides, reducing both the cost of inputs and the environmental impact.

However, despite the evident benefits of these practices, the adoption of climate-smart farming methods and waste management systems remains slow. One of the major challenges is the high initial investment required for new technologies and infrastructure, such as biogas plants or water-efficient irrigation systems (GIZ, 2022). Additionally, there is a lack of technical knowledge and training among farmers, which limits their ability to implement these practices effectively. Resistance to change, combined with weak enforcement of environmental regulations, further complicates the situation.

To overcome these barriers, it is essential to foster collaboration between farmers, governments, research institutions, development agencies, and civil society (MEPA, n.d.) in order to:

- Provide targeted extension services and farmer field days on composting, biogas production, and CSA practices.
- Offer financial incentives or cost-sharing models for smallholders to adopt waste-to-resource technologies.
- Strengthen legal frameworks around agrochemical packaging and establish rural recycling infrastructure.
- Promote youth engagement and innovation in green agri-entrepreneurship by linking sustainable waste solutions with income-generating activities.

Ultimately, the road to sustainable agriculture in the South Caucasus runs through the integration of waste management into broader climate resilience strategies. By recognizing waste not as a problem, but as an untapped resource, the region has the opportunity to lead by example in transforming its marginal environments into hubs of sustainable growth.

The adoption of Agricultural Waste Management Systems (AWMS), when paired with climate-smart farming practices, presents a vital pathway for strengthening agriculture in the marginal environments of the South Caucasus. These regions, often constrained by poor soil, limited water availability, and climatic extremes, require integrated and localized strategies to remain productive and sustainable. AWMS provides a structured approach to managing farm waste from production and storage to treatment and reuse, ensuring that waste becomes a resource rather than a liability (Zhou & Wang, 2020).

One of the most noticeable and important impacts of improving agricultural waste management systems (AWMS) is how much it can help reduce environmental pollution. In many rural parts of Georgia and Armenia, practices like open dumping and field burning are still quite common. By adopting AWMS, we can start to move away from these harmful habits and instead protect our water resources, improve air quality, and preserve the health of surrounding ecosystems (Sustainability Directory, n.d.). By minimizing open dumping and field burning, which are still common in rural areas of Georgia and Armenia, AWMS helps protect water bodies, air quality, and surrounding ecosystems.

Another key benefit is the potential to cut down greenhouse gas emissions. Embracing more circular and climate-smart ways of managing waste gives the agricultural sector a real opportunity to support broader efforts to tackle climate change (Jha, 2024). Methods like anaerobic digestion not only prevent methane release from decomposing manure but also convert it into biogas, contributing to renewable energy generation. This is particularly valuable for smallholder farmers seeking cost-effective and climate-friendly energy alternatives. Composting of organic waste further contributes to improved soil fertility, reducing dependency on chemical fertilizers and enhancing soil structure and nutrient content. When managed effectively, these systems also lead to greater resource efficiency, a crucial factor in marginal zones where agricultural inputs are scarce or expensive.

However, realizing the full potential of AWMS demands more than just technology. It requires sustained cooperation between farmers, researchers, and local institutions, as well as tailored training and incentives. The integration of these practices into everyday farming routines calls for flexibility and innovation, especially as environmental and economic conditions continue to evolve. In this context, farm waste management and climate-smart agriculture should not be treated as separate initiatives but as mutually reinforcing components of a broader strategy for sustainable agricultural development under climate stress.

Conclusion

Farm waste management often operates behind the scenes in the broader conversation about sustainable agriculture, yet its impact in fragile environments like the South

Caucasus, is undeniable. This article has explored how mismanaged agricultural waste, when left unaddressed, exacerbates environmental degradation, intensifies greenhouse gas emissions, and places additional stress on already vulnerable farming systems in Georgia and Armenia.

At the same time, the region's marginal conditions offer a compelling opportunity to rethink traditional practices and innovate locally. Encouragingly, small-scale pilots and case studies show that simple, climate-smart waste management techniques, such as composting, biogas systems, and mulching, can make a measurable difference. These practices not only reduce environmental pressure but also support long-term soil health and resilience.

What's evident throughout is that farmers are not resistant to change, they're looking for practical, cost-effective solutions that align with their daily realities. When empowered with knowledge, tools, and institutional support, many are open to rethinking how waste is viewed and managed on their farms. This points to a need for integrated approaches, ones that combine waste management with conservation agriculture, water efficiency, and pest control under a unified climate-smart agriculture framework.

Introducing new technologies alone is not enough to drive regenerative solutions. What's essential is deeper, ongoing collaboration between researchers, policymakers, and farming communities, so that innovations are grounded in real-world needs and can be implemented in ways that actually work on the ground (Zhao et al., 2024). National agricultural strategies and extension systems must place greater emphasis on waste utilization and regenerative farming as essential components of climate adaptation and rural development.

In the South Caucasus, where climate risks and economic limitations intersect, farm waste management can no longer be treated as an afterthought. It must be woven into the broader narrative of resilience and sustainability (Zhou & Wang, 2020). The path forward includes not only technical solutions, but also rethinking our assumptions, seeing waste not as a by-product to be discarded, but as a potential resource to be recycled, reused, and reinvested in the land.

Ultimately, sustainable agriculture in marginal environments requires more than innovation, it requires intention. Intention to support those working closest to the land, intention to build systems that regenerate rather than deplete, and intention to listen to the overlooked insights of rural farmers. With targeted action and shared responsibility, the South Caucasus can become a model of climate-smart transformation rooted in local realities and global relevance.

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Establishment of Windbreaks in Semi-Arid Zones as a Method to Ensure the Sustainability of Agroecological Transformations

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ABSTRACT

In the context of ongoing global climate change, establishing protective forest layers that enhance the stability of agroecosystems has become increasingly essential. This issue is particularly pressing in arid regions such as Armenia. Prior to the 1990s, the creation of protective forest layers was a widespread practice across the Republic of Armenia, primarily aimed at reducing wind intensity and preventing the intrusion of cold air masses into agricultural and residential areas. In addition to serving as windbreaks, these forest layers played a vital role in regulating the soil's water regime and creating a favorable microclimate for the growth and development of both plant and animal life. Despite their proven importance, most of these protective forest layers have been removed across the country—including in semi-desert zones—due to shortages of fuel and energy resources. As a result, no new protective layers have been established since.However, agro-ecological transformation now presents an opportunity to develop sustainable agro-food systems, making the restoration of windbreaks in the Ararat Valley not only desirable but necessary. Such practices will support environmental sustainability while also delivering substantial socio-economic benefits. This study presents an analysis of agroecological indicators, based on which a model for the establishment of windbreaks in the study area has been developed.

Introduction

Until the 1990s, protective forest belts were established in the Republic of Armenia. However, due to shortages of fuel and energy resources, particularly in semi-desert regions, these belts were largely removed, and no new ones were planted. In the Ararat Plain, where the effects of climate change are becoming increasingly evident, implementing and maintaining strategies to enhance the stability of agroecosystems is essential. Such measures can help mitigate drought, prevent biodiversity loss, and contribute to long-term socio-economic benefits. Two representative locations were selected for the establishment of protective forest belts: roadside and mid-field sections. The proposed models serve as exemplary frameworks for designing protective belts in semi-desert zones. Agro-ecological transformations based on this approach can contribute to mitigating wind intensity, reducing the penetration of cold air currents, and regulating the soil water regime. These improvements foster a favorable microclimate, enhancing the growth and sustainability of plant and animal life.

Materials and methods

The research methodology is based on a comprehensive analysis of the literature on protective forest layers, the selection and examination of representative sites, and insights gathered from group discussions with residents. The identification of typical sites and comparative analyses were conducted using topographic maps, including Google Maps and Google Earth applications. Additionally, the vegetation cover was assessed using the route method, which involved documenting the presence of trees and plant communities within the selected sites (Harutyunyan et al., 2010). As a result of the research and analysis, representative models for establishing protective forest layers in the semi-desert zone have been developed. These models incorporate plant species native to the region, which also possess the potential to mitigate existing environmental challenges.

Results and discussions

The selected sample areas are situated in a human-induced pollution zone, resulting from industrial activities conducted by enterprises in the surrounding areas. Additionally, these locations are traversed by the Yerevan-Ararat and Yerevan-Armavir highways, further contributing to environmental stress in the region.

Picture 1. The selected sample areas at the Yerevan-Ararat highway.

The research was conducted within the agroecosystems of the Vedi community, selected due to their increased vulnerability to the aforementioned impacts. The restoration and establishment of forest belts in these areas is essential, as they play a dual role in reducing emissions from highways and mitigating the adverse environmental impacts of nearby industrial activities, particularly those associated with “Araratcement” CJSC and “Geopromining Gold” LLC (Ararat Gold Extraction Factory). Furthermore, the newly established forest belts are expected to serve multifunctional purposes, contributing to both ecological stability and landscape improvement.

Picture 2. Example of a Protective Forest Belt (www.glavagronom.ru).

In the main zones of the studied areas, the land cover is predominantly homogeneous, characterized by mountainous gray semi-desert landscapes and cultivated, irrigated soils. The mountainous gray semi-desert soils prevalent in the aforementioned zone are characterized by a chalk-rich, pulverized structure, with humus content typically not exceeding 1–2 %. However, in cultivated areas, these soils have gradually become enriched with humus, developed a silty texture over time, and transformed into fertile cultivated-irrigated soils. The geological structure of the studied areas is predominantly composed of sedimentary sandstone, gravel and gravel formations, as well as tuff formations, which serve as the parent rocks. The groundwater table is relatively high, which significantly influences the soil quality indicators, leading to increased salinization.

Table 1. Results of the soil sample analysis conducted in the agroecosystems of the Vosketap settlement (2024)*

N	Soil sample	pH	The concentration of water-soluble salts, %	$CaCO_3$, %	Hummus, %	Organic content, %	Barium concentration (mg/100g soil)		Plant-available nutrient concentration (mg/100g soil)		
							Cu	Zn	NO_3-N	P_2O_5	K_2O
1	Sample 1	7,1	0,222	13,83	2,45	6,51	0,133	-	8,4	9,42	39,9
2	Sample 2	7,9	0,069	12,37	2,57	6,82	0.118	0,214	3,06	5,27	32,0
3	Sample 3	8,0	0,075	10,51	2,55	6,63	0.040	0,158	0,83	3,97	24,5
4	Sample 4	8,0	0,039	11,44	2,62	6,72	0.037	0,045	1,77	3,92	28,8

*Composed by the authors.

In soil samples 1 and 2, the soil pH is weakly basic, while in the other two samples, it is predominantly strongly basic. The concentration of water-soluble salts in soil sample 1 surpasses the recommended threshold, with the optimal range being 0.05–0.2 %, whereas in the remaining samples, the levels of water-soluble salts are within the acceptable range for optimal plant growth.

The analyzed soil samples are calcareous. Overall, the study area demonstrates a moderate to adequate availability of key macronutrients, with phosphorus (P) and potassium (K) being relatively abundant. In contrast, nitrogen (N) is generally found in limited to moderate amounts (Table 1) (Forest Restoration and Climate Change in Armenia – FORACCA Project, Plan for the Establishment of Protective Forest Layers, 2024).

The results of the soil sample analysis from the study sites also indicated that the soils are predominantly light clay in terms of their texture and mechanical composition. Additionally, these locations are traversed by the Yerevan-Ararat and Yerevan-Armavir highways, further contributing to environmental stress in the region. I n the observed areas, specifically within the agroecosystems adjacent to the Yerevan-Ararat highway, studies conducted between 2008 and 2010 revealed that the concentrations of Cu and Pb in vineyards and vegetable crops exceeded the acceptable limits for various soil types. In contrast, the levels of other heavy metals (Zn, Mn, Ni, Cd) remained within permissible limits. This contamination is primarily attributed to emissions from motor vehicles and industrial activities, particularly from the Ararat Cement Plant.

It is important to note that the analysis of yield indicators for tomatoes, eggplants, and peppers cultivated in the studied areas revealed that crops grown within 150-200 meters from highways exhibited weaker growth and development compared to those grown at distances of 500 meters or more. Additionally, the plant density per unit area was 5-10% lower in the former group (Table 2). Based on the findings, it can be concluded that the concentrations of certain heavy metals in the soils do not pose a significant threat to the ecological safety of agricultural products (Galstyan, et al., 2010).

Windbreaks offer many direct effects on agricultural production with maximum benefits of ecosystem biodiversity. Despite the indisputable advantages and favorable effects of permanent linear vegetation elements, their representation in the agricultural landscape is not as frequent as it used to be (Podhrázská, et al., 2021).

Table 2. Yield indicators of vegetable crops in agroecosystems adjacent to the Yerevan-Ararat highway (average data for 2008-2010)*

Name of the highway	Distance from the highway (m)	Average yield (c/ha)		
		tomato	eggplant	pepper
Yerevan-Ararat	500 (checker)	410	354	285
	250	400	341	280
	50	352	330	250
	25	326	310	230

*Composed by the authors.

Table 3. Results of heavy metal concentrations in soil samples collected from the agroecosystems of the Vosketap settlement (2024)*

Soil sample	Studied elements (mg/kg)											
	Cr	+/-	Pb	+/-	As	+/-	Mo	+/-	Zn	+/-	Mn	+/-
Sample 1	1350	140	11	7	0	0	4	4	8	6	3200	120
Sample 2	1090	140	0	0	0	0	0	0	9	5	2930	110
Sample 3	2630	170	0	0	0	0	13	13	0	0	3620	120
Sample 4	2080	150	0	0	0	0	10	10	0	0	2310	100

*Composed by the authors.

In 2024, studies conducted in the same areas revealed a significant increase in heavy metal contamination. The concentration of chromium (Cr) in soil samples exceeded the threshold limit value (TLV) by approximately 15 to 37 times, while molybdenum (Mo) levels were exceptionally high, surpassing the TLV by 3 to 10 times. Additionally, manganese (Mn) concentrations were at least twice the TLV, whereas the levels of zinc (Zn) and arsenic (As) remained within acceptable limits. These findings indicate that the selected sites are directly impacted by severe anthropogenic pollution (Table 3).

The analysis of data from the Urtsadzor meteorological station for the period 2019-2023, provided by the Hydrometeorology and Monitoring Center of the RA Ministry of Environment, reveals that climate change has contributed to an increase in wind currents and intensity in the studied region. Local residents report that this change has adversely affected both the qualitative and quantitative characteristics of the crops. (This is a recommendation which is not relevant for this chapter, you would rather move it to the conclusion part).

Windbreaks are often created by leaving existing trees in strips or by planting trees between fields, inside fields, and near farm buildings (Dawid, 2021). Windbreaks play a significant role in minimizing soil erosion and reducing evapotranspiration, while also contributing to improved crop yields and offering a range of additional on-farm benefits. Notably, their establishment and maintenance require relatively low investment, and they can be integrated into agricultural landscapes without occupying substantial land area (University of Florida IFAS, 2017; Center for Agroforestry, 2024).

By significantly decreasing wind speed, windbreaks contribute to the modification of the microenvironment within crop fields, thereby influencing factors such as evapotranspiration, soil moisture retention, and temperature regulation. Depending on the crop, the type of soil, and the local climate, various benefits to crop growth and development occur (Hevs, 2019).

Based on the studies, considering the characteristics of the zone, the agrochemical properties of the analyzed soil samples, and input from local residents and government authorities, models for the establishment of protective forest belts were developed through collaborative design (Tables 2 and 3).

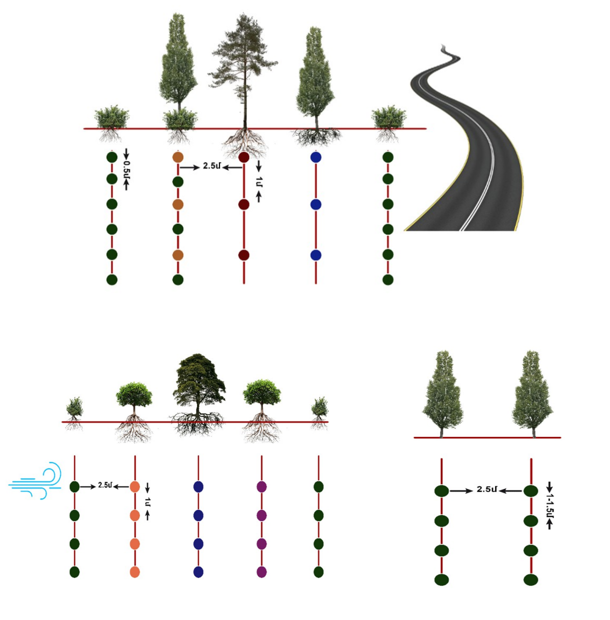

Figure. Proposed roadside and auxiliary protective forest layer models (*composed by the authors*).

Picture 3. 3D model of the proposed primary protective forest belt.

The proposed protective forest belts—comprising roadside, main, and auxiliary belts—incorporate plant species characteristic of the region (Table 4). These species are selected not only for their suitability to the local environment but also for their potential to mitigate prevailing environmental challenges. Such practices, widely implemented and recognized as successful in global green agriculture initiatives, contribute to the long-term sustainability of these systems (Ghazaryan, et al., 1974).

Table 4. Proposed plant species for the protective forest belt models*

Arboreal species	Populus deltoides (Canadian poplar) E. orientalis (Elaeagnus) Salix alba (Willow) Morus alba (Mulberry) *Zízíphus jujúba* (Jujube) Armeniaca vulgaris Lam. (Apricot tree) Ulmus pumila ”Pinnato-ramosa” Dieck (Pinnate-branched elm) Gleditsia triacanthos L. (Honey locust) Pyrus caucasica Fed. (Caucasian pear) Salix alba L. (White willow) Acer ibericum M.Bieb. (Georgian maple) Elaeagnus angustifolia L. (Narrow-leaved oleaster) Sorbus torminalis (L.) Crantz (Wild service tree, sometimes called Eastern apple tree)
Shrub species	Caragana arborescens Lam. (Siberian peashrub) Ribes aureum Pursh (Ribes) Rosa canina L. (Rosehip)

*Composed by the authors.

Conclusion

To establish an optimal agroecosystem structure in the semi-desert zone, protect soils from anthropogenic impacts and vehicle emissions, and facilitate agro-ecological transformations, it is essential to restore and establish protective forest belts. These belts hold significant ecological value, as they contribute to the creation of a microclimate that fosters plant growth and development, enhances crop yields, and improves their quality. As phytoameliorants, forest belts will also positively influence the ecological safety of agricultural products derived from agroecosystems adjacent to highways. Thus, to ensure the stability of agro-ecosystems, enhance the production of ecologically safe agricultural products in areas adjacent to the Yerevan-Ararat highway, and mitigate the adverse effects of wind, we propose the restoration and establishment of protective forest belts (www.armstat.am/file/article/eco_book_2023_1ent).

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Discovering and Studying an Endangered Apricot Variety in the Republic of Armenia

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ABSTRACT

The aim of this research expedition was to identify, map, and sample indigenous apricot (*Prunus armeniaca L.*) varieties in the Ararat Valley of the Republic of Armenia. The study focused on conducting morphological assessments to support further testing, breeding, and the development of innovative cultivation technologies (www.nature.com). These efforts are intended to promote the expansion of apricot orchards and enhance the production of high-quality, productive, and competitive apricot varieties native to Armenia. Samples were collected from these trees and subjected to laboratory-based morphological studies, which included standardized measurements and weight analyses based on established protocols. The study material was apricot fruit and leaf samples selected from apricot orchards in the Surenavan, Aralez and Taperakan settlements of Ararat province. To ensure accurate identification, the samples underwent biometric measurements and were weighed using precision electronic scales. Based on this process, the study aimed to achieve the following objectives: 1. To develop a detailed phenotypic characterization of apricot fruits. 2. To document the morphological features of apricot pits and kernels 3. To describe the structural characteristics of apricot leaves. The apricot varieties examined during the scientific research study were in the stage of industrial maturity, providing a solid foundation for continued study and evaluation. These distinguished varieties will be considered for inclusion in the national assortment of fruit crops in the Republic of Armenia. Ultimately, the most economically valuable species, forms, and varieties will be identified and recommended for commercial production, contributing to the diversification of apricot cultivation in the country.

Introduction

In the Republic of Armenia, the apricot tree holds significant importance among leading fruit crops. In fruit production, it is highly valued for its early fruit-bearing capacity, consistent annual yields, and early ripening characteristics. Moreover, apricots are recognized for their high nutritional value and medicinal properties (Santrosyan, et al., 2024).

According to data from the Statistical Committee of Armenia (2024), the total area of fruit and berry orchards in the country is 47,912 hectares. Of this, stone fruits occupy 26,428 hectares, with 23,300 hectares currently fruit-bearing. Apricot orchards alone cover approximately 13,000 hectares (FAO, Yerevan, 2015). During the Soviet era, Armenia was home to more than 50 ancient-local apricot varieties and over 40 selectively bred cultivars (www.fao.org/armenia/news/detail-events/en/c/195546), each represented by numerous clones. In addition, hundreds of elite hybrids and thousands of valuable seedling forms, often referred to as "wild" or "kharji," were preserved (Kamel, Ahmed Mohamed, and Mohamed Ali Farag, 2022). This rich genetic diversity was concentrated in the gene pool and breeding orchards of the Armenian Branch of the All-Union Institute of Horticulture (https://pubmed.ncbi.nlm.nih.gov/38143573). However, following land privatization in 1992, much of this diversity has reached the brink of disappearance (Tareen, 2021).

Over the past four years, a fruit crop germplasm collection orchard has been established at the Nalbandyan Experimental Farm of the "Voskehat Viticulture and Winemaking Scientific Center," a branch of the Armenian National Agrarian University. This orchard now includes more than 30 local apricot varieties, clones, and forms, with ongoing efforts to expand the collection (Harutyunyan and Harutyunyan,1986).

In Armenia, commercial apricot orchards are primarily concentrated in the Ararat Valley and its foothill zones. The dominant cultivated variety, prized for its flavor and visual appeal, is the Yerevani variety, which accounts for approximately 85–87% of production. The Satenik variety, comprising 10–12%, is mainly used as a pollinator (Morikyan,1988). However, many other valuable varieties are found across the country, including in the regions of Ararat, Yeghegnadzor, Meghri, Talin, Kotayk, Ashtarak, Alaverdi, and beyond (Stepanyan, 2005).

It is well known that all apricot varieties in Armenia are highly flavorful, large, beautiful, and come in shades of yellow, golden, white, and orange. The fruits are rich in various biochemical compounds and biologically active substances. They have a sweet kernel, making them suitable for all forms of processing as well as fresh consumption. This reputation extends internationally, leading to a steady increase in the export of both fresh and processed apricots from Armenia year after year (armstat.am, 2025; Chen, et al., 2020).

The cultivation of apricots in Armenia dates back to ancient times. This is evidenced by numerous historical and literary references, as well as archaeological findings. Apricot pits discovered in the Garni settlement and Shengavit site belong to the Eneolithic period, dating back 6,000 years (Morikyan, 1988).

The objective of the research was to discover indigenous, disappearing apricot varieties, clones, and forms in the Ararat Valley of Armenia. The project aimed to map these varieties, collect samples, and conduct morphological studies. Through further testing and dissemination, along with the implementation of new technologies, technical tools, and the introduction of advanced practices, the goal is to establish apricot orchards with optimal varieties for different ripening periods. This would enhance productivity, ensure sustainable and high-quality yields, and generate competitive products that meet both domestic and export demands.

Materials and methods

The research surveys were conducted in 2023, during different stages of apricot ripening. The study materials consisted of samples taken from apricot orchards in the Surenavan, Aralez, and Taperakan settlements of the Ararat region. The identified trees were briefly described in the field and numbered according to their row and tree identification numbers. Samples of leaves and fruits were then collected for further study under laboratory conditions.

For identification purposes, the samples were subjected to biometric measurements, scanned with a digital caliper, and weighed using electronic scales. Based on the obtained data, the characteristics of the tree, leaf, fruit, stone/pit, and kernel were described.

During the expeditions, the apricot varieties studied were found to be at the stage of full ripening.

Table. Ararat Region*

Data on the Orchards	**Surenavan**	**Surenavan**	**Aralez Vedi Community**	**Taperakan**
Orchard Owner				
	Vigen Ghazaryan	Asatur Mkrtchyan	Martik Tevanyan, Hovhannes Tevanyan	Suren Sargsyan
Orchard Description				
Orchard Age	12 years	12 years	40 years	38 years
Altitude above sea level	820-830 m	820-830 m	824 m	824 m
Ripening Period	05.06.23-13.06.23	05.06.23-13.06.23	17.06.23-27.06.23	05.06.23-15.06.23
Planting Spacing	7x6m^2	8x8m^2	8x8m^2	7x6m^2
Other Orchard Characteristics	The orchard has a northeast orientation, the soil is stony, and the slope is 4°. It is irrigated using a drip system. The orchard was established with Yerevan and Sateni varieties.	The orchard has a west-to-east orientation, and the slope is 3°. The orchard was established with Vaghahas Surenavan, Aghjanabad, or Aygezard varieties.	The orchard has a northwest orientation, with a slope of 2°, and is irrigated using furrows. The orchard was established in 1984 with Yerevan, Aghjanabad, and Ordubad varieties.	The orchard has a northeast orientation. The orchard was established in 1986 with Khosroveni and Ordubad varieties.

*The studies were carried out according to accepted methodologies (*Khachatryan, 2002; Sedov and Ogaltsova, 1999*).

Results and discussions

As a result of the study, 13 distinct morphological forms were identified in the apricot orchards, of which 8 were selected for detailed examination. The biometric characteristics of these 8 selected samples are presented below.

1.Taperakan 13/1 (Yerevan Large-Fruited Type)

Figure 1. Fruit, pit, and kernel of the Taperakan 13/1 *(Yerevan Large-Fruited Type)*.

The sample was discovered in the village of Taperakan, in a 38-year-old apricot orchard owned by Suren Sargsyan.

Leaf. The leaf is very large, measuring 85 × 86 mm, broadly cordate with a pointed tip. The leaf blade is of medium thickness, dark green, and non-glossy. The main vein is white, and the margins are doubly serrated. The petiole is 46 mm long and dark red on the upper side.

Fruit. The fruits are large, measuring 57.26×49×45.01 mm, with an average weight of 79 g and a maximum of 170 g. They are broad and elliptical in shape. The suture is deep and wide, with a compressed apex and a moderately deep groove that divides the fruit into two equal halves. The skin is thin, firm, slightly pubescent, and adheres tightly to the flesh. It is yellow-golden in color, with an attractive red blush covering about one-third of the sun-exposed side. The flesh is firm, meaty, golden-colored, juicy, sweet-tart, with a pleasant flavor and delicate aroma. It is of excellent quality and separates easily from the stone(https://magazine.wsu.edu/2024/08/01/stone-fruit). The fruit stalk is green and loosely attached to the fruit (https://en.wikipedia.org/wiki/Glossary_of_botanical_terms).

Stone. The stone is large, measuring 34.87×22.39×14.20

mm, though relatively small compared to the fruit. It weighs 2.84 g, is light brown, and elliptical in shape. The neck is elongated, the apex is pointed, the ventral suture (keel) is well developed, with the middle ridge being more prominent. The dorsal side is open at the base.

Kernel. The kernel is sweet and weighs 0.85 g.

2. Surenavan 2

Figure 2. Fruit, stone, and kernel of Surenavan 2.

Leaf. The leaf is medium-sized to small (80 mm × 60.1 mm), dark green, broadly oval, with a tip that narrows sharply and tilts downward. The blade is thick, leathery, and glossy. The main and secondary veins are colored at the base, with large, doubly serrated margins. The petiole is reddish from the top, measuring 4.1 cm.

Fruit. The fruit is large (57.09×45.24×42.0 mm), with an average weight of 69.38 g(www.wyzant.com/resources/answers/790819/a-particular-fruit-s-weights-are-normally-distributed-with-a-mean-of-756-gr). It is elliptical in shape, with a long neck and sharp apex. The apex is moderately deep, and the ventral suture is prominent, dividing the fruit into two unequal halves. The fruit stalk is weakly attached. The skin is thick, slightly pubescent, yellowish-green, with a light pink blush on the sun-exposed side. It adheres tightly to the flesh. The flesh is delicate, medium-thick, sweet-tart with a noticeable fragrance, yellowish-green in color, and separates easily from the stone.

Stone. The stone is medium-sized, weighing 3.72 g, and is knife-shaped or elliptical in form. The neck is long, the apex is pointed, and the surface is uneven, light brown in color(https://seaworld.org/animals/all-about/elephants/characteristics). The ventral suture has sharp edges on all sides, with the dorsal side deepening at the base.

Kernel. The kernel is large, sweet, flavorful, and full, weighing 1.33 g.

3. Surenavan 3 (Almond-Apricot Type)

Figure 3. Branch and fruit of Surenavan 3 *(Almond-Apricot Type)*

Leaf. The leaf is dark green, heart-shaped, leathery, and non-glossy, with a medium thickness and pointed tip that curves downward. The main vein is red at the base, the margins are rounded and serrated. The petiole is thin, dark red, and measures 3.5 cm (http://dev.floranorthamerica.org/Ibervillea_lindheimeri).

Fruit. The fruit measures 59.8×47.93×42.95 mm, weighing 66.81 g. It is elliptical in shape, with a weakly defined ventral suture, which is only deepening at the base. The pedicel is small. The skin is delicate, thin, and colored a yellow-apricot shade, with about half of the sun-exposed side covered in red. The skin adheres tightly to the flesh. The flesh is yellow, juicy, without fibers, sweet, mildly tart, with a pleasant aroma, and separates easily from the stone.

Stone. The stone is elliptical and smooth, weighing 2.87 g. The ventral suture is sharp at the apex, and the dorsal side deepens at the base.

Kernel. The kernel is sweet, full, and weighs 1.05 g.

4. Aralez 3/9 (Typical Khosroveni Type)

Figure 4. Fruit, stone, and kernel of Aralez 3/9 (*Typical Khosroveni Type*).

Leaf. The leaf is round and heart-shaped (7.0 × 7.8 cm), with a thin, light green, non-glossy blade. The veins are white, and the margins are finely serrated with double teeth (www.extension.purdue.edu/extmedia/fnr/fnr_237.pdf). The petiole is green, reddish on the front side, and measures 4.6 cm.

Fruit. The fruit is flat, roundish, measuring 49.5 × 42.39 × 40.85 mm, weighing 52.15 g. The pedicel is small. The skin is yellowish, with a light reddish tint on the sun-exposed side. The ventral suture is weakly defined. The flesh is crunchy, pale yellow, sweet, without fibers, with a mild aroma, and separates easily from the stone.

Stone. The stone is flat and roundish, of medium size (30.12 × 21.60 × 12.28 mm), weighing 3.30 g. It is rough and irregular. The ventral sides are well-defined.

Kernel. The kernel is full, sweet, and weighs 0.97 g.

5. Taperakan 6/5 (Ordubad or Khosroveni Red Type)

Figure 5. Fruit, stone, kernel, and leaf of Taperakan 6/5 (*Ordubad or Khosroveni Red Type*).

Leaf. Large (10.1 × 9 cm), heart-shaped, with a slightly sharp tip. The blade is thin, non-glossy, with double serrations, and the veins are green. The petiole is short, measuring 4 cm.

Fruit. Large to medium-sized (51.9×50.39×42.99 mm), weighing 66.65 g. The fruit is flat and roundish, compressed on the sides. The skin is thin, nearly bare, golden-colored, and does not separate from the flesh. The flesh is golden, juicy, without fibers, sweet, with a pleasant tartness, and separates easily from the stone. It matures at the end of June and has a very delicious taste.

Stone. Large, weighing 4.26 g, oval-shaped with a rough surface, brown in color (https://pmc.ncbi.nlm.nih.gov/articles/PMC9818792). The ventral suture is not well-defined and has a longitudinal crack (www.jstor.org/stable/10.1086/430096). The dorsal side is closed.

Kernel. Sweet, full, weighing 1.17 g.

6. Taperakan 7/2 (Ordubad or Khosroveni Red Type)

Figure 6. Fruit, leaf, stone and kernel of the Taperakan 7/2 (Ordubad or Khosroveni Red Type) cultivar.

Leaf. Medium-sized (7.4 x 7.6 cm), wide heart-shaped, with a gradually narrowing tip, inclined downward. The leaf blade is thin, glossy, green, with finely serrated, wavy edges. The main vein is colored at the base, and the leaf petiole is 3.8 cm long.

Fruit. Medium-large (50.22 x 45.69 x 42.01 mm), weighing 52 g, oval-shaped, compressed on the sides, with a rounded base and flat top. The abdominal suture is barely noticeable, dividing the fruit into unequal parts. The stem is small, and the fruit stalk is firm and attached. The skin is thin, delicate, slightly fuzzy, yellowish-golden, and inseparable from the flesh. The flesh is yellow, medium firm, juicy, with fine fibers, sweet-tart, and lightly fragrant, separating from the stone (https://veritablevegetable.com/apple-variety-guide).

Stone. Medium-sized (2.1 g), oval-shaped with a sharp tip, brown, smooth. The abdominal sides are not pronounced and have a lateral cut.

Kernel is sweet, weighing 0.7 g.

7. Surenavan 4/1

Fruit. Medium-sized (47.99 x 45.68 x 41.07 mm), weighing 52 g, flat-rounded. The skin is thin, slightly fuzzy, golden, and inseparable from the pulp. The pulp is of medium thickness, firm, juicy, with fine fibers, sweet-tart, with a noticeable fragrance, separating from the stone. The fruit stalk is firmly attached.

Stone. Medium-sized (1.46 g), oval-shaped, rough, brown. The abdominal suture is well defined. The kernel is sweet, full, weighing 1.0 g.

Figure 7. Fruit, stone and kernel of the Surenavan 4/1 cultivar.

8. Surenavan 4/7 (Gold Type)

Figure 8. Fruit, leaf, stone and kernel of Surenavan 4/7 (Gold Type).

Fruit. Medium-sized (48.08 x 44.44 x 40.64 mm), weighing 51.1 g, rounded, compressed on the sides, with a distinct abdominal suture. The fruit skin is of medium thickness, firm, almost smooth, glossy, golden, with a beautiful red hue covering half of the sun-facing side. The flesh is golden, with a mild fragrance, juicy, slightly fibrous, very sweet, and easily separable from the stone.

Stone. Large (2.8 x 2.23 x 1.23 mm), weighing 2.8 g, rounded or broad oval, slightly rough, with a well-defined abdominal suture and a closed ventral side.

Kernel. Full, sweet, weighing 1.2 g.

Conclusion

Based on the conducted scientific expeditions, several important conclusions were drawn. The expeditions organized in the Ararat region proved to be highly effective. During this period, 8 out of the 13 apricot varieties identified in the orchards were selected in alignment with the objectives of the basic program established by the Fruit Growing and Physiology Department of the Scientific Center of Viticulture. In light of these findings, it is recommended to continue the comprehensive study of the discovered varieties and to develop a new, multi-purpose and effective varietal composition to enhance the production orchards of farming enterprises. Furthermore, it is advisable to carry on scientific expeditions across various agricultural zones of Armenia with the aim of identifying and preserving new, disappearing varieties, clones, and forms of apricot.

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Bioeconomy Concept and Its Relation to Circular Economy and Resource Management

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ABSTRACT

Bioeconomy is referred as a main contributor to solve several of the big societal challenges (e.g. biodiversity loss, climate change, raw material shortage, etc.). But the concept of Bioeconomy does not have a general acknowledged description. This article gives a historic background, describes the present concepts and gives an overview of planed political strategies and action plans.

Introduction

During the first oil shock, when mankind swiftly became aware of the finite nature of fossil resources, the concept of the Bioeconomy, which had already been philosophized about by Linnaeus and Darwin, made its first career (Reinheimer, H. 1913). Cautionary calculations about the limits of growth or measures such as the "Car-free day" and a return to "Mother Earth" were based on scientific considerations about the Bioeconomy. The holistic approaches that emerged at that time are now subsumed under the term "Ecological Bioeconomy" (Zawojska und Siudek, 2016). When oil prices fell again, bioeconomic considerations quickly lost their appeal.

At the beginning of the 21st century, the Bioeconomy began a second career. By this time industrialized countries recognized biomass as a new economic factor. The Bioeconomy was now defined as the replacement of non-renewable raw materials with biomass (Patermann und Aguilar, 2018). With this "Substitutive Bioeconomy", new sustainable products and materials were to be developed from biomass, or fuels were no longer to be produced from crude oil but from biomass.

However, the "Substitutive Bioeconomy" has shown its pitfalls: In the first decade of the 2000s more corn was grown for fuel than for food production in the USA. The price of corn quadrupled on the Chicago mercantile exchange and as a consequence the price of corn for tortilla production in Mexico was suddenly four times as high, which led to social tensions.

Building on the knowledge gained, a sustainable circular Bioeconomy, also known as a "Transformative Bioeconomy" (Friedrich, et al. 2021; Ramcilovic-Suominen, et al., 2022; Eversberg und Fritz, 2022; Pungas, 2023) is developing today.

Materials and methods

Sustainable circular bioeconomy

Earth is currently the only known planet in the solar system that provides a habitat for living beings. As the Earth is a closed system (with the exception of solar energy), all raw materials are available in limited quantities. In the current linear economic system, we extract raw materials from the planet and process them into material or energy products. Now that the demand for the limited available raw materials has risen sharply due to the industrial revolution and the increase in the earth's population, a shift away from the linear economic system towards a circular economy is inevitable.

The aim of the sustainable, circular Bioeconomy is to increasingly replace raw material requirements with renewable raw materials (biomass). Renewable raw materials grow in large quantities every year with the help of solar energy. All other raw materials, such as fossil or mineral raw materials, take millions of years to be created or renewed. All raw materials on earth are subject to a natural cycle. However, this cycle has been altered in many ways by human production and consumption and is no longer sustainable (Eversberg, et al., 2023a; Giuntoli, et al., 2023; Schmidlehner, 2023; Giampietro, 2023b). In order to prevent further negative changes and effects (climate change, loss of biodiversity, etc.) the cycle must be made sustainable again and the demand for raw materials must be greatly reduced. The sustainable, circular Bioeconomy strives to achieve this while taking economic, ecological and social aspects into account.

Results and discussions

Principles of the sustainable, circular bioeconomy

The 2nd thermodynamic principle states that the concentration of matter decreases with a change of state (i.e. use) and can only be maintained or increased by adding energy. What does this mean in practice? Even in the utopian state of a perfect circular economy, there will always be energy and material losses in the processes (e.g. sampling, sorting, transporting, etc.) and both new material and energy must be added to compensate for the losses (Georgescu-Roegen and Nicholas, 1971). Since biomass, in contrast to all other raw materials, grows back in periods relevant to humans and the energy required for recycling is covered 100% by the sun, it should generally be prioritized as a source of raw materials. However, it is important to bear in mind that, on the one hand, the globally sustainably available biomass is limited and, in addition to human use, biomass serves to preserve all ecosystems which are again the basis for human life (Erb, et al., 2022).

In order to remain within global boundaries, a sustainable, circular Bioeconomy is based on the efficient design of processes (efficiency) in a regenerative circular economy (consistency) with greatly reduced raw material requirements (sufficiency).

Efficiency refers to the design of processes and the development of new innovations. This enables highly effective use of the available biomass, where residual materials serve as recyclables for other applications.

Consistency is understood to mean systems that are in harmony with natural processes and the recycling of available raw materials should be optimized for this purpose. It should be noted that there are losses in every process due to physical laws (2nd thermodynamic law, see above).

Sufficiency is understood as the reduction of resource consumption based on the amount of raw materials and energy that is sustainably available.

These principles should be combined in such a way that social needs can be met through the use of biomass.

Challenges in the Bioeconomy

A major limiting factor for the Bioeconomy is the limited availability of biomass (Erb, et al. 2022). From this point of view, the key question is what the available biomass should be used for: as food, as animal feed, for the manufacture of material products or as a source of energy? In most cases, energy use excludes further material use (an exception is, for example, the production of biochar, where energy is obtained and a product is produced at the same time), while energy use is still possible after material use. It is therefore essential to define a hierarchy of use (cascading use) for the available biomass in order to prevent conflicts of use and interest due to the limited availability of biomass.

The transformation to a circular Bioeconomy increases the demand for biomass. However, despite cascading use, not enough biomass can be provided to produce the same number of products as we produce today with non-renewable materials. "The same as before but in green" does not solve the social challenges of our time (Hausknost, et al., 2017). The sustainable, circular Bioeconomy has recognized this and, in addition to technically feasible and ecologically justifiable solutions, also focuses on increasing social acceptance of sufficiency: "What do I not need and still be happy".

Future developments and strategies

Beside several regional bioeconomy strategies, more than 60 countries worldwide have already published a national Bioeconomy strategy or a Bioeconomy related strategy. At European level, the first Bioeconomy strategy was published in 2012 and revised in 2018. A further revision is currently planned for 2025 (EU Europe, 2025). The evaluation of the European Bioeconomy strategy is a good example how the concept of the Bioeconomy is still under development. In 2022, the EU Commission presented a progress report on the basis of which, together with the 2023 reports from the Joint Research Centre (JRC), the European Council called on the Commission to revise the Bioeconomy strategy once again. In the aforementioned reports, the political context questions for the first time whether the necessary transformation is compatible with the "green growth" paradigm pursued by the Green Deal and the Bioeconomy strategy. However, the strategies based on economic growth, technological innovation and anthropocentric values have not led to the desired social and ecological changes. The JRC reports (Giuntoli et al. 2023) therefore present perspectives that are underrepresented in the Bioeconomy discourse and integrate them into an alternative vision for a "green, just and sufficient Bioeconomy". This vision places environmental sustainability and social justice - independent of economic growth - at the centre.

Conclusion

Transforming the Bioeconomy requires us to reflect on the stories we tell about ourselves, our place in nature and our relationship with each other. A participatory perspective with care, respect and reciprocity for and with other humans and non-humans is central to this. Technologies are important to achieve the green, just and sufficient Bioeconomy goals, but ethical considerations for new technologies need to be openly discussed.

Similar considerations to those in the JRC report are presented in the "Bioeconomy Youth Vision" of the EU Youth Ambassadors in 2024 as part of the Bioeconomy Changemakers Festival and at the same time 70 NGOs called in a position paper for the new EU Bioeconomy strategy to be both environmentally sustainable and socially just.

These documents indicate that, from the perspective of both science and civil society, the current revision of the Bioeconomy strategy should focus on a "new transformative Bioeconomy". The areas of ecological sustainability and social justice should play a particularly important role in this.

The Circular bio-based Europe Joint Undertaking (CBE) organizes annual calls for projects. The design of the 2024 call for projects shows that the bio-based industry is aware that the raw material biomass is a scarce commodity and must therefore be used more consciously, efficiently, sustainably and in a cascading manner. Furthermore, there is also a focus on biogenic niche raw materials (e.g. microalgae, yeasts, insects) and opportunities to utilize side streams/waste from the bio-based industry that are currently not or only little used.

Cooperation with the primary producers of biomass is also being intensified. Particular attention is being paid to the production of biomass outside of food and animal feed production.

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Declarations of interest

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Why do Strategies Remain Silent: The Discourse of Food Waste Management in the Regional Development Agendas of Armenian Marzes

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ABSTRACT

This research examines the alignment between the socio-economic and environmental goals set in the Regional Strategic Development Plans of Armenian Marzes and their actual progress as of 2025, with a particular focus on food waste management. Using a deductive analytical approach, the study evaluates regional strategies through keyword-based content analysis and benchmarks their stated targets against available statistical data from 2015 to 2023. While notable progress was observed in increasing formal employment outside the agricultural sector, most regions failed to meet their GDP and unemployment reduction targets. Crucially, the analysis reveals a substantial policy gap: despite Armenia's commitment to sustainability under the EU-Armenia CEPA agreement, food waste management is entirely absent from all regional strategies. The lack of legislative frameworks and institutional accountability has led to limited awareness and poor environmental practices across the country. The study concludes with a call for the integration of food waste as a strategic priority in regional planning and the urgent need for national regulation and stakeholder collaboration.

Introduction

In recent decades, food waste has increasingly become a key issue on the global agenda. Addressing food waste is not only an environmental concern that many governments are tackling, but also a critical aspect of social and economic transformation and development (et al, 2011; Principato, 2018). Armenia has agreed to reforms in the field of sustainability as part of the agreement signed with the European Union concerning further and stronger cooperation under the CEPA agreement. ("Comprehensive and Extended Partnership Agreement between Republic of Armenia and EU", 2021) A study conducted in Yerevan revealed that residents are generally not well informed about the significance of food waste as a global challenge, with participants self-assessing their knowledge at an average of 4.1 out of 10. The research further indicated that lavash, bread, fruits, and vegetables are the most frequently discarded items. Respondents who reported wasting food daily were estimated to lose approximately 50,000 AMD annually on bread and fruits alone. (Gevorgyan and Aleksanyan, 2024) The Municipality of Yerevan has not yet set specific targets for food waste reduction. In past few years, numerous recycling bins have been introduced throughout the city, however, these are primarily designated for plastic, paper, aluminum, and glass. There is still no infrastructure in place for the collection or processing of food or organic waste. While this may partly be attributed to a lack of facilities for handling biodegradable materials, it also reflects a matter of policy priorities: highlighting the need for the capital city to take strategic action in establishing such systems. As part of EU-funded initiatives, the Yerevan Municipality implemented a pilot project in selected kindergartens to educate children about sustainability, the circular economy, and food waste separation. However, on a broader scale, this approach has not yet been systematically adopted across all kindergartens in Yerevan or in the regions (Marzes).(Yerevan Municipality, 2024)

Considering the regional development plans, all Marzes of Armenia have established specific targets to be achieved by 2025, with the overarching objective of fostering the sustainable development of rural areas. These plans emphasize the transformation of rural communities into livable environments: rural areas designed not for outmigration, but for long-term living and growth. Aligned with this strategic vision, the present research aims to investigate the following:

RQ1) To what extent the socio-economic objectives outlined in the Regional Development Plans of Armenian Marzes have been realized by 2025?

RQ2) How the Regional Development Plans address environmental challenges, particularly in the context of food waste management?

Materials and methods

This research employed a deductive analytical approach as a central methodological framework, allowing for a structured and hypothesis-driven examination of regional development strategies across Armenia. Guided by predefined theoretical concepts, the analysis focused on identifying how key socio-economic and environmental indicators-such as 'waste', 'GDP', 'unemployment rate', and 'food waste'-are reflected and prioritized in each region's strategic development plans. The process began with a systematic literature review, incorporating national policy frameworks and strategic planning documents, which were analyzed using the AI-based tool docAnalyzer.ai. This tool enabled efficient keyword coding and text mining to trace thematic occurrences and patterns across documents. Subsequently, a conceptual content analysis was performed to extract region-specific targets, challenges, and approaches to waste management, particularly in the context of environmental policy integration. This method facilitated a comparative assessment of regional commitments against national environmental and socio-economic objectives. Quantitative data analysis complemented the qualitative findings by benchmarking the targets set in 2015 with actual performance indicators available as of 2021 and 2023, using the most recent statistics provided by the Statistical Committee of the Republic of Armenia. This dual-level methodology ensured both depth and rigor in assessing the alignment between strategic intent and measurable progress.

Results and discussions

GDP

The analysis of the strategic development plans of the Marzes of the Republic of Armenia reveals that all regions envision the promotion of sustainable economic and social development by 2025 through targeted, cross-sectoral measures. Particular emphasis is placed on the efficient utilization of local resources, the modernization of infrastructure, and the introduction of innovative technologies. The measures taken in this direction aim to foster rural communities characterized by sustainable growth, social security, and harmonious coexistence with the environment. The analysis of the strategic programs was conducted in the first half of 2025, which necessitated the use of 2021 as the reference year for comparative analysis, due to the absence of more recent statistical data. Special attention was paid to several priority areas set by the Government of Armenia, specifically: narrowing the gap between regional and national averages of GDP per capita, reducing poverty rates, and increasing formal non-agricultural employment. Within the context of environmental issues, particular importance was attributed to the strategic integration of food waste management challenges. As of May 2025, no data more recent than 2021 has been published in the official database of the Statistical Committee of the Republic of Armenia. This is due to the fact that the indicators for 2022 are to be calculated based on population estimates derived from the 2022 census. However, these figures are not comparable to the 2022 regional statistics or those of previous years, as the earlier data were based on the 2011 census. According to the official statement of the Statistical Committee, the indicators for 2022 remain subject to revision following the publication of the final census results and will be released in subsequent updates. A comparison between the available 2021 GDP data and the targets set in 2015 for the year 2025 shows that only two regions Syunik and Kotayk (20% of the regions-exceeded the national average GDP per capita level. Although all regional strategic plans emphasize the need to bring per capita GDP closer to the national average or to improve upon the 2015 levels, the majority of these targets have not yet been achieved. For example, the strategic development plan of Lori province set a target to reach 72% of the national average by 2025; however, in 2021, the figure did not surpass 56%. In Aragatsotn, Shirak, and Tavush provinces, the strategic target was to reach 60% of the national average per capita GDP, but as of 2021, these levels had not yet been attained. Table 1 presents a detailed comparison of the target values set by each Marz with their actual 2021 gross domestic product (GDP) per capita expressed as a percentage of the national average in Armenia.

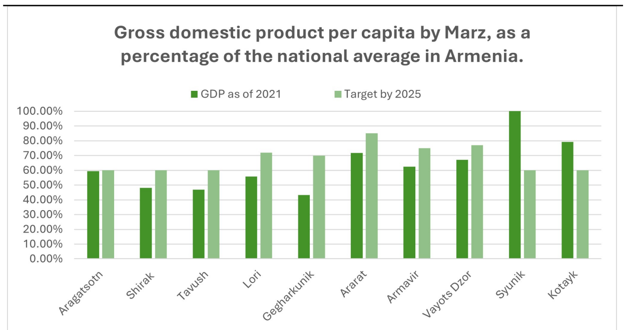

Table 1. Gross domestic product per capita by Marz, as a percentage of the national average in Armenia. *(ՀՀ վիճակագրական կոմիտե, no date; Republic of Armenia Kotayk Region Development Strategy for 2017–2025., 2017; Republic of Armenia Tavush Region Development Strategy for 2017–2025, 2017; Republic of Armenia Lori Region Development Strategy for 2017–2025., 2017; Republic of Armenia Gegharkunik Region Development Strategy for 2017–2025., 2017; Republic of Armenia Vayots Dzor Region Development Strategy for 2017–2025., 2017; Republic of Armenia Syunik Region Development Strategy for 2017–2025., 2017; Republic of Armenia Ararat Region Development Strategy for 2017–2025., 2017; Republic of Armenia Armavir Region Development Strategy for 2017–2025., 2017; Republic of Armenia Shirak Region Development Strategy for 2017–2025., 2017; Republic of Armenia Aragatsotn Region Development Strategy for 2017–2025., 2017).*

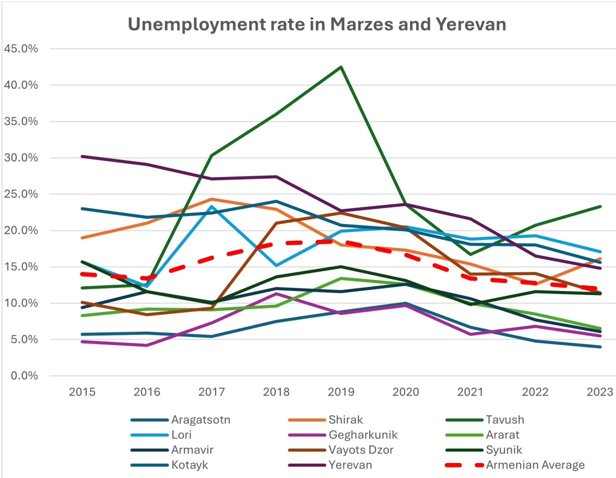

Table 2. Unemployment rate in Marzes and Yerevan *(ՀՀ վիճակագրական կոմիտե, no date; Republic of Armenia Kotayk Region Development Strategy for 2017–2025., 2017; Republic of Armenia Tavush Region Development Strategy for 2017–2025, 2017; Republic of Armenia Lori Region Development Strategy for 2017–2025., 2017; Republic of Armenia Gegharkunik Region Development Strategy for 2017–2025., 2017; Republic of Armenia Vayots Dzor Region Development Strategy for 2017–2025., 2017; Republic of Armenia Syunik Region Development Strategy for 2017–2025., 2017; Republic of Armenia Ararat Region Development Strategy for 2017–2025., 2017; Republic of Armenia Armavir Region Development Strategy for 2017–2025., 2017; Republic of Armenia Shirak Region Development Strategy for 2017–2025., 2017; Republic of Armenia Aragatsotn Region Development Strategy for 2017–2025., 2017).*

Unenployement rate

In the strategic plans, particular emphasis is placed on the issue of unemployment, with the reduction of its level identified as a priority goal. The table 2 presents the unemployment rates in the regions of Armenia and the capital Yerevan from 2015 to 2023, compared to the national average. It becomes evident that, for example, in the Tavush region, the unemployment rate has increased significantly from 12.1% to 23.3%. This trend contradicts the priority outlined in the strategic plan, which aimed to reduce the unemployment rate to below 10% by 2025. Only three regional strategic plans - those of Tavush, Syunik, and Kotayk - set target unemployment rates to be achieved by 2025. However, these targets have not been met.

Meanwhile, table 3 illustrates the target unemployment rates set for all regions, as well as the actual performance of each Marz as of 2023.

Marzes	Unemployment rate in 2023	Taregt by 2025	Level of Completeness
Aragatsotn	4.0%	No specific target	[green]
Shirak	16.1%	No specific target	[green]
Tavush	23.3%	<10%	[red]
Lori	17.1%	No specific target	[red]
Gegharkunik	5.5%	No specific target	[red]
Ararat	6.5%	No specific target	[green]
Armavir	6.1%	No specific target	[green]
Vayots Dzor	11.4%	No specific target	[red]
Syunik	11.3%	10.70%	[yellow]
Kotayk	15.6%	13%	[yellow]

Table 3. Unemployment rate targets and their level of completeness as of each Marz *(ՀՀ վիճակագրական կոմիտե, no date; Republic of Armenia Kotayk Region Development Strategy for 2017–2025., 2017; Republic of Armenia Tavush Region Development Strategy for 2017–2025, 2017; Republic of Armenia Lori Region Development Strategy for 2017–2025., 2017; Republic of Armenia Gegharkunik Region Development Strategy for 2017–2025., 2017; Republic of Armenia Vayots Dzor Region Development Strategy for 2017–2025., 2017; Republic of Armenia Syunik Region Development Strategy for 2017–2025., 2017; Republic of Armenia Ararat Region Development Strategy for 2017–2025., 2017; Republic of Armenia Armavir Region Development Strategy for 2017–2025., 2017; Republic of Armenia Shirak Region Development Strategy for 2017–2025., 2017; Republic of Armenia Aragatsotn Region Development Strategy for 2017–2025., 2017).*

[red]	Decrease in the unemployment rate.
[yellow]	Nearly met the target
[green]	No specific target, positive change in the unemployment rate over the years.

Formal Employment percentage in non-agricultural sphere.

The overwhelming majority of Armenia's regions explicitly outline in their strategic development plans an increase in the number of formally employed individuals in the non-agricultural sector. For instance, Aragatsotn region projected a 10% absolute increase in employment by 2025, while Tavush aimed for 13.9%, Lori for 10%, Gegharkunik for 10%, Ararat and Armavir each for 20%, Syunik for 12%, and Vayots Dzor for 10%. As shown in Table 4, which presents the targets set in 2015 and their performance as of 2023, only Ararat region failed to meet its target: although it had set a 20% increase, it achieved only a 10.2% growth. These indicators are largely influenced by the government's policy measures implemented after 2018 aimed at combating the shadow economy, which led to a significant increase in the number of officially registered employees as many employers transitioned to the legal framework.

Region	Target	2015	Target 2025	Real 2023	Real growth in %,
Aragatsotn	10.0%	30.4	33.4	41.5	36.5%
Shirak	-	42.6		57.5	35.0%
Tavush	13.9%	26.1	29.7	33.6	28.7%
Lori	10.0%	48.8	53.7	54.8	12.3%
Gegharkunik	10.0%	38.8	42.7	56.3	45.1%
Ararat	20.0%	57.7	69.2	63.6	10.2%
Armavir	20.0%	45.6	54.7	70.3	54.2%
Vayots Dzor	10.0%	11.7	12.9	14.6	24.8%
Syunik	12.0%	30.8	34.5	40.2	30.5%
Kotayk	-	17.2		90.2	424.4%

Table 4. Formal Employment % in non-agricultural sphere for each Marz, their targets of 2015 and the real growth as of 2023. *(ՀՀ վիճակագրական կոմիտե, no date; Republic of Armenia Kotayk Region Development Strategy for 2017–2025., 2017; Republic of Armenia Tavush Region Development Strategy for 2017–2025, 2017; Republic of Armenia Lori Region Development Strategy for 2017–2025., 2017; Republic of Armenia Gegharkunik Region Development Strategy for 2017–2025., 2017; Republic of Armenia Vayots Dzor Region Development Strategy for 2017–2025., 2017; Republic of Armenia Syunik Region Development Strategy for 2017–2025., 2017; Republic of Armenia Ararat Region Development Strategy for 2017–2025., 2017; Republic of Armenia Armavir Region Development Strategy for 2017–2025., 2017; Republic of Armenia Shirak Region Development Strategy for 2017–2025., 2017; Republic of Armenia Aragatsotn Region Development Strategy for 2017–2025., 2017).*

Food waste management under the light of environmental issues:

Considering the above-mentioned socio-economic indicators, it becomes essential to address environmental issues, particularly in the context of food waste management. Regional strategic plans completely lack any mention of food waste management, identifying potential volumes, or exploring possible solutions.

In certain regions, for example, in the Gegharkunik region, the waste problem is presented mainly in the context of household, construction, and environmental waste accumulated over the years around Lake Sevan and its surrounding areas. There is also a specific mention of scattered waste near historical and cultural monuments. However, the strategic plan of the region does not define the term "food waste," nor does it contain any roadmap on how to address this issue. (Republic of Armenia Gegharkunik Region Development Strategy for 2017–2025., 2017).

In the strategic plan of the Armavir region, reference is made to the Czech "Greeneco-KAS" LLC and a planned €33 million investment project aimed at establishing a waste processing plant on a 15-hectare area in the region. Discussions regarding this project resurfaced in the media in 2017, but as of May 2025, no tangible steps have been taken. Moreover, there is a complete absence of references to food waste issues not only at the regional level but also specifically in Armavir. (Republic of Armenia Armavir Region Development Strategy for 2017–2025., 2017).

In the strategic plan of the Vayots Dzor region, under the section "Environmental Issues and Energy Efficiency," there is a clear reference to the amount of waste generated by organizations and the increase in its quantity. However, it is presented as follows: "Between 2011 and 2015, the amount of waste generated by the region's organizations increased 4.5 times, and despite that growth, it still constitutes only 0.005% of Armenia's total waste." This reference lacks any detailed presentation of the types of waste, the challenges of their management and effective use, or how they could be utilized in potential circular economy models. The absence of targeted and specific concepts in the context of waste leads to ambiguity and the neglect of the urgency of this issue. (Republic of Armenia Vayots Dzor Region Development Strategy for 2017–2025., 2017).

In reality, this is manifested through the public's indifferent attitude toward the environment, and the lack of knowledge also leads large economic players to make suboptimal decisions regarding food waste management. The issue of food waste management is of national importance, yet it is not regulated by law. Research conducted mainly in cooperation with EU countries suggests that Armenia must first establish clearly defined legislation, and a tax policy directed at various economic actors and citizens, aimed at fostering a more conscious and sustainable environment. Within this framework, the priority involvement of certain stakeholders must also be considered. Local self-government bodies, businesses, and educational institutions, including preschools, must cooperate around a unified concept: the effective management of waste and its reduction in the environment.(RA Government, 2015; Markosyan and Aleksanyan, 2023; Gevorgyan Sargis, 2025).

Conclusion

The comprehensive analysis of Armenia's regional strategic development plans highlights a significant gap between socio-economic ambitions and environmental commitments-particularly concerning food waste management. While measurable progress is noted in goals related to GDP per capita, formal employment in non-agricultural sectors, and unemployment reduction, the absence of concrete action plans for food waste management across all Marzes (regions) underscores a critical weakness in sustainable development strategy. This neglect is particularly concerning given the rising volume of waste, increasing environmental degradation, and lack of public awareness, all of which signal an urgent need for systemic reform.

Despite some reference to large-scale waste management projects such as the stalled Greeneco-KAS initiative in Armavir there is a widespread lack of definitions, targets, and roadmaps related to food waste. Additionally, the current strategic documents fail to engage with the concept of circular economy or explore the integration of environmental policies into economic growth models. The failure to address food waste as a specific and actionable category of environmental concern leads to ambiguity, lost economic opportunities, and poor waste governance.

Suggestions for Future Strategic Planning

1.Legislative Reform and Regulatory Framework

The Government of Armenia must prioritize the development of a national law dedicated to food waste prevention, reduction, and management. This should include clear definitions, classification systems for food waste types, and obligations for both public and private sectors. Additionally, tax incentives and penalties should be designed to encourage sustainable waste practices.

2.Integration of Food Waste Management into Marz-Level Plans

Future regional strategic plans must include specific, measurable goals related to food waste management. This includes identifying potential waste volumes, setting reduction targets, and establishing monitoring mechanisms. Plans should align with national legislation and support local-level implementation.

3..Partnership with the Armenian National Agrarian University (ANAU)

ANAU should be actively involved in research, pilot projects, and educational initiatives on food waste and circular economy. This collaboration can support data collection, develop region-specific strategies, and build local expertise among students and professionals alike.

4. EU Collaboration and Knowledge Transfer

Continued cooperation with the European Union and its member states should be leveraged to adopt best practices, technological solutions, and policy models related to waste reduction. EU-funded programs and Horizon Europe projects can be utilized to support innovation and capacity-building in this field.

5. Research-Led Policy Innovation

Researchers from both Armenian and European institutions should be involved in impact assessments, life-cycle analysis of food products, and behavioral studies to inform targeted interventions. Creating a central database for waste data will support evidence-based policymaking.

6. Multi-Stakeholder Governance and Public Awareness

Municipalities, businesses, schools, and community groups must work under a unified environmental strategy. Awareness campaigns, waste separation initiatives, and educational curricula should be developed to foster a culture of sustainability from an early age.

7. Circular Economy Implementation

Future plans must embed circular economy principles by promoting food rescue, redistribution platforms, composting systems, and innovations in packaging and supply chain efficiency. Pilot programs should be tested in select regions to scale up successful models.

In conclusion, the path toward environmentally responsible and economically inclusive regional development in Armenia lies in the strategic incorporation of food waste management policies, grounded in legal reform, cross-sectoral cooperation, and academic partnerships. Only through such an integrated approach can Armenia meet its sustainable development goals and transition toward a circular, low-waste economy.

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Integrating Circular Economy Principles in Armenia's Agriculture: A Pathway to Sustainable Development

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ABSTRACT

Armenia's transition to a circular economy (CE) in agriculture represents a critical opportunity to address environmental degradation, optimize resource use, and improve food system resilience. Despite ongoing policy alignment with the European Union and initial pilot projects, Armenia's agricultural sector still lacks a coherent CE strategy and institutional capacity for wide-scale implementation. This paper explores a strategic framework for CE adoption by analyzing international best practices including cases of Italy, Georgia, Finland, Moldova, Spain and Serbia. Using comparative case analysis and policy mapping, the study identifies key components essential for Armenia's transition: waste valorization, closed-loop nutrient systems, regenerative farming practices, enabling policy reforms, financial instruments, and capacity building. The findings offer a roadmap for integrating CE principles into national agricultural planning, with recommended milestones leading to a 50% reduction in agricultural waste, 40% increase in organic input use, and widespread deployment of biogas and composting infrastructure by 2040.

Introduction

The global agricultural sector faces urgent and complex challenges—ranging from resource depletion and climate change to soil degradation and food insecurity. In this context, the circular economy (CE) has emerged as a transformative paradigm that prioritizes waste minimization, resource efficiency, and regenerative production systems. Unlike the conventional linear model of "take-make-dispose," CE in agriculture fosters a closed-loop system where organic waste is repurposed into valuable inputs, and production processes are designed to preserve ecosystem health (https://ellenmacarthurfoundation.org/completing-the-picture).

The circular economy (CE) in agriculture focuses on maximizing resource efficiency by valorizing waste, implementing closed-loop systems, and promoting sustainable farming practices. It aligns closely with the principles of Resource Efficient and Cleaner Production (RECP)—a framework that seeks to optimize the use of water, energy, and materials while reducing emissions, pollution, and waste generation throughout the production process. Together, CE and RECP form a complementary foundation for transforming agriculture into a more sustainable and economically viable sector.

For Armenia—a landlocked and resource-constrained country with agriculture contributing significantly to employment and rural livelihoods—the adoption of CE and RECP principles are not only desirable but necessary. Yet, while Armenia has initiated pilot efforts and aligned some policies with EU environmental directives, the agriculture sector remains largely linear. Agricultural residues, including grape pomace, fruit peels, wheat husks, and animal manure, are often underutilized or discarded, contributing to environmental degradation and missed economic opportunities.

Materials and methods

This study argues that Armenia is uniquely positioned to leverage circular economy models and RECP strategies to transform its agricultural sector. Drawing upon international case studies, the research highlights both the potential impact and the necessary conditions for CE implementation in Armenia. These cases demonstrate how targeted investments in waste valorization, nutrient recycling, and regenerative practices yield substantial environmental, social, and economic benefits.

Through comparative policy analysis, investment profiling, and technological mapping, this paper identifies scalable strategies for Armenia to build a CE-aligned agricultural system. Special focus is placed on policy reform, financial mechanisms, capacity-building initiatives, and the alignment of Armenian practices with international CE and RECP standards. The paper further proposes a phased roadmap and monitoring framework to support long-term transition, aiming to reduce agricultural waste by 50%, increase the use of organic fertilizers by 40%, and expand CE-related infrastructure and certifications by 2040.

By embracing CE and RECP principles and adapting global best practices to its local context, Armenia can modernize its agricultural system, foster green innovation, and establish itself as a regional leader in sustainable food production.

Results and discussions

Agriculture, as both a major resource consumer and waste generator, is uniquely positioned to benefit from the integration of CE (https://ellenmacarthurfoundation.org/completing-the-picture) and RECP frameworks. These two interrelated concepts offer a strategic pathway to decouple agricultural development from environmental degradation, while enhancing productivity, climate resilience, and economic value.

Circular Economy in agriculture refers to a model that designs out waste, keeps resources in use for as long as possible, and regenerates natural systems. It emphasizes biological loops—where organic matter is continuously recycled into the soil through composting, biofertilizers, and other nutrient recovery processes—and technical loops, which involve the reuse and remanufacturing of agricultural equipment, irrigation systems, and packaging.

In the context of advancing the circular economy, it is essential to concurrently assess the principles and applications of RECP as a complementary framework for sustainable transformation. RECP is about optimizing resource use, minimizes waste, and reduces environmental impact while maintaining or improving productivity. RECP focuses on three main areas - efficient use of resources; minimizing waste and pollution; and enhancing economic and environmental performance. In agriculture, RECP is mainly applied through precision farming (https://www.unido.org/sites/default/files/files/2019-10/RECP_Guidelines.pdf).

Together, these two approaches offer a comprehensive strategy for agricultural sustainability—RECP minimizes resource consumption and waste generation, and CE ensures the regeneration and reintegration of those resources. In Table 1 below, it is presented the differences and similarities between these two terms.

In the context of Armenia, it is particularly relevant to conduct an in-depth examination of both the CE and RECP frameworks.

Within the CE, waste valorization refers to the process of transforming agricultural waste and by-products into valuable resources, rather than discarding them as pollutants - reusing waste as input for new production processes. This principle is central to the CE and focuses on extracting economic and environmental benefits from waste materials. At the same time, a closed-loop system focuses on reusing, recycling, and repurposing waste materials to minimize resource depletion and environmental impact (https://www.eea.europa.eu/themes/economy/resource-efficiency/country-profiles/estonia). Unlike a linear economy, which follows a "take-make-dispose" approach, a closed-loop system ensures that waste from one process becomes an input for another, reducing overall waste generation and enhancing resource efficiency. Key components of closed-loop systems includes nutrient recycling; biogas production from agricultural waste and water recycling and reuse (https://www.eea.europa.eu/en/analysis/publications/circular-economy-and-bioeconomy).

Table 1. CE and RECP: Similarities and differences*

Aspect	Circular Economy (CE)	RECP
Definition	An economic system aimed at eliminating waste and keeping resources in use for as long as possible.	A production-focused approach that enhances efficiency while reducing waste and pollution.
Main Goal	Designing out waste, keeping materials in circulation, and regenerating natural systems.	Reducing the use of natural resources and minimizing pollution during production.
Approach	Systemic transformation of production and consumption cycles.	Optimization of processes and resource inputs.
Focus Area	End-of-life resource reuse and regeneration.	Input use and waste prevention during production.
Stage of Application	Primarily applied at the end of the production cycle and beyond.	Applied early in the production process.
Key Strategies	Composting, recycling, reuse, bio-based production, product redesign.	Energy and water efficiency, cleaner production technologies, emissions reduction.
Environmental Impact	Reduces landfill, improves biodiversity, supports closed-loop nutrient cycles.	Reduces emissions, pollution, and water/energy waste.
Economic Benefit	Creates new markets for recycled products, boosts green innovation.	Lowers input costs, increases production efficiency, reduces environmental fines.
Role in Agriculture	Transforms waste into resources (e.g., compost, bioenergy); promotes regenerative farming.	Improves input efficiency in irrigation, fertilization, and energy use.
Relation to Sustainability	Focuses on long-term circularity and material sustainability.	Supports environmental compliance and operational efficiency.

*Composed by the authors.

At the same time, promoting sustainable farming practices involves adopting regenerative agricultural techniques that enhance soil fertility, conserve water, and reduce environmental impact. This includes crop rotation to prevent soil depletion and pest outbreaks, conservation tillage to protect soil structure and retain moisture, and organic fertilizers to replace synthetic inputs and restore natural nutrient cycles. Agroforestry, which integrates trees into agricultural landscapes, can enhance biodiversity, improve soil health, and sequester carbon, while precision farming technologies, such as drip irrigation and sensor-based nutrient management, optimize resource use and minimize waste. Additionally, reducing pesticide and herbicide dependency through integrated pest management supports pollinators, maintains ecosystem balance, and safeguards long-term productivity (https://www.fao.org/3/i6583e/i6583e.pdf).

It is evident that well-designed policy frameworks and targeted incentive mechanisms play a pivotal role in accelerating the transition toward a circular economy in the agricultural sector, by facilitating the widespread adoption of sustainable practices among farmers, agribusiness enterprises, and associated value chain actors. Effective policy interventions provide regulatory support, financial incentives, and institutional/regulatory frameworks that promote waste reduction, resource efficiency, and long-term environmental sustainability (https://www.oecd.org/en/data/datasets/policy-instruments-for-the-environment-pine-database.html).

Governments play a key role in promoting circular economy (CE) education by integrating CE principles into agricultural training programs. Through national training initiatives, digital platforms, financial incentives, and public-private partnerships, they can expand knowledge-sharing and support widespread adoption. These efforts empower farmers, boost resource efficiency, and foster sustainable growth.

Thus, RECP and CE are complementary approaches: RECP minimizes waste and pollution at the production stage, while CE focuses on reusing and recycling outputs into valuable products. Together, they offer a comprehensive model for sustainable and efficient agriculture.

Armenia is in the early stages of transitioning toward the CE, with key focus areas including agriculture, waste management, and energy efficiency. While CE principles have been recognized in national strategies and development dialogues—especially through Armenia's partnership with the European Union—their practical application remains fragmented and underdeveloped. The country's circular economy agenda is still largely driven by donor-supported pilot projects, scattered institutional efforts, and a limited number of policy commitments.

Table 2. Main Policy Frameworks and Sustainability Initiatives in Armenia*

	Policy/Initiative	**Description**
Circular Economy & Green Transition	EU-Armenia CEPA	Legal agreement aligning Armenia's environmental laws with EU directives.
	EU4Environment - Green Economy	Program to integrate circular economy, EPR schemes, and green governance.
	Green Agenda Project (2023-2026)	Project aligning Armenia with EU Green Deal principles and sustainability goals.
Waste Management	Law on Waste (2004)	Framework for waste classification, handling, and disposal.
	Law on Waste Collection and Sanitary Cleaning (2011)	Defines municipal waste collection responsibilities.
	National Waste Management Strategy (2017-2036)	Set goals for landfill reduction and recycling; repealed in 2021.
	Waste Sector Reform Plan (2024-2031)	World Bank plan proposing EPR schemes, regional landfills, and legislative updates.
	EPR Initiatives	Ongoing policy effort to implement producer responsibility schemes.
Water Management	Water Code of Armenia	Main law governing water allocation, protection, and use rights.
	EU Water Directive Alignment	Efforts to align national law with EU water policies under CEPA.
	Water Sector Adaptation Plan (2022)	Addresses climate-driven water security and adaptation.
	OECD Water Policy Reforms	Technical support to modernize Armenia's water governance.
Environmental Governance & Climate Policy	EIA and SEA Laws	Mandate project and policy-level environmental impact assessments.
	UNFCCC 4th National Communication	Reports Armenia's climate actions and obligations.
	Energy Sector Program to 2040	Long-term plan for renewable energy and GHG reduction.
ISO	ISO 14001	Environmental Management Systems (EMS)
	Armenia has not yet formally adopted or integrated the new ISO 59000 series including:	
	ISO 59004:2024	Circular economy - Vocabulary, principles and guidance for implementation
	ISO 59010:2024	Circular economy - Guidance on the transition of business models and value networks
	ISO 59020:2024	Circular economy - Measuring and assessing circularity performance
	ISO/UNDP WD 53001.2 – (emerging working draft)	Linking Circular Economy to the SDGs (Armenia has not incorporated it into policy discourse, training curricula, or investment screening mechanisms.)
Institutional & Civil Society Initiatives	ISO 37120	Sustainable development of communities - Indicators for city services and quality of life

*Composed by the authors.

An overview of Armenia's key laws, regulations, strategies, and initiatives related to the circular economy, environmental protection, waste management, and water governance are presented in the Table 2.

Armenia's commitments under the EU-Armenia Comprehensive and Enhanced Partnership Agreement (CEPA) have laid a solid basis for alignment with the EU Waste Framework Directive and the broader CE

Action Plan. Yet progress in legislative harmonization and institutional adaptation has been slow. Efforts remain scattered, and no central agency or legal framework for CE currently exists. This institutional gap has caused poor coordination between ministries and diminished the capacity for cross-sectoral CE planning. At the same time, Armenia's membership in the Eurasian Economic Union (EAEU) adds regulatory complexity, as EAEU policies on waste and environmental management are still developing and lack full alignment with CE principles. Navigating between EU and EAEU standards presents challenges in governance and implementation. Nonetheless, Armenia's experience in aligning with EU environmental norms and piloting CE initiatives enables it to act as a regional connector. It can support CE integration within the EAEU by sharing best practices, advocating for harmonized standards, and contributing to regional policy dialogue.

At the same time, international cooperation has played an instrumental role in seeding CE-related reforms and pilot initiatives. The EU4Environment Program has delivered policy support, RECP audits, EMS integration, and SME training. In parallel, the Green Agriculture Initiative (GIZ) has promoted eco-innovation and circular practices in rural agri-value chains. Programs such as SwitchMed and CirculUP! have contributed to the promotion of eco-entrepreneurship and sustainability in light industry and startups. While these initiatives demonstrate promise—particularly in composting, biogas production, and organic input innovation—they remain limited in geographic scope and heavily donor-dependent, with little integration into national policy structures.

Pilot projects, like those led by ORWACO and Armbiotechnology SPC, offer tangible models for circular farming and waste valorization, including composting and biofertilizer production. However, these remain isolated examples. National replication is constrained by insufficient co-financing, weak ownership by public institutions, and limited capacity building for rural actors.

On the financing side, Armenia has access to instruments like the Green Climate Fund (GCF) and the EBRD's Green Economy Financing Facility (GEFF). However, CE project uptake remains modest, largely due to regulatory uncertainties, limited bankable project pipelines, and gaps in technical proposal preparation. These constraints prevent effective mobilization of climate and green finance at scale.

In terms of sectoral potential, agriculture emerges as the most viable entry point for circularity—especially in the areas of waste valorization, closed-loop irrigation, composting, and biogas production. Despite this, the real-world application remains rare, and knowledge among farmers is low. Most actors lack the necessary information, training, and capital investment needed for a CE transition.

Systemic shortcomings are especially evident in the waste management sector. By 2022, Armenia's total waste generation reached nearly 60 million metric tons, including an estimated 400,000 metric tons of municipal solid waste (MSW). "Recycling rates in the country remain at a mere 4.5%, far behind the targets set by the EU's Circular Economy framework." The lack of waste separation at source, infrastructure for recycling and composting, and energy recovery systems underscores the urgent need for policy and investment reforms (Kurkdjian and Hayrapetyan, 2024).

In the energy and industrial sectors, there is growing conceptual interest in bioenergy (e.g., livestock waste-to-energy), but actual deployment is minimal, with only a few small biogas plants in operation. Concepts like industrial symbiosis, eco-design, and circular manufacturing are largely absent from current industrial policy. When green upgrades do occur, they tend to be donor-driven rather than market-driven, limiting their scalability and long-term impact.

In summary, Armenia's CE journey is at a critical juncture. Foundational strategies and international partnerships are in place, and the country has demonstrated initial success through pilot initiatives. However, progress remains hampered by fragmented governance, weak enforcement, insufficient financing, and underdeveloped infrastructure. With concerted action, Armenia can evolve from pilot-based initiatives to mainstream CE adoption, contributing meaningfully to the country's climate goals, economic resilience, and regional sustainability leadership.

To identify the most effective circular economy (CE) strategy framework for Armenia's agricultural sector, a comprehensive analysis of successful CE strategies is essential. Comparative success cases such as those of Italy, Georgia, Finland, Moldova, Spain, Estonia, and Serbia provide practical models that resonate closely with Armenia's own socio-economic and environmental context.

Launched in 2012, Italy's AgriWasteValue Project is a successful circular economy initiative that transforms olive oil production waste—such as pomace and leaves—into high-value bio-based products. Supported by the EU, the project promotes waste reduction, resource efficiency, and new income streams for farmers. Through advanced biotechnology, residues are converted into essential oils, antioxidants, and biopolymers with applications in pharmaceuticals, food, cosmetics, and bioplastics (https://www.agriwastevalue.eu/). This model has reduced environmental impact while supporting rural development and innovation. For Armenia, the AgriWasteValue experience offers practical insights into how similar waste—like fruit pulp, grape pomace, and wheat husks—can be repurposed into profitable, eco-friendly products, advancing both sustainability and economic diversification. Georgia has pioneered waste valorization in its winemaking sector, transforming grape pomace into bioethanol and organic fertilizers. This initiative not only reduces over 30,000 tons of winery waste annually but also cuts CO_2 emissions by 10–15% and enhances soil fertility (https://www.ge.undp.org/content/georgia/en/home/presscenter/articles/2021/grape-waste-to-green-energy.html). Georgia's success in transforming grape pomace into bioethanol and organic fertilizers is the result of a coordinated strategy that blends policy support, pilot demonstration projects, and collaboration with international partners such as the FAO, UNDP, and the World Bank. The strategy aligns waste valorization with Georgia's broader green growth and climate action agenda, integrating it into national policies that support the Sustainable Development Goals (SDGs). With the help of these international partners, the country introduced technologies such as fermentation systems and composting solutions specifically adapted for the wine sector. Public–private partnerships between wineries, research institutions, and technology providers enabled the scaling of pilot projects and the sharing of best practices across regions. These efforts were further reinforced by rural development goals, allowing wineries—particularly in wine-rich areas like Kakheti—to diversify income and create new employment opportunities.

Although incentive structures were limited, donor-supported subsidies and financing mechanisms helped small and medium-sized producers invest in waste processing infrastructure. Georgia also emphasized awareness-raising and capacity building, training farmers on the benefits of circular practices and sustainable soil management. Ultimately, Georgia's approach was not a standalone initiative, but part of a multi-stakeholder, internationally backed strategy embedded in the country's circular economy vision. Its experience illustrates how targeted sector-specific valorization, supported by both policy and practice, can drive sustainable transformation. As such, Georgia's model provides important lessons for Armenia and other wine-producing countries aiming to integrate circular economy principles into agriculture.

For Armenia, a country with a rich winemaking tradition, this model offers a replicable strategy to tackle agricultural waste, support renewable energy initiatives, and create rural employment. Establishing cooperative-based processing facilities and promoting policy incentives could help local producers scale up similar practices.

Finland has made significant progress in advancing nutrient recycling as part of its circular economy strategy in agriculture. By converting animal waste into biofertilizers through composting and bio-fermentation, Finland has reduced reliance on synthetic fertilizers, improved soil health, and minimized environmental impacts. The strategy's key components include policy support (setting clear targets, providing subsidies, and allocating €12 million in pilot funding to encourage nutrient recycling), infrastructure development (with over 130 biogas plants processing 2 million tons of waste annually to generate renewable energy and fertilizers), capacity building (training farmers in composting and fermentation, leading to the processing of over 600,000 tons of waste annually at composting centers), and integrated farming practices (such as precision fertilization and crop-livestock nutrient exchanges to minimize runoff and enhance fertilizer efficiency).) These efforts led to reduced chemical fertilizer use, lower GHG emissions, improved water quality, and the creation of over 5,000 jobs, while also positioning Finland as a leader in nutrient recycling technology exports (https://julkaisut.valtioneuvosto.fi/).

Finland's nutrient recycling strategy offers valuable insights for Armenia's transition to circular agriculture, particularly in transforming animal waste into biofertilizers through composting and bio-fermentation—reducing dependence on synthetic fertilizers while improving soil health and biodiversity. Armenia can adapt Finland's model by introducing targeted policy incentives, such as subsidies and pilot funding, and investing in biogas and composting infrastructure in livestock-intensive regions like Shirak and Gegharkunik. Additionally, Finland's emphasis on farmer training and research-based innovation highlights the importance of building capacity through institutions like ANAU. Integrated farming approaches—such as precision fertilization and regional manure exchange systems—further demonstrate scalable solutions Armenia could apply to optimize resource use and prevent environmental degradation. Notably, Finland's experience shows that nutrient recycling not only lowers emissions and water pollution but also generates green jobs and exportable technologies. Drawing from these practices, Armenia can build a sustainable, resilient, and economically viable nutrient management system aligned with its circular economy goals.

In Moldova, the agricultural sector has adopted decentralized composting systems, especially in fruit-producing regions. Small-scale composting units, farmer training, and policy incentives have driven the reuse of organic waste into biofertilizers, effectively closing the nutrient loop (https://www.fao.org/moldova/news/detail-events/en/c/1413636/). Armenia, particularly in the Ararat Valley and other fruit-growing areas, can benefit from this model by reducing dependence on synthetic fertilizers, improving soil quality, and supporting local compost markets.

Spain's AlVelAl Project demonstrates the value of regenerative agriculture, using no-till farming, agroforestry, and water-efficient irrigation to restore degraded land. The initiative has led to a 35% reduction in soil erosion, improved biodiversity, and a 20% increase in farmer income through organic certification (https://www.commonland.com/project/alvelal/). Given Armenia's semi-arid conditions, adopting similar practices can improve land productivity while also aligning with EU market standards for organic produce.

Estonia's national CE roadmap is a comprehensive example of policy integration. The country combines financial incentives for circular technologies, such as biogas and precision farming, with strong monitoring frameworks and mandates for on-farm composting (https://envir.ee/en/circular-economy-roadmap). Armenia can follow Estonia's lead by developing a CE roadmap that includes specific agricultural targets, regulatory reforms, and targeted funding.

Serbia has focused on education and capacity building, launching a national CE training program aimed at rural communities. By 2022, over 3,000 farmers were trained in composting and biogas production, and organic waste recycling in agriculture increased by 25% (https://www.rs.undp.org/content/serbia/en/home/library/environment_energy/circular-economy-capacity-building.html). Armenia, where awareness of CE principles remains limited among smallholders, can adapt Serbia's model to boost grassroots implementation through field demonstrations, digital learning, and financial support for training.

In conclusion, these countries offer complementary models that Armenia can customize to suit its agricultural landscape. Georgia and Moldova provide technical models for waste reuse and nutrient cycling. Spain and Estonia offer holistic approaches that combine land regeneration with economic and environmental monitoring. Serbia presents a blueprint for building long-term CE capacity among rural stakeholders. Integrating these lessons into Armenia's national strategy can accelerate the shift toward a resilient, low-waste, and high-efficiency agricultural sector aligned with CE principles and the Sustainable Development Goals.

Conclusion

Armenia should adopt a phased and complementary strategy integrating Circular Economy (CE) and Resource Efficient and Cleaner Production (RECP) to support sustainable agricultural transformation. Drawing on international best practices and adapted to Armenia's socio-economic and institutional realities, the strategy envisions three stages: short-term RECP implementation, mid-term CE infrastructure development, and long-term circular integration and export expansion covering 2026–2040 timeline.

Short-term - Foundation and Capacity Building (2025–2030) which will focus on RECP implementation in key agricultural zones, capacity building (e.g., at ANAU), and targeted incentives for cleaner production through prioritizing the integration of Resource Efficient and Cleaner Production (RECP) practices in Armenia's key agricultural zones, particularly in regions like Ararat Valley, Gegharkunik, and Vayots Dzor. The focus will be on improving input use efficiency, introducing clean technologies, and raising awareness among farmers and agribusinesses. RECP's accessibility and low capital requirements make it ideal for early adoption, especially among smallholders.

Key actions include:

- Launching national and regional RECP demonstration projects in water efficiency, composting, and nutrient management.
- Establishing capacity-building platforms, notably through ANAU and local agricultural extension systems, modeled after Serbia's CE education initiatives.
- Introducing financial incentives—grants, tax reductions, and cost-share schemes—for clean production tools and waste separation infrastructure.
- Drafting and adopting Armenia's first Agricultural Circular Economy Law, establishing institutional mandates and regulatory mechanisms in line with Estonia's CE roadmap.
- Formulating standards for compost, organic fertilizers, and processed agricultural waste that align with Circular Economy principles, in compliance with the ISO 59000 series and relevant European Union directives.

This phase also includes a national assessment of Armenia's priority organic waste streams—grape pomace, fruit pulp, livestock manure, orchard residues—to inform targeted pilot interventions. Inspired by Italy's AgriWasteValue project and Georgia's winery waste model, Armenia will initiate pilot projects for converting such residues into bio-based products including fertilizers, bioethanol, and bioplastics.

This phase is the most logical and impactful place to formally introduce training and education as a core pillar, which includes launching a National Circular Agriculture Training Initiative, coordinated with ANAU and regional agricultural colleges, to provide foundational knowledge in RECP and CE practices; developing modular training programs; establishing demonstration farms and model pilot sites in priority regions to serve as hands-on learning hubs; and introduce incentive-linked certification schemes, where farmers who complete training modules gain eligibility for CE-related grants, certification discounts, or green financing.

Mid-term - Infrastructure Development and System Integration (2026–2035), which will scale successful RECP practices into CE systems by developing compost-based products, biogas units, and aligning with EU CE policies.

Building on the institutional foundation and early RECP results, the second phase transitions toward scaling Circular Economy systems through infrastructure deployment and systemic integration. The goal is to shift from isolated pilot actions to regionally coordinated circular models, particularly in livestock-rich areas such as Shirak and Tavush, and horticultural centres like Ararat Valley.

Key priorities during this phase include:

- Developing regional composting hubs and nutrient recycling centres for organic fertilizer production, modeled on Moldova's decentralized composting approach.
- Installing biogas units and anaerobic digesters for livestock waste management and renewable energy generation, drawing on Finland's example where over 130 biogas plants support nutrient cycling and energy security.
- Promoting circular regenerative farming practices, including no-till farming, crop-livestock integration, and cover cropping, supported by technical assistance and co-financing.
- Streamlining organic certification processes and introducing partial reimbursement schemes to support farmers transitioning to CE-aligned production, taking lessons from North Macedonia.
- Establishing a CE Investment Facilitation Unit under the Ministry of Economy to coordinate national and international financing, liaise with donors (e.g., GCF, EBRD GEFF), and support PPPs in CE infrastructure.

In addition, a national closed-loop agriculture policy should be introduced to formally recognize circular farming practices and outline policy instruments for nutrient recovery, water recycling, and clean energy use. This policy will support the expansion of precision irrigation systems, greywater reuse, and farm-level composting, particularly in water-stressed regions like Armavir and Aragatsotn. In this phase, training becomes more specialized and operational covering scaling up advanced technical training; training extension officers and local CE specialists to support farmers during infrastructure rollout and integrating CE modules into vocational education and lifelong learning programs.

Long-term - circular maturity, export readiness, and global integration (2026–2004) which should establish full CE loops in half of Armenia's agricultural regions, adopt a national CE law for agriculture, and expand exports of low-emission, CE-certified products.

The final phase envisions the full institutionalization of CE practices across Armenia's agricultural value chains. By this stage, CE should be embedded in law, infrastructure, and market access, with active participation from farmers, cooperatives, academic institutions, and private investors.

Strategic outcomes by 2040 should include, but not limited:

- Establishing full CE loops in at least 50% of Armenia's agricultural regions, enabling efficient waste-to-product pathways for fertilizers, energy, and bio-based goods.
- Achieving a 50% reduction in agricultural waste, by valorizing organic residues through composting, fermentation, and bio-refining.
- Increasing organic fertilizer use by 40% and reducing synthetic fertilizer use by 30%, based on demonstrated outcomes from Finland and Moldova.
- Certifying 25% of Armenia's arable land for organic production, leveraging EU and Russian market demand and Estonia's proven growth path.
- Creating a 15% increase in CE-related jobs in rural areas through composting centers, CE education services, and sustainable farming cooperatives.

This phase will also focus on positioning Armenia in international CE trade networks. Dedicated CE branding, participation in EU green supply chains, and export certification for circular agri-products will help Armenian producers access premium global markets. Engagement with platforms such as the European Circular Economy Stakeholder Platform and FAO organic networks will strengthen Armenia's global visibility.

Monitoring systems will be operationalized by 2035, using national CE indicators to track GHG reductions, waste recovery rates, soil health improvements, and circular employment growth. Annual progress reviews will ensure policy adaptation and stakeholder feedback loops.

In this phase, education supports institutionalization and export competitiveness including launching the Circular Economy Academy; organizing annual CE innovation forums and promoting CE education in agricultural trade fairs and certification programs.

Through this phased 2026–2040 strategy, Armenia can progressively transform its agricultural sector from a linear, input-intensive system to a circular, regenerative model rooted in efficiency, innovation, and inclusiveness. International experience shows that successful CE implementation requires both top-down policy frameworks and bottom-up engagement from farmers, educators, and local businesses. With careful planning, financing, and learning-by-doing, Armenia can position itself as a regional leader in sustainable, circular agriculture—delivering economic, environmental, and social benefits for decades to come. At the same time, Armenia should act as a pioneer within the EAEU to bring all members' economies into the circular economic models.

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Declarations of interest
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Enhancing Food Loss and Waste Management for Improved Sustainable Agri-Food System: Empirical Study in the Republic of Armenia

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ABSTRACT

This study investigates the relationship between food security and waste management in Armenia's agri-food system, which faces challenges such as low productivity, small landholdings, soil degradation, and inefficiencies in livestock and crop production. These issues contribute to food insecurity and dependence on imports. Emphasizing the importance of reducing food loss, the research analyzes data from 2005 to 2022 to identify correlations between food loss and variables such as food import, use, and export. The findings indicate that increased imports, use, and exports of food commodities are linked to higher food loss. Statistical and regression analyses highlight the impact of these factors on food waste and security, identifying key areas for intervention. Recommendations for reducing food loss include improving infrastructure for food imports, enhancing supply chain efficiency, and investing in better storage and preservation facilities. The study advocates for applying circular economy principles, such as redistributing surplus food and valorizing food waste. Strategies like community-supported agriculture (CSA) and clustering actors in the agri-food value chain are suggested to reduce waste and promote sustainable practices.

Introduction

Agriculture is an important sector in Armenia's economy, although its contribution to the country's value-added has been diminishing over the past five years due to low level of productivity and efficiency, lack of infrastructure and market development (MoE, 2024). The favorable soil and climate conditions create huge potential for agriculture to emerge as a leading driver of economic growth in the foreseeable future (EU, 2020). To stimulate the advancement of the agricultural sector, the Government of Armenia is providing ongoing support with targeted policies for improving the status. This support aims to facilitate improved access to finance, encourage the broader adoption of advanced technologies, and enhance farming productivity. Currently, around 30% of the Armenian workforce is employed in the agriculture. According to the International Trade Administration, over 335,000 farms are currently operational in Armenia, each holding an average land area of 1.4 hectares per household (International Trade Administration). However, these relatively small landholdings hinder the development of an efficient and diversified production system encompassing both crops and livestock. Soil degradation is also a significant concern, compounded by the fact that only 15 percent of Armenia's total territory is arable land, despite agricultural land making up 70 percent of the country's territory. The livestock sector is confronted with several challenges, including unsustainable pasture management and underutilization, persistent livestock diseases, processing and marketing limitations, and declining productivity (International Trade Administration). Due to these factors, imported meat now constitutes half of the nation's meat consumption, reflecting the inadequacies in the domestic livestock sector and the unreliable availability of meat and milk. Notably, there are substantial fluctuations in the supply of dairy products, with most of the milk produced during the summer months and scarce availability during the winter and spring seasons. These constraints undermine Armenia's ability to capitalize on opportunities arising from growing domestic and international demand. In the crop cultivation, as well as in vegetable and fruit processing sector the major issues evolve around the storage, transportation and infrastructure development causing food waste and loss. On the other hand, the agri-food processing sector has been pivotal in the country's economy, dating back to the Soviet era. It has a significant role for rural employment, income generation, and ensuring food and economic security for the state. Moreover, it fosters a stable supply of safe, high-quality food for the population- while contributing to market dynamics and agricultural stability (MoA, 2024). In the food sector, there are 1600 companies, which include fruit and vegetables processing, grape processing, milk processing, meat processing and slaughtering, fish processing, bread baking, confectionary production, mineral and drinking water production, nonalcoholic beverage production, and alcoholic beverage production.

According to the Ministry of Economy of RA, the ramping up of processing operations and increasing export volumes have notably eased agricultural product sales challenges and boosted farm marketability. In 2019, Armenia witnessed a 10.7 % increase in foreign trade turnover of agrifood products, amounting to $1,671.7 million. Imports totaled $866.6 million, constituting 15.7 % of total imports, while exports reached $796.4 million, comprising 30.2 % of total exports. Notably, agrifood exports increased by 12.5 %, driven by products such as fresh fruits, vegetables, beverages, canned goods, and fish.

Literature Review

As outlined in the 1996 World Food Summit, food security is achieved when individuals consistently have both physical and economic access to enough safe and nutritious food to meet their dietary requirements and preferences for an active and healthy lifestyle (Shaw, 2007).

There are four major aspects to consider within food security (FAO, 2008):

- *Physical availability of food:* This pertains to the supply aspect of food security and relies on factors such as food production levels, available stock, and trade balances (Gibson, 2012).
- *Economic and physical access to food:* Merely having sufficient food at the national or global level doesn't ensure food security at the household level. Issues regarding inadequate access to food have led to increased attention on factors like income, spending, market dynamics, and prices to achieve food security goals.
- *Food utilization:* Utilization refers to how effectively the body absorbs and utilizes nutrients from food. Adequate nutrient intake depends on factors such as caregiving practices, food preparation methods, dietary diversity, and fair distribution within households. The combination of these factors, along with effective biological utilization, determines individuals' nutritional status.
- *Stability of the other three dimensions over time:* Food security isn't just about having enough food today; it's also about maintaining consistent access over time. Even if an individual's food intake is adequate presently, periodic disruptions in access due to factors like adverse weather, political instability, or economic fluctuations (such as unemployment or rising food prices) can lead to food insecurity and nutritional deficiencies.

For food security to be achieved, all four dimensions must be addressed concurrently and continuously (WB, 2024). From 2015 to 2022, the self-sufficiency rates for various food commodities have displayed notable fluctuations, highlighting the intricate dynamics within agricultural production systems. However, according to the Ministry of Economy, examination of the Republic of

Armenia's national food accounts data for 2019 indicates that the self-sufficiency level of crucial food items, as measured by their energy value, stood at approximately 52.5 % (MoE, 2019). While some commodities, such as potatoes and vegetables, have consistently maintained high levels of self-sufficiency, others, like wheat and maize, have witnessed a decline in their self-sufficiency rates over the same period. These shifts underscore the multifaceted influences impacting food production and self-reliance, ranging from environmental factors and technological advancements to market forces and policy decisions. Notably, the self-sufficiency rates for certain fruits, such as figs and berries, have shown remarkable growth, possibly reflected changing consumer preferences or shifted in agricultural practices. However, challenges remain, particularly in achieving self-sufficiency for staple crops, highlighting the need for targeted interventions and sustainable strategies to enhance food security and resilience. As efforts continue to build a sustainable food system, understanding and addressing the fluctuations in self-sufficiency rates across different food categories become paramount. These fluctuations not only reflect the complexities inherent in agricultural production but also have significant implications for food security and economic stability at both national and global levels. By identifying the underlying drivers of these fluctuations and implementing targeted policies and initiatives, stakeholders can work towards enhancing self-sufficiency in key food commodities while fostering resilience in the face of evolving challenges such as climate change, population growth, and resource constraints (Tchonkouang et al. 2024). Ultimately, achieving sustainable food security requires a holistic approach that considers the diverse range of factors influencing food production, distribution, and consumption, thereby ensuring access to nutritious and affordable food for all (Pawlak and Kołodziejczak 2020). Additionally, the disparities in self-sufficiency rates underscore the interconnectedness of global food systems and the need for collaboration and coordination among nations. While some regions may excel in the production of certain commodities, they may rely heavily on imports for others, highlighting the importance of international trade in ensuring food security (Unnevehr 2003). However, overreliance on imports can also expose countries to risks such as supply chain disruptions and price volatility. Therefore, promoting a balanced approach to food production that integrates both domestic production and trade becomes imperative for building resilient food systems capable of withstanding shocks and meeting the diverse needs of growing populations. Fostering cooperation and investing in sustainable agriculture practices, nations can work together to address the challenges posed by fluctuating self-sufficiency rates and pave the way for a more secure and equitable food future. On top of the self-sufficiency, the Global Food Safety Index was calculated for the first time, revealing an overall score of 57.1 with regards to food security. This score comprised sub-indices of 51.7 for food product availability, 66.2 for accessibility, and 45.4 for quality and safety. In the discourse of the food security, it's imperative to address the issue of food waste in Armenia. This underscores the importance of economic efficiency, emphasizing the need to produce food for those in need while minimizing significant losses due to spoilage or logistical inefficiencies. It prompts a reflection on the ethical concerns imposed by the current production system on our society (Santeramo, 2021). Another study, that has highlighted the role of associations between food waste, loss and food security, belongs to Marsh et al. Their findings suggested that food losses are a persistent issue across most traded agricultural commodities. These studies have given credibility to the body of literature dedicated to investigating how food losses increase the risk of food insecurity, particularly in developing countries reliant on trade and in need of innovative solutions. Below food waste and loss within various parts of the food supply chain in the Republic of Armenia has been investigated. It is crucial to emphasize that when assessing the extent of losses, one must also highlight the level at which the product is produced and imported. According to a study conducted by Urutyan and Yeritsyan (2014), the food waste and loss in Armenian agri-food industry happens due to the following reasons:

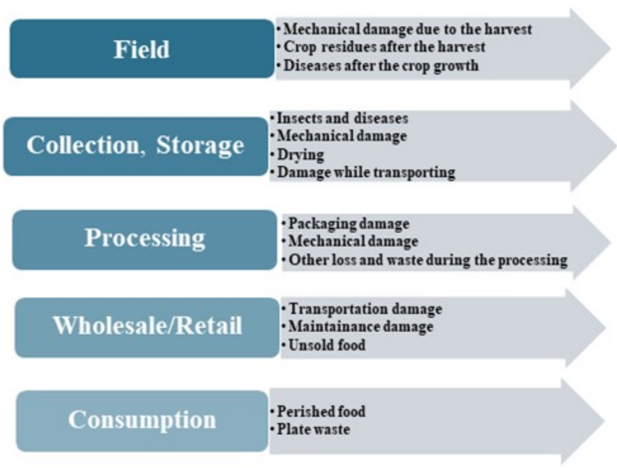

Figure 1. The reasons of the agri-food waste and loss

Foods characterized by a relatively elevated self-sufficiency level exhibit a diminished apparent waste volume. For instance, the self-sufficiency level of milk in the Republic of Armenia witnessed an augmentation to 99.34% between 2016 and 2022, in contrast to the average of 85.64% recorded during 2011-2015. Despite a substantial surge in milk imports, amounting to an 83% increase in 2022 compared to 2005, no discernible alterations were noted in terms of losses. Throughout the period spanning 2005-2022, annual milk losses remained below 1% of the total quantity of milk produced and imported. A parallel trend was observed in the case of another highly self-sufficient food product, namely eggs. The self-sufficiency level for eggs from 2016-2022 also stood at 99.34%, with production volume experiencing growth in recent years compared to 2005. In 2022, there was a 45% surge in egg production; however, the waste per imported and produced egg during the same period averaged below 3%.

Materials and methods

In this study have analyzed annual statistical data collected from the Armstat database. We aimed to analyze the relationship between food loss and different food security indicators across various groups of food commodities, namely grains, vegetables, fruits, meat, and beans, using panel data from 2005 to 2022. Panel data, which combines cross-sectional and time-series data, provides a robust framework to observe and analyze these relationships over time.

As a result, we have acquired 828 observations. The dependent and independent variables are provided below:

Table 1. Variables for Food Loss Estimation in Armenia*

Dependent Variable	Independent Variable
Food Loss (thousand tonnes) (FL)	(1) FCI- Food Commodity Import
	(2) FCU – Food Commodity Use
	(3) FCE – Food Commodity Export
	(4) FCP – Food Commodity Production
	(5) FCS – Food Commodity Storage
	(6) OE – Other Uses

*Composed by the authors.

Utilizing a log-log model, our analysis expresses the data in terms of percentage changes. This approach offers a nuanced perspective, emphasizing the relative shifts rather than absolute values.

Our next step was to conduct a pair-wise correlation study of the selected dependent and independent variables. Scatter plots reveal moderate to strong relationships between food loss and various food commodity-related factors. Notably, there are robust positive correlations indicating that increases in food commodity imports, production, storage, commodity use, exports, and other uses are linked with increases in food loss.

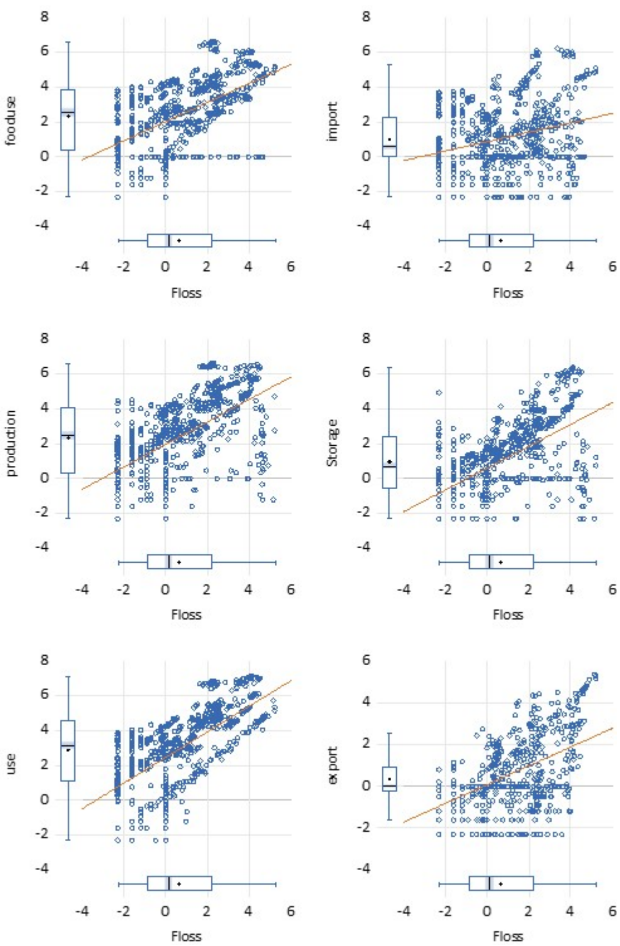

Figure 2. Scatter Plot Map of the Variables Selected

Results and discussions

Import and food use exhibit a positive correlation (0.621), suggesting that higher imports are associated with increased food use. This relationship implies that regions importing more food tend to consume more, possibly due to better availability and variety. Imports and export show a week positive correlation (0.277), indicating that regions with higher imports also tend to export more. Food use and overall use have a very strong positive correlation (0.902), meaning that higher food consumption directly contributes to overall use of the produce, which is expected. Export and overall use also share a moderate positive correlation (0.281).

Table 2. Matrix of Correlation

Variables	(1)	(2)	(3)	(4)	(5)	(6)
(1) FCI	1.000					
(2) FCU	0.621	1.000				
(3) FCE	0.359	0.250	1.000			
(4) FCP	0.247	0.698	0.187	1.000		
(5) FCS	0.318	0.574	0.244	0.708	1.000	
(6) FCOU	0.546	0.903	0.376	0.751	0.639	1.000

*Composed by the authors.

To avoid multicollinearity, we have excluded the FCOU variable from the model due to its strong correlation with "food use." Given our research focus, we determined that it is more appropriate to concentrate on "food use" and omit "overall use" to ensure the clarity and reliability of our analysis.

In analyzing panel data, Pooled OLS, Fixed Effects (FE), and Random Effects (RE) regression models were employed. Pooled OLS, a basic linear regression method, treats all data points equally without considering individual or time-specific variations. FE models, by contrast, eliminate the influence of time-invariant characteristics, like culture, enabling the assessment of net predictor effects. RE models, assuming random and uncorrelated variations across entities, provide flexibility but make stronger assumptions about individual-specific effects. The choice between FE and RE was determined through Hausmann test, which assesses the correlation between individual effects and predictors.

Table 3. Hausman Test

	coef.
Chi-square test value	4.543
P-value	0.209

*Composed by the authors.

The test yielded a chi-square value of 4.543 and a P-value of 0.209. Since the P-value is greater than the significance level of 0.05, we fail to reject the null hypothesis. This indicates that the random effects model is suitable for our data. The results of the regression analysis are provided below and as can be noted from the scatter plot map and the regression output, the coefficients have the signs which were supposed theoretically.

loss	Coef.	St.Err.	t-value	p-value	[95 % Conf	Interval]
(1) Import	.183	.0375	4.7	0.00	.1092885	.2567116
(2) Food Use	.686	.040	17.1	0.00	.6074536	.7649292
(3) Export	.465	.025	17.9	0.00	.4141026	.5158853
(4) Storage	.070	.003	2.04	0.00	.0028004	.1512413
(5) Production	.182	.039	4.66	0.00	.1058421	.2598068
Constant	.618	.008	6.95	0.00	.5333957	.7933957

Mean dependent var	0.732	SD dependent var	2.088
R-squared	0.615	Number of obs	828
F-test	36.25	Prob > F	0.000
Akaike crit. (AIC)	1872.110	Bayesian crit. (BIC)	1896.021

*** p<.01, ** p<.05, * p<.1

The coefficient for Food Commodity Import (FCI) is 0.183, and it is highly significant (p<0.01). This coefficient suggests that a 1 % increase in food commodity imports is associated with an average increase in food loss by 0.183 %. This could be due to several reasons. One possibility is that higher imports of food commodity might need longer transit times and more complex supply chains, increasing the likelihood of spoilage or damage during transportation and storage (Kiaya 2014). In addition, importers may not have the necessary infrastructure or expertise to properly store and handle imported food, leading to higher rates of spoilage or contamination.

The coefficient for Food Commodity Use (FCU) is 0.686, indicating a strong positive relationship with food loss. This variable is also highly significant (p<0.01). A 1 % increase in the use of food commodities is associated with an average increase in food loss by 0.686 %. Increased use might lead to more pressure on the supply chain, potentially causing more waste if the infrastructure is not adequate to handle higher volumes efficiently.

With a coefficient of 0.465, Food Commodity Export (FCE) shows a positive and highly significant (p<0.01) relationship with food loss. A 1 % increase in food commodity exports is associated with an average increase in food loss by 0.465 %. This could be due to the complexities and challenges involved in exporting goods, such as longer transportation times and the risk of spoilage, which can contribute to higher food loss. The coefficient for Food Commodity Use (Other) (OU) is 0.077, with a p-value of 0.042, making it moderately significant. This positive relationship implies that a 1 % increase in other uses of food commodities is associated with an average increase in their loss by 0.077 %. Diversifying the ways in which food commodities are utilized can add complexity to the supply chain, potentially leading to more waste. Food Commodity Production (FCP) has a coefficient of 0.183, which is highly significant ($p<0.01$). The positive relationship suggests that a 1 % increase in food commodity production is associated with an average increase in food loss by 0.183 %. This correlation can be attributed to several factors. Firstly, higher production levels can lead to excess supply, which may put strain on distribution and storage systems and ultimately increase the amount of food that goes to waste. Additionally, peak harvest periods, market dynamics, and downward price pressures can exacerbate these challenges, prompting farmers to discard excess produce. Quality control issues, logistical constraints, and inadequate storage and preservation facilities further contribute to spoilage and wastage, underscoring the complex interplay between production levels and food loss. The coefficient for Food Commodity Storage (FCS) is 0.08, with high significance ($p<0.01$). This relationship indicates that a 1 % increase in food commodity storage is associated with an average increase in food loss by 0.08 %. Effective storage solutions can significantly reduce spoilage and waste, thereby decreasing food loss. The regression model has an R-squared value of 0.616, meaning that approximately 61.6 % of the variance in food loss is explained by the independent variables included in the model. The overall model is highly significant, as indicated by the F-test ($p<0.01$). The Akaike Information Criterion (AIC) and Bayesian Information Criterion (BIC) values are 1780.033 and 1808.347, respectively, providing measures of the model's goodness of fit. In the context of Armenia, the findings from this regression analysis shed light on the critical factors influencing food loss within the country's agricultural sector. The significant coefficients for Food Commodity Import, Use, Export, and Production emphasize the need for targeted interventions to mitigate food loss at various stages of the supply chain. The highly significant coefficient for Food Commodity Import suggests that Armenia's reliance on imported food commodities may be contributing to increased food loss. To address this, there is a need to enhance the infrastructure and expertise for handling imports, including better transportation, storage, and distribution systems. Reducing transit times and improving the efficiency of supply chains can help minimize spoilage and damage. Similarly, the strong positive relationship between Food Commodity Use and Food Loss indicates that as the utilization of food commodities increases, so does the pressure on the supply chain. Investing in robust infrastructure, including modernized storage facilities and efficient logistics, is essential to handle higher volumes and reduce waste. The positive coefficient for Food Commodity Export highlights the challenges associated with exporting goods, such as longer transportation times and the risk of spoilage. Enhancing export processes and ensuring that exported food commodities are well-preserved during transit can help mitigate these losses. Food Commodity Production also shows a significant impact on food loss, pointing to the need for effective management of production surpluses and improved quality control measures. Implementing better storage and preservation facilities, especially during peak harvest periods, can help reduce spoilage and wastage.

The coefficient for Food Commodity Storage, although lower compared to other variables, underscores the importance of effective storage solutions in minimizing food loss. Investing in advanced storage technologies and practices can significantly reduce spoilage and waste.

Incorporating circular economy principles into Armenia's agricultural sector can further enhance the efficiency and sustainability of food systems. A circular economy approach emphasizes the reduction of waste and the continual use of resources. This can be achieved through several strategies:

- *Redistribution of Surplus Food:* Surplus food that is still safe for consumption can be redistributed for social purposes and other organizations to support vulnerable populations, reducing food waste and improving food security.
- *Valorization of Food Waste:* Food waste can be converted into valuable by-products, such as animal feed, compost, or bioenergy. This not only reduces waste but also creates additional revenue streams for farmers and businesses.
- *Improved Packaging and Storage Solutions:* Using innovative packaging and storage technologies can extend the shelf life of food commodities, reducing spoilage and waste during transportation and storage.
- *Enhanced Supply Chain Coordination:* Implementing better coordination and communication across the supply chain can help match supply with demand more

accurately, minimizing excess production and waste.

- *Education and Awareness:* Raising awareness among consumers and stakeholders about the importance of reducing food waste and adopting circular economy practices can drive behavior change and promote more sustainable consumption patterns.

Community Supported Agriculture and Cluster Solutions to Existing Challenges

Due to economic, ecological, and ethical reasons many stakeholders in the agri-food sector agree that a fundamental transformation is necessary, asserting that the current system is unsustainable (German Commission for the Future of Agriculture, 2021). Agroecology is one proposed approach, aiming to transition towards an agri-food system that is sustainable in ecological, economic, and social terms, characterized by direct relationships between producers and consumers (Gliessman, 2016). According to Gliessman (2016) and Méndez et al. (2013), community-supported agriculture (CSA) represents a form of institutional or social innovation that can drive this transformation, providing an alternative to the current system (Mert-Cakal and Miele, 2020).

"CSA is a direct partnership based on the human relationship between people and one or several producer(s), whereby the risks, responsibilities and rewards of farming are shared, through a long-term, binding agreement" (URGENCI 2016).

A significant distinction from traditional farming and consumption is that a social mechanism, rather than the price mechanism, governs the market's dynamics (Gruber 2020). CSA members collectively decide on the types of produce, the cultivation methods, and a local distribution channel, basing their choices on moral and ethical considerations and shared values such as regionality (Wellner and Theuvsen 2016). Fostering solidarity between CSA members and farmers is crucial to advancing key principles like responsible resource management, equitable conditions for everyone involved, seasonal and locally based agroecological production, as well as openness, dialogue, and direct personal connections(Carlson and Bitsch 2019). Moreover, CSAs can significantly reduce the waste associated with our food system, which is another strong selling point that can help attract more members. When CSA members become more closely involved in food production, they become more aware of the factors that affect produce quality. They are much more likely to accept completely edible but imperfect-looking produce, such as misshapen carrots or blemished apples, which would likely be rejected by supermarkets. CSA programs can significantly reduce waste through a variety of innovative practices. Firstly, they can supply produce in reusable bags or boxes that can be returned by members. When packaging is necessary, CSAs can opt for recyclable or compostable materials. Loose produce can be placed directly into boxes to minimize packaging needs. To further cut down on plastic waste, CSAs can ask members to recycle plastic punnets or return them for reuse. Offering different share sizes allows members to choose the quantity that best fits their household, thereby reducing the risk of produce going unused. Surplus fruit can be processed into juice or cider, which can be sold or enjoyed at events. Additionally, organizing a team to make chutneys, jams, or fermented foods ensures that extra produce is preserved and utilized. Excess produce can be redirected to charities, food banks, or food waste initiatives such as Food Cycle, helping to ensure that surplus food is put to good use rather than being discarded (European Union, 2019). Volunteers or staff can take home any excess produce, and organizing communal meals using gluts of produce helps ensure that all food is consumed. Vegetable waste can be fed to livestock, and any remaining organic waste can be composted on the farm, completing the cycle of sustainability.

Conclusions

The study explores the relationship between food loss and food security implications in Armenia. The agricultural sector in Armenia faces challenges like low productivity, small landholdings, soil degradation, and inefficiencies in livestock and crop production. These challenges lead to food insecurity and reliance on imported products. The study emphasizes the importance of addressing food loss to improve economic efficiency and food security. It also analyzes data on food loss in Armenia from 2005 to 2022, emphasizing the relationships between food loss and variables such as food imports, consumption, and exports. The findings suggest that higher imports, use, and exports of food commodities are associated with increased food loss. The study applies statistical methods to demonstrate how these factors influence food waste and food security in Armenia. Through regression analysis, it pinpoints the main determinants contributing to food loss within the country's agricultural sector. Import, use, export, and production of food commodities play significant roles, suggesting a need for interventions at various supply chain stages. Strategies to reduce food loss include enhancing infrastructure for food imports, improving supply chain efficiency, and investing in better storage and preservation facilities. Circular economy principles, such as redistributing surplus food and valorizing food waste, offer additional ways to minimize waste. Community-supported agriculture and clustering actors in the agri-food value chain are recommended for reducing food waste. CSAs allow for direct producer-consumer relationships, promoting sustainable practices and reducing waste. Cluster solutions involve different sectors collaborating to enhance efficiency and sustainability, ultimately reducing food loss and promoting responsible resource use. Promoting consumer awareness and sustainable consumption practices is also crucial in driving a shift towards a more sustainable food system.

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Digital Tools Paving the Path towards a more Sustainable and Resilient Agricultural Production

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ABSTRACT

Agriculture faces numerous challenges ranging from climate change to a dramatic decrease in labor force. Making agriculture more sustainable and resilient summarizes all the challenges also including economic welfare and environmental aspects.

Different technologies and methods have been suggested to achieve the aim of increasing sustainability and resilience, such as the reduction of meat consumption, the replacement of meat by in-vitro meat and the application of advanced breeding methods such as CRISPR/Cas.

Another option helping to improve agricultural production with respect to economic, ecological and social aspects is the application of digital tools also known as Precision Farming or Digital Farming. These tools and the related resources have become increasingly attractive due to (1) a strong decline in prices for software, hardware and data, (2) the increasing availability of data and (3) the increasing accuracy and resolution of data and sensor systems.

Introduction

Agricultural production heavily interfaces with natural resources and thus affects, amongst others, water quality, human health and biodiversity. At the same time agriculture is the primary source of feed, food, energy and raw materials covering the basic needs of human beings (physiological needs according to Maslow). Thus, reducing agricultural production with respect to area or its intensity for the sake of reducing its impact on environmental resources is not an option.

A growing world population and given the limited resources with respect to the agricultural production area even requires an increase in production per area due to a growing demand for food, feed, raw materials and energy. At the same time the number of people involved in farming is decreasing worldwide and is in some regions already at a low level. With farm sizes growing in most parts of the world, we are also facing the problem of knowledge erosion (Brodt, 2001) where less people farm more land and traditional knowledge about local variations of soil and weather conditions is declining.

We can summarize the boundary conditions for agricultural production as follows: "We need to increase production on the existing production area with less input of labor and material". For meeting these conditions, the efficiency of production must be increased, we need to produce more output with less resources (labor, fertilizer, agrochemicals).

Looking at the potential to increase production, there seems to be room for improvement to different extents depending on the region: some European countries already have achieved up to 88% of their production (Home - Global Yield Gap Atlas, 2025), other areas may even double production when comparing the current level to the yield potential being limited by soil and climatic conditions.

Figure. Winter wheat yield gap in Europe (data source: www.yieldgap.org/).

In the past decades machinery size has grown continuously which has helped to increase efficiency, especially with respect to labor input and acreage performance. However, both the size and the weight of machinery has now reached its limits given by legislation (operation on public roads) and application constraints: the lateral accuracy of distribution (straw, fertilizer, agrochemicals) generally degrades with increasing working width and is thus counter-productive when it comes to increasing precision.

Several options, tools and technology may help to increase efficiency and reduce negative impact on humans and natural resources. New breeding methods such as CRISPR/Cas can help to increase yield based on given resources, reduce the susceptibility to plant diseases and help to mitigate plant stress induced by the consequences of climate change. Productivity may also be increased by reducing the production and consumption of meat in favor of alternative protein sources such legumes or even cultured meat (cellular agriculture).

Last, but not least, data driven and automated for agriculture may play an important role when it comes to increasing productivity. This is supported by both continuously decreasing prices and increasing accuracy of digital tools and an increasing volume of data being and becoming available at no cost.

Materials and methods

Current State of Knowledge

One core technology in digitalization is software. With the concept of FOSS (Free and open-source software) numerous solutions with the capability to support digital solutions in agriculture have become available at no cost during the last decades. They range from operating systems such as Linux or (ROS: Home, 2025) (Robot Operating System), over programming languages ((Welcome to Python.Org, 2025), Java), data science environments (R Statistic, Knime), geographic information systems ((QGIS Web Site, 2025), (SAGA - System for Automated Geoscientific Analyses, 2025)) to various database systems (MySQL, PostgreSQL, Hadoop). The ability to store and process data with these tools opens the door for a wide range of applications to support agricultural decision support and the automation of processes with no financial investment.

The amount of publicly available data sources has been steadily increasing over the last decades as well, serving as an input for the software solutions listed above. Geodata in general is being made available by public authorities and especially the Space agencies such as the (European Space Agency, 2025) (European Space Agency), the (USGS, 2025) (U.S. Geological Survey) and the (USDA, 2025). Correction data for GNSS systems is provided free of charge on a European level ((EGNOS | EU Agency for the Space Programme, 2025)) and on a national level (e.g. (SAPOS - Satellitenpositionierungsdienst der Deutschen Landesvermessung, 2025)). Different entities offer access to weather data (e.g. (Current Weather and Forecast - OpenWeatherMap, 2025), (WMO OSCAR | Observing Systems Capability Analysis and Review Tool - Home, 2025)), soil data (e.g. (ISRIC — World Soil Information, 2025)) and a wide range of statistical data ((FAOSTAT, n.d.)).

Numerous hardware systems, such as sensors and controllers, have become available or dramatically dropped in price during the past years. One example is GNSS technology enabling the measurement of position, time, speed and movement of direction thus serving as basis for data acquisition and automation of processes and complete machines. RTK-GNSS receivers with an accuracy of 2,5 cm (1 inch) were available on a price level of between 20.000 US$ and 50000 US$ when they were first introduced in the 1990s leaving almost no room for commercially viable applications in agriculture. The prices have lately dropped far beyond 1000 US$, paving the way to completely new applications in the field of agricultural production. Also, cameras, ultra sonic sensors, microcontrollers (e.g. Arduino, ESP32) and single board computers (e.g. Raspberry PI) are substantially cheaper than some years ago, enabling the collection of additional data from fields, barns, greenhouses and storage silos serving as supplementary data sources for decision support and automation. The wireless transmission of data is supported by decreasing prices for using mobile networks and new technologies such as (LoRa Alliance - Homepage, 2025) and (Sigfox, 2025).

The ability to acquire images or spectra beyond the wavelength of visible light (UV and NIR) as well as capturing noises and vibrations with microphones also opens new applications in agriculture but also represents a challenge when it comes to transforming multivariate data into information. Audio and image data will vary with respect to the frequency/wavelength, in the space and in the time domain producing large numbers of input variables with mostly only one target information.

Artificial Intelligence (AI) and especially Artificial Neural Networks are concepts that have been designed to recognize patterns in multivariate datasets and have proven to be helpful when focusing large amounts of data to predict practically relevant information for agricultural decision making. Fortunately, the application of AI has been supported by the development of intuitive interfaces and an increased computing performance.

Results and discussions

The challenges which agriculture is facing due to the declining workforce, the demand for protecting natural resources by minimizing the application of fertilizer and agrochemicals may be addressed with digital tools helping to increase efficiency.

However, some issues need to be addressed to pave the path of digital tools in the future:

Given the trends that software and data are mostly available at no cost and the cost for sensors and hardware is continuously decreasing, it is the lack of well trained and educated people making use of these opportunities slowing the adoption of digitalization in agriculture.

The varying quality of data with respect to accuracy and its representation of physical properties as well as the lack of relevant metainformation about available data currently requires substantial data curation for deriving relevant information from data for increasing the efficiency of agricultural production.

Data and information need to be handed over different routes towards a process finally deriving recommendations and decision support. Fostering resilient data flow and enhancing interoperability between different data sources and processes requires the adoption of open and standardized interfaces.

The acceptance of end users and the reduction of operating errors relies on the user centric design of both software and hardware given the fact that the majority of end users only have low to medium skills with respect to computer literacy.

Conclusion

While having negative impacts on the environment, agriculture is a key business sector delivering food, feed, energy and raw materials and thus serves the basic needs of all human beings. Apart from environmental aspects it is currently facing additional challenges like the stagnating amount of production area, the decrease in workforce and the large variability of production environments which are reinforced by climate change.

Digital Tools can address some of the issues with decision support and automation, especially given their declining costs and availability. However, extended training and education, enhanced data quality, the development and adoption of open standards and the user centric design of digital solutions need special attention to accelerate the adoption of digital solutions into agricultural processes.

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Leveraging Nanotechnology and Radiometric Sensing For Sustainable Agriculture: Innovations For Green Growth

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ABSTRACT

In the context of the global shift towards sustainable agriculture, innovative technologies play a pivotal role in enhancing environmental management and productivity. This paper explores the integration of nanotechnology and radiometric sensing techniques to optimize agricultural practices, reduce environmental impacts, and promote long-term sustainability. By harnessing the power of nanomaterials and advanced sensors, we can achieve more precise soil analysis, water management, and crop health monitoring, addressing key challenges in modern agriculture. Nanotechnology offers solutions for enhancing soil nutrient delivery, improving crop resistance to climate stress, and fostering efficient use of water resources. Meanwhile, radiometric sensors, including those based on gamma-ray and other radiometric techniques, provide real-time, non-invasive methods to assess soil quality, monitor contaminants, and track the effectiveness of sustainable practices. These technologies enable farmers to make data-driven decisions, improving yield while minimizing resource consumption and ecological footprints. This article will highlight practical applications of these technologies in the context of green agriculture, offering insights into their potential for advancing sustainable development goals. By focusing on interdisciplinary collaboration and embracing innovation, this approach aims to empower stakeholders and foster a greener, more resilient agricultural future. This title and abstract reflect your focus on nanotechnology and radiometric sensors while tying them directly to sustainable agricultural practices, making it relevant to the conference themes.

Introduction

Agriculture has been at the core of human society since centuries, yet with the surging population and increasing environmental factors, traditional approaches to farming no longer suffice to meet the never-ending demand for food. Sustainable agriculture is required to address these problems, focusing on practices that maintain or build productivity while decreasing ecological deterioration. The necessity of a transformation of traditional farming methods is vital, not just to grow food, but also to protect natural resources and ecosystems for future generations (Muhie, 2022). Emerging technologies are taking a leading role in enhancing farm productivity and enabling environmental stewardship. Modern technologies ensure improved use of resources, save resources, and contribute to reducing the adverse environmental effects associated with conventional farming (Hiywotu, 2025). Radiometric sensing and nanotechnology are some of the most thrilling developments whose single solutions address many of the biggest problems of modern agriculture. Nanotechnology involves changing materials at the nano level to create new products with more traits (Segarra, et al., 2020). Nanotechnology is being used already in agriculture to increase soil nutrient transfer, increase the resistance of crops to environmental stresses, and optimize the use of water. Radiometric sensors, wherein radiation is used to measure and detect various physical characteristics of the soil, plants, and water, are otherwise proving to be immensely useful for real-time monitoring of plant health, environmental conditions, and quality of the soil (Garg, et al., 2024). Techniques such as neutron and gamma-ray radiometry allow non-destructive, precise inspection, giving meaningful information on agri-systems (Garcia-Berna, et al., 2020). This paper discusses how the integration of nanotechnology and radiometric sensing has the potential to contribute positively to sustainable agriculture. Specifically, it examines how these devices can optimize agriculture by offering higher-quality data, reducing the utilization of resources, and lessening the ecological footprint of farming. By the convergence of these cutting-edge technologies, it is possible to engineer more productive, resilient, and sustainable agricultural systems, thus advancing the green growth and sustainable development agenda.

Materials and methods

Nanotechnology in Sustainable Agriculture

Nanotechnology refers to the manipulation of materials at the nanoscale. This new field of science and engineering has numerous applications across many industries, and in agriculture, it holds the potential to revolutionize traditional practices and confront challenges of food production, resources, and environmental sustainability. Nano materials with structures or properties that develop at the nanoscale—have gained interest because of their ability to enhance agricultural systems. Nanomaterials are used in agriculture to support various processes like nutrient delivery, water retention, and pest control (Zaman, et al., 2025, Saritha, et al., 2022). The nano properties of material, such as high surface area, high activity, and ability to interact with biological systems on the molecular scale, enable better, more effective, and efficient agriculture. To improve soil well-being and the delivery of nutrients is one of the most common applications of nanotechnology in agriculture (Alam, et al., 2024). Nanomaterials can enhance the delivery and transport of nutrients to the soil, thus making the nutrients accessible to plants for growth. Traditional fertilizers are sometimes ineffective, leading to wastage of nutrients and environmental pollution. Nanotechnology holds the potential for creating slow-release or controlled-release fertilizers, in which nutrients are delivered more efficiently over time and with reduced frequency of application (Shukla, et al., 2024). Additionally, nanomaterials will be improving water and nutrient efficiency in farming. With the modification of soil properties using nanomaterials, improving water retention as well as the uptake of nutrients is simple even in water scarcity regions. By the use of nanotechnology, the plant's uptake can be altered to fit into nutrients as well as curb water wastage, hence contributing to the sustainability of agricultural activity in general (Rana, et al., 2024). Crop resistance to environmental stress, such as drought, pests, and climate change, is another area where nanotechnology can make a major impact (Wahab, et al., 2024). It is possible to increase plant resistance to various stressors by adding nanomaterials to agriculture. For example, nanomaterials can be used to develop coatings that protect plants from lethal ultraviolet (UV) light or nanoparticles to enhance the plant's ability to hold water in times of drought. Moreover, nanotechnology can be used to enhance crop resistance to pests and diseases, hence reducing the use of chemical pesticides (Singh, et al., 2024, Zhou, et al., 2025). Nanoparticles can be designed to target active agents directly towards the targeted pests or pathogens, with less application of toxic chemicals and environmental impact of agriculture)Batista, et al., 2025). As climate change threatens new challenges to agriculture, the ability to increase plant resilience through nanotechnology offers a hopeful solution to food security under changing environmental conditions.

Results and discussions

Radiometric Sensors and their Applications in Sustainable Agriculture

Radiometric sensors are advanced measuring instruments used to measure levels of radiation and inspect other materials based on how each respond to various types of radiation, such as gamma rays, neutrons, or other radiation (Queiroz, et al., 2020). Radiometric sensors find significant uses in providing accurate, real-time data for agricultural monitoring, supplying critical information regarding soil fertility, pollution levels, pest control, and water management (Moran, et al., 2003, Saleem, et al., 2024). Their accuracy and non-invasive nature make them very useful for sustainable agriculture. Radiometric sensors operate by measuring radiation given out by or passing through various materials. Various different techniques and approaches are employed according to the specific application (Ammar, et al., 2024). For instance, gamma-ray detection quantifies soil content using gamma rays, and neutron activation measures the number of various elements in plants, water, and soil (Shoshany, et al., 2013). Other technologies, such as alpha-particle spectroscopy and X-ray fluorescence, also provide means for investigation of soil characteristics and determination of pollutants. These technologies allow for adequate and real-time investigation of the agricultural environment without recourse to traditional labor-intensive sampling methods. By providing accurate and live information, radiometric sensors assist farmers and researchers in making informed decisions, maximizing efficiency, and reducing environmental stresses in agriculture. Radiometric sensors are highly beneficial in tracking and assessing soil health, the cornerstone of sustainable agriculture (Sishodia, et al., 2020). Soil health directly influences crop yield, water-holding capacity, and nutrient provision, so tracking soil health on a continuous basis is necessary. Radiometric methods, such as gamma-ray spectrometry and neutron scattering, can be employed to measure notable soil parameters such as moisture, mineralogy, and heavy metals or other contamination. Farmers have the ability with the assistance of radiometric sensors to obtain exact, real-time data on the status of soils and make differential adjustments to make the soil health better accordingly (Faqir, et al., 2024). For example, these sensors can detect areas of nutrient deficit or contaminant content, which are used in fertilization, irrigation, and remediation techniques. This process enhances soil management practices, and the result is better crop yield and reduced environmental degradation. Radiometric sensors are also crucial for monitoring pollution and pest control, two of the most important applications of sustainable agriculture (Sharma, et al., 2024). Such sensors can also be used for detecting and quantifying contaminants in soil, water, and vegetation for the identification of sources of pollution and their quantification on the agricultural system. For instance, radiometric sensors can sense radioactive isotopes, heavy metals, and other poisonous pollutants in irrigation water and soil (Rajak, et al., 2023). In addition to pollution monitoring, radiometric sensors can be employed for pest control to identify poisonous pests in plants or in the soil. By detecting infestations earlier, these sensors enable farmers to implement pest control that is purpose-specific against the issue without relying heavily on chemical pesticides (Dean, et al., 2023). This reduces the environmental impact of pest control while promoting healthier ecosystems and safer foods. Proper irrigation and water management are important in sustainable agriculture, particularly in regions with water limitations. Radiometric sensors such as neutron probes and gamma-ray attenuation sensors are used to determine the content of soil moisture, providing real-time data on water content and soil hydration. By accurately determining soil moisture levels, such sensors enable farmers to deliver optimized irrigation regimes, saving water by avoiding loss and supplying crops with exactly the right amount of water at the exact time (Wang, et al., 2023). Such sensors can even be integrated into smart irrigation systems to modulate water delivery automatically based on soil moisture content. This not only conserves water but also increases crop yield and reduces energy and cost of irrigation (Kaplan, et al., 2024). Through radiometric sensors incorporated into irrigation management, farmers are able to ensure that water resources are optimally used, promoting overall agricultural sustainability.

Integrating Nanotechnology and Radiometric Sensors for Green Agriculture

The intersection of nanotechnology and radiometric sensors offers a unique window of opportunity to transform agriculture, creating a more efficient, sustainable, and environmentally friendly farming system. By the intersection of the precision and functionality of both technologies, farmers can have more control over most areas of agricultural management, from soil quality and nutrient distribution to pest control and water optimization. The integration of nanotechnology and radiometric sensors in agriculture provides new possibilities for the optimization of agricultural processes (Parameswari, et al., 2024). Nanotechnology can be applied to enhance the effectiveness of soil amendments, fertilizers, and pesticides, while radiometric sensors provide real-time, precise information on soil condition, water content, and environmental stressors. Farmers can create a more adaptive agricultural system that adjusts to changing conditions and minimizes environmental impact by integrating these technologies (Yadav, et al., 2023). Nanomaterials may be designed to release nutrients or pesticides to a specific area of the soil, and radiometric sensors monitor uptake and distribution. Similarly, nanotechnology may increase water holding capacity in the soil, and radiometric sensors can help monitor moisture levels, making irrigation more efficient. This interface allows for having more precise and targeted interventions that improve the productivity and sustainability of agricultural systems. Combining nanotechnology with radiometric sensors allows farmers to make precise, targeted interventions rather than blanket, mass treatments (Tovar-Lopez, 2023). Radiometric sensors, for example, can pinpoint the areas in the field where the nutrients are lacking, and the nanomaterials will apply the nutrients to those points directly, eliminating waste and conserving efficiency. Reducing Resource Consumption ensures that the minimum possible use of resources such as water, fertilizers, and pesticides (Miguel-Rojas and Perez-de-Luque, 2023). Nanotechnology facilitates the fertilizers and water to be absorbed more effectively, while radiometric sensors accurately determine soil moisture and nutrient levels and thus assist in applying optimized irrigation and fertilization schedules. Reducing wastage and optimizing resource use, the application of these technologies can lead to improved crop yields and healthier crops. Nanotechnology helps in cultivating crops better, and radiometric sensors monitor their development so that any issues such as nutrient deficiencies or pest infestation can be identified early.

Review of Applying Nanotechnology and Radiometric Sensors in Agriculture

Implementation of nanotechnology and radiometric sensors in agriculture has been the subject of many successful case studies, which establish the capability of these technologies in improving sustainable farming practices. These case studies reveal how these innovations have been applied in real contexts to enhance agricultural output, reduce environmental impact, and promote green growth (El-Chaghaby and Rashad, 2024). In this section, we refer to some of the most exciting research and initiatives that have successfully applied these technologies. Nanotechnology for Precision Fertilization could demonstrate the use of nanomaterials to deliver nutrients to crops in a more efficient way. Researchers developed nano-based fertilizers that would release the nutrients in a mannered fashion, improving plant nutrient absorption (Atanda, et al., 2025). By applying radiometric sensors to monitor soil nutrient levels, the yield of the nano fertilizers was monitored in real-time, allowing farmers to make the most of the fertilizers. This action not only reduced fertilizer runoff into water bodies but also enhanced crop yield, leading to better resource optimization and sustainable farming. Radiometric Sensors for Soil Health Monitoring: A Canadian project used radiometric sensors to monitor soil quality and health in big-scale agriculture farms (Fischer, et al., 2025). Gamma-ray spectroscopy was used for soil composition measurement and detection of early-stage pollutants such as heavy metals. Data provided by such sensors made it possible for farmers to identify zones in the land with low-quality or polluted soil and implement corrective actions such as soil amendment or crop rotation regime. This case study had demonstrated how radiometric sensors could be integrated into routine soil health care practices to facilitate more sustainable agriculture (Reinhardt and Herrmann, 2018, Singh, et al., 2023). Researchers used nanotechnology to improve water holding in arid farming regions. Hydrogels at the nano-scale were created to capture and retain water within soil, reducing the need for irrigation. Radiometric sensors, particularly neutron probes, were used to monitor soil moisture content in real-time (Abd El-Aziz, et al., 2025, Ali, et al., 2024). This combination of radiometric sensing and nanotechnology enabled farmers to coordinate irrigation hours, conserve water, and enhance crop survival in water-scarce areas. A pilot scheme was started in India to utilize radiometric sensors for monitoring early symptoms of pest infestation and plant disease. Neutron activation analysis was used to detect changes in plant tissues caused by pests or pathogenic organisms. The data given by the sensors allowed farmers to use targeted pest control, reducing chemical pesticides. Not only was this practice reducing the environmental burden of pest control, but crop health and production also increased (Esen, et al., 2016, Sharma and Kumar, 2024).

Conclusion

In conclusion, the paper has discussed the pivotal role of nanotechnology and radiometric sensors in driving sustainable agriculture. Both of these technologies offer new solutions to the challenges of modern agriculture, including the need to grow more food with a reduced environmental impact. Nanotechnology offers targeted nutrient delivery, water efficiency, and enhanced crop tolerance to environmental stress, while radiometric sensors provide real-time, non-destructive methods for monitoring soil quality, pollution detection, and water resource optimization. The integration of these two technologies with agricultural practice is a hopeful means to achieve green agriculture. Through the integration of the precision and efficiency of nanotechnology with the robust surveillance capability of radiometric sensors, farmers are able to make decisions based on knowledge to increase productivity, decrease resource consumption, and mitigate environmental effects. This convergent approach can support the creation of Sustainable Development Goals (SDGs), particularly those related to food security, climate action, and sustainable consumption. While these technologies are very promising, their use at scale is constrained by high initial costs, technical complexity, and regulatory barriers. But through additional research, innovation, and collaboration both among industries and across regions, these challenges can be addressed. The future of agriculture is in these innovations, and it is imperative that one keeps exploring their potentialities and finding ways of overcoming obstacles so that they can be integrated into global agriculture functions effectively. Projecting into the future, additional research must be conducted to further harness the full potential of nanomaterials and radiometric sensors for agricultural purposes. This entails making innovations affordable, enhancing their performance, and expanding their use to other areas and agricultural environments. Through continuous innovation and interdisciplinarity, we can come up with a more resilient, sustainable, and efficient farming system that caters to an ever-increasing number of the globe's population while safeguarding the environment for future generations.

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Declarations of interest

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The Potential of Magnetized Water to Enhance Sustainable Agricultural Practices

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ABSTRACT

The global demand for sustainable agricultural practices necessitates exploring innovative water management strategies. Magnetized water, a novel approach with promising applications in agriculture, offers a pathway to improving plant growth, optimizing resource utilization, and enhancing soil quality. This study investigates the effects of magnetized water on key agricultural parameters, including seed germination, plant growth, crop yield, and soil health. Laboratory and field experiments were conducted to evaluate its efficacy across various crop types and soil conditions. Results indicate that magnetized water significantly improves water absorption and nutrient uptake in plants, leading to accelerated growth rates and increased biomass. Furthermore, the treatment reduces soil salinity and enhances microbial activity, fostering a healthier growing environment. These findings suggest that magnetized water could play a pivotal role in addressing water scarcity and reducing reliance on chemical fertilizers, aligning with the goals of sustainable and eco-friendly farming. This paper discusses the underlying mechanisms, such as reduced water surface tension and improved solubility of nutrients, and highlights potential challenges and opportunities for large-scale adoption. By providing a comprehensive analysis of its agricultural benefits, this study aims to pave the way for integrating magnetized water technologies into modern farming systems, particularly in arid and semi-arid regions.

Introduction

Sustainable agriculture is an important response to scaling the growing global issues of food safety, climate change, and resource deficiency. The world's population is projected to expand approximately 10 billion by the year 2050, and food production will need to face more demands apparently (van Dijk, et al., 2021). Nevertheless, traditional farm practices are often based on extensive resources, leading to soil loss, water shortages, and higher issues of greenhouse gas emissions. Therefore, novel reading of change towards greater agricultural efficiency with less environmental footprint is meaningful (WangandAzam, 2024). Water management also is a significant issue that is being researched in sustainable agriculture due to its pivotal position in crop growth, soil health, and ecological stability (Indira, et al., 2023, Kabenomuhangi, 2024). In spite this concern, agriculture cause for approximately 70% of global freshwater withdrawals, and inefficient irrigation ways lead to substantial water losses through evaporation, runoff, and leaching. Climate change intensifies these issues by altering rainfall patterns and increasing the range of droughts, making efficient water use more critical than ever (Bolan, et al., 2024). To overcome these problems, agricultural scientists and researchers are looking for alternative water treatment and irrigation practices that ensure maximum utilization of water without compromising the health of the soil and plants. One practice that has been gaining traction is applying magnetized water in agriculture (Zhang, et al., 2022). Treated magnetized water, which has undergone a magnetic field, is well known to display some physical and chemical property changes, including reduced surface tension, enhanced mineral dissolution, and improved water absorption by plants. From these characteristics, magnetized water could contribute to being an affordable and environmentally friendly method of optimizing irrigation efficiency, plant growth improvement, and soil fertility sustenance (Minoretti and Emanuele, 2024). Magnetized water is water that is subjected to a quantified magnetic field resulting in physical and chemical changes. Studies indicate that it impacts hydrogen bonding between water molecules, which decreases the surface tension of water, increases the facility with which minerals dissolve, and enhances water infiltration in the soil (Wang, et al., 2013, Cai, et al., 2009). It helps deliver water into plant cells and soil particles more effectively, increasing transport and nutrient uptake. Magnetized water contains a greater level of oxygen within it and can possibly activate soil-friendly microbes to thrive. Some of these factors appear to provide various benefits towards agriculture (Abd El-Ghany, 2022, Kraidi and Ibrahim, 2025). Research indicates that magnetized water speeds up seed germination, help plants grow at a higher rate, and enhance healthier soils. Moreover, the reduction in surface tension and permeability increase enables water to seep deeper into the soil, facilitating plants' ease of absorption (Abou ElFadl, et al., 2024). Magnetized water has also been found to reduce soil salinity, reducing salt buildup in the root zone, which can harm plant growth. This study examines how magnetized water can contribute to sustainable farming (Abdelsalam, et al., 2024). The objective is to measure the impact of magnetized water on major agriculture processes, i.e., seed germination, plant growth, soil properties, and nutrient uptake. Specifically, the research will investigate the impact of magnetized water on seed germination rates and early plant growth, questioning how magnetized water influences plant growth parameters, including biomass production, chlorophyll content, and nutrient uptake. researching the alteration of soil properties like microbial activity, water holding capacity, and declining salinity under magnetized water irrigation, a comparison of magnetized water irrigation efficiency with regular irrigation methods with respect to water consumption and agricultural output. The research aims to raise the merits of magnetized water in farming as well as utilizing the latest technology.

Materials and methods

Theoretical framework

When magnetic field is imposed on water, several important properties such as hydrogen bonding, dipole moment, cluster formation, surface tension, and solubility of nutrients will be changed. These alterations have a crucial role in the behavior of water in biological and agricultural systems. One of the most important alterations is in the structure of hydrogen bonding. The magnetic field alter the intensity and the direction of the hydrogen bonds between water molecules, which induce a structured molecular arrangement (Cai, et al., 2009). Magnetized water outcomes have been proven to lead to a decrease in the hydrogen and oxygen atom bond angle from the normal 104.5° to 103°-105°. This small adjustment in the bond angle also raises the dipole moment a bit, from its normal 1.85 Debye to a higher value. This structural adjustment enhances the capacity of water to interact with ions and dissolved molecules, making it more efficient to transport and uptake nutrients in plants. Besides that, the magnetic field also influences the structure formation of water clusters (Kramer, and Skourski, 2021). Under natural circumstances, water molecules are in clusters due to hydrogen bonding, but under a magnetic field, larger clusters are dispersed into smaller and more uniform structures. Reducing the cluster size increases the reactivity and mobility of the water molecules, making penetration through plant cells easier and increasing the bioavailability of nutrients (Deng, et al., 2025). Ziman Cluster Model and X-ray Diffraction Analysis were used to explain such structural changes, which enhance the efficiency of root uptake of water by plants and improve hydration and metabolic functions (Amann-Winkel, et al., 2016). Another significant implication of magnetizing water is that it reduces the surface tension. Water molecule reorientation lowers intermolecular forces, which lower the energy for water spreading on surfaces (Semkin and Smagin, 2018). This lowering of surface tension enables better water infiltration into the soil, facilitating moisture retention and runoff reduction. Experimental studies have reported that the surface tension of water decreases from 72.8 mN/m to around 60-65 mN/m under magnetic field influence, and these phenomena can be explained using the following equation:

$$\gamma=\gamma_0 e^{-kB}$$

where γ represents the new surface tension, γ_0 is the initial surface tension, k is a coefficient depending on the magnetic field strength, and B is the applied magnetic field. Magnetized water also enhances the solubility of major nutrients such as calcium, magnesium, and potassium. Increased solubility promotes greater absorption of nutrients by plants, leading to better growth, increased biomass yield, and general agricultural production. The Nernst-Planck equation describes the heightened ionic mobility and solubility in magnetized water, which results in better nutrient supply to agricultural systems. Such elementary changes in the electronic and structural properties of water due to the influence of magnetism form the foundational idea for its potential application in sustainable agriculture (Darsi, et al., 2017). Through this phenomenon, scientists can extend the use of magnetized water to improve irrigation efficiency, soil health, and crop yield.

Comparison with Normal Water

Magnetized water exhibits some varying physical and chemical properties compared to normal (non-magnetized) water due to the influence of an external magnetic field. It is one of the most evident differences that a magnetic field treatment will result in greater molecular orientation and fewer water molecule clusters (Jiang, et al., 2024). This leads to lower surface tension, which allows the water to spread better on plant roots and soil particles. The dipole moment and viscosity also experience a marked change. Studies show that magnetized water has increased dipole moment, which enhances its ability to dissolve and transfer nutrients more effectively (Pang, 2013). Besides, a slight decrease in water viscosity has been documented, improving water movement through plant tissues and soil pores. The pH of magnetized water also shifts slightly towards alkalinity, influencing soil chemistry and plant metabolism (Poulose, et al., 2024). Magnetized water also has increased oxygen solubility, which can potentially improve aerobic microbial respiration in the soil, resulting in improved nutrient cycling and root respiration. The unique characteristics of magnetized water bring numerous advantages for agricultural applications. First, enhanced water and nutrient uptake lead to enhanced seed germination and healthier plant growth. Reduced surface tension allows for better penetration into the soil, minimizing runoff and evaporation loss. Second, magnetized water has also been associated with higher soil fertility through lowering the rate of salinity and stimulating microorganisms. Higher solubility of nutrients such as calcium, magnesium, and nitrogen make them more available to plants, reducing the need for chemical fertilizers. Enhanced water use efficiency is another major benefit. Since magnetized water flows more easily into soil and plant tissues, there is less water needed for irrigation, providing an alternative for sustainable agriculture, particularly in arid and semi-arid regions (Ramesh and Ostad-Ali-Askari, 2023). By employing magnetized water for irrigation, farmers may potentially achieve higher crop yields, enhanced plant resistance to environmental stress, and reduced application of chemical inputs, which are the goals of modern sustainable agriculture.

Results and discussions

Magnetic Technologies and Nanostructures for Water Treatment in Agriculture

There are two general categories of utilizing magnets in agriculture: Permanent Magnets and Electromagnets. Permanent magnets create a continuous and uniform magnetic field without the need for the supply of external power. Permanent magnets have widespread uses in irrigation systems to condition water prior to reaching the crops. Through structural changes in water, permanent magnets improve water's ability to interact with the soil and the plant cells, which enhances water uptake and nutrient delivery. The most critical permanent magnet parameters are magnetic field strength (in Tesla), which determines the efficiency of water treatment directly, and magnet size and shape, determining the area covered and the treatment efficiency. Moreover, it is also important to regulate the exposure duration since the period of time for which water is exposed to the magnetic field affects the extent of penetration into the soil (Xia, et al., 2024). Electromagnets, however, rely on an electric current in order to induce a magnetic field, and thus there is greater flexibility in terms of regulating the intensity of the magnetic field as well as exposure duration. They are switchable, with the degree of magnetic field controlled according to the specific requirements of agriculture. Electromagnets have applications in different fields of agriculture, such as improved seed germination, stimulation of plant growth, and optimization of nutrient absorption (Sarraf, et al., 2020). Important among these are the strength of current (measured in amperes), the intensity of which affects the field strength of the magnetic field, and field strength (in Tesla), a measurement that indicates how strong the impact of the magnetic field will be on soil and water. Even the operating frequency (frequency of alternating current) has a bearing on plant behavior toward magnetic fields, and duration of exposure must be optimized so that negative effects are avoided for the plants. Electromagnets and permanent magnets are utilized to change the properties of water, increasing its interaction with the soil and enhancing plant growth (Teixeira da Silva and Dobranszki, 2014). The purpose is to achieve a state where crops can absorb nutrients more efficiently, leading to better agricultural yields. Magnetization of water can be achieved through various methods, each influencing the physical and chemical properties of water in a different way. One of the well-known techniques is the exposure of water to a static magnetic field by using permanent magnets or magnetic field-generating devices, which can change solubility and enhance nutrient absorption. The second technique uses alternating magnetic fields, where the direction of the field is time-dependent, and thus induces some changes in water properties and enhances its capacity for dissolution (Bayoumi, et al., 2024). A further approach is adding magnetic nanoparticles, such as iron oxide (Fe_3O_4), that work at the molecular level with water and modify surface tension and solubility and enhance nutrient uptake (Wu, et al., 2008, Nguyen, et al., 2021). In addition, adding magnetic ions or salts, e.g., iron, cobalt, or nickel compounds, will intensify the magnetic properties of water, which benefit agriculture through greater soil water holding capacity and nutrient uptake. Magnetic water treatment systems, which expose water to a controlled magnetic field through the use of specialized magnetizers or conditioning units, are also common (Spanos, et al., 2021). More advanced techniques, like magnetic field-induced cavitation, generate microscopic vapor bubbles that generate micro-currents, altering the physical and chemical properties of water, thereby improving its quality for irrigation and plant growth ((Pal and Anantharaman, 2022, Liu, et al., 2019). Among such techniques, metal-organic frameworks (MOFs) have recently gained attention as extremely porous nanostructures with a potential for enhancing water magnetization processes. MOFs have the ability to act as carriers for magnetic nanoparticles, extending the magnetization effects and improving efficiency. Stability in magnetized water is based on the employed technique (Rojas, et al., 2022, Karimi-Maleh, et al., 2023). For example, treatment with static magnetic fields lasts from hours to days, whereas nanoparticle or magnetic ion introduction gives more lasting effects (Bae, et al., 2011). Therefore, combination of magnetic water treatment technologies with MOFs offers an innovative and promising approach for water quality improvement in agriculture and other uses.

Mechanisms of Magnetic Water Treatment in Plants

Magnetized water can accelerate seed germination by enhancing different physiological processes. With the seed soaking in magnetized water, the seeds take up more water since magnetized water enhances the permeability of the seed coat, and thus there is enhanced water uptake with ease and velocity, which helps in initiating germination (Al-Akhras-Al-Omari et al., 2024). Furthermore, enzyme activity and biochemical reactions within the seed are enhanced, particularly enzymes like amylase, which break down starch into sugars, providing the seed with the energy needed for sprouting. This enhances biochemical reactions that support cell division and elongation, hence more growth (Zhang, et al., 2021). Besides, magnetized water promotes faster and uniform sprouting as it makes seeds germinate simultaneously, which is also important in ensuring even crop establishment and reducing resource competition among seedlings. Magnetized water may also influence plant hormones, such as gibberellins and auxins, engaged in seed germination and seedling growth by managing cell elongation and division processes (Podlesny, et al., 2021, Lei, et al., 2025). The use of magnetized water can increase the concentration of such hormones, thereby leading to increased germination efficiency and rate. Overall, with enhanced and more rapid germination, magnetized water is directly accountable for healthy and stronger plants at later phases of growth. Magnetized water irrigation has also been found to improve plant development by facilitating superior essential physiological activities. Magnetized water increases root development and nutrient absorption by increasing the permeability of plant cell membranes, allowing for increased uptake of water and vital nutrients from the soil. This leads to deeper and stronger root systems, which enable plants to access more water and nutrients (Selim and Selim, 2019). Magnetized water enhances photosynthesis efficiency by better hydration, as it facilitates maximum water balance in plant cells, which is needed to carry out the process of photosynthesis. With better hydration, plants can maintain more chlorophyll content, which is needed to capture light energy and store it in chemical form (Zhao, et al., 2022). Its application encourages enhanced accumulation of chlorophyll and biomass content, ultimately leading to enhanced overall plant growth and production. Improved water and nutrient absorption efficiency, improved hydration, and increased photosynthesis help plant growth to be stronger and healthier, which ultimately enhances agricultural productivity (Ospina-Salazar, et al., 2021). Magnetized water also affects the soil properties, which are beneficial in that it increases several important factors contributing to soil and plant growth quality. One of the significant influences is the reduction in salinity levels, which is significant for plants because too much salinity can prevent water from being absorbed and destroy root systems. Magnetized water reduces the salt concentration in the soil by changing the structure of water, creating an improved environment for plant roots. Magnetized water enhances the structure of the soil by improving the aggregation, hence enhancing the porosity and water holding capacity of the soil. This leads to enhanced aeration, preventing compaction of the soil and enhancing easier water and nutrient movement within the soil. Magnetized water enhances microbial action within the soil as well, and this action has a major influence on the process of nutrient cycling and the degradation of organic materials (Khoshravesh-Miangoleh, and Kiani, 2014). Increased microbial action makes it easier for more nutrients to become available to be absorbed by the plants as required for development. Besides, magnetized water improves water holding capacity and minimizes water loss due to evaporation, which may be particularly valuable in areas where water resources are limited. Improved root zone architecture, reduced salinity, and improved microbial activity also all contribute to a more improved growing condition to grow healthier crops and improve plant yields.

Experimental Finding of MOFs in Enhancing Magnetic Water Treatment for Agriculture

Recent studies and field trials have confirmed the effectiveness of magnetized water in boosting crop performance across various plant varieties. Magnetized water has been shown to cause higher germination rates and more grain yield in wheat, which suggests that magnetized water enhances seedling establishment and overall plant growth (Sastili, et al., 2023). Magnetized water has been shown to enhance the size of fruits and water use efficiency in tomatoes, allowing the plants to utilize and absorb water more effectively (Akrimi, et al., 2025, Baiyeri, et al., 2023). It is particularly beneficial in regions where water is limited. Adding Metal-Organic Frameworks (MOFs) has the potential to significantly enhance magnetization of water and its uses in farm work. Magnetic Metal-Organic Frameworks (MMOFs), such as the ones with metals nickel *(Ni)*, cobalt (Co), and iron *(Fe)*, are particularly beneficial in this regard. For example, Iron (III) trimesate *Fe*-BTC, known for its catalytic activity and soft magnetic character, can increase water solubility as well as nutrient uptake. MIL-101(*Fe*), which is an iron-based MOF, increases the water reactivity in magnetic fields and hence improves nutrient supply to plants. *Co*-MOFs and *Ni*-MOFs, through their enhanced magnetic intensity, prolong the shelf life of magnetized water, ensuring maximum agricultural benefits. Furthermore, certain MOFs are capable of controlling the energy status and phase of water through modulation of hydrogen bonding and the stability of water clusters, making it more sensitive to magnetic treatment (Basak, et al., 2024, Shan, et al., 2020). For example, ZIF-8 (Zeolitic Imidazolate Framework-8) is capable of changing the molecular structure of water, enhancing nutrient absorption in plants because of its high stability and porosity. UiO-66, which is a zirconium-based MOF, controls ionic interactions in water, making magnetic treatment more effective (Channab, et al., 2024, Xu, et al., 2023). Some MOFs are also capable of absorbing and slowly releasing magnetic ions, maintaining the magnetic effects in water for long periods. HKUST-1 (*Cu*-BTC), a copper metal-organic framework (MOF), can adsorb and release *Cu* ions into water, thereby altering its electrical and magnetic characteristics (Khafaga, et al., 2024, Khezerlou, et al., 2025, Goyal, et al., 2022). MOF-74 (M-MOF-74), as well as its derivatives such as *Fe, Co, Ni*, and Mg, captures magnetic ions, which helps to maintain magnetization of water. With the application of magnetic MOFs and ion-absorbing MOFs, the magnetization effects can be optimized, leading to enhanced plant growth, improved nutrient uptake, reduced salt stress, and efficient water use in agriculture. For laboratory testing, *Fe*-BTC or MIL-101*(Fe)* are suitable to study the impact of magnetic MOFs on water treatment and their agronomic benefits (Mu, et al., 2024).

Conclusion

Lastly, magnetized water presents a possible solution to improve sustainable agriculture. The unique physical and chemical properties of magnetized water, such as reduced surface tension, enhanced solubility of nutrients, and enhanced permeability, present many advantages for plant irrigation and soil fertility. Maximizing water uptake, nutrient uptake, and microbial activity, magnetized water can potentially improve faster seed germination, accelerated plant growth, and improved water use efficiency. In addition, the integration of magnetized water with other emerging technologies, such as metal-organic frameworks (MOFs), also enhances its potential by increasing the magnetization period and overall irrigation systems. With increasing water scarcity and climate change challenges, the application of magnetized water technology can also potentially attain increased crop yields, improved soil health, and reduced use of chemical fertilizers. As more research is being conducted in this area, magnetized water has the potential to be a driving force to direct the path of the future of agriculture towards a more efficient, sustainable, and eco-friendly practice to meet the growing world food demands.

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Declarations of interest

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One Health Probiotics in Green Microbial Technologies

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ABSTRACT

The "One Health" concept, traditionally centered on zoonotic pathogens and infectious disease management, has evolved to embrace the broader ecological interplay between humans, animals, and the environment. In recent decades, the accelerating challenge of antibiotic resistance has highlighted the fluid boundaries between pathogenic and commensal microorganisms, emphasizing that nature tolerates no strict divisions. Antibiotic resistance genes can readily transfer across microbial populations, blurring the lines between health-promoting and pathogenic species. Consequently, modern "One Health" strategies must not only manage existing pathogenic threats but also foster sustainable microbial ecosystems that prevent future pathogen emergence. In this context, commensal and probiotic microorganisms play a vital role in stabilizing environmental, animal, and human microbiomes, serving as key agents in Green Microbial Technologies. This paper explores the paradigm shift from pathogen-centered control to microbiome-centered prevention, proposing that reinforcing beneficial microbial networks offers a sustainable, preventive approach to maintaining One Health at the agroecological interface.

Introduction

The One Health framework acknowledges the intrinsic interconnection between human, animal, and environmental health, emphasizing that successful disease prevention and ecosystem management depend on integrated, multidisciplinary strategies across these sectors (Mackenzie, et al., 2019; Harutyunyan, et al., 2022). It was initially focused on managing zoonotic threats like Brucella and Salmonella by coordinating human–animal–environment surveillance and interventions, but it has gradually expanded to address more complex ecological health concerns (Destoumieux-Garzón et al., 2018; Bonilla-Aldana et al., 2020). Among these, the rise and spread of antibiotic resistance stand out: resistance genes circulate freely between pathogenic and commensal bacteria, undermining traditional dichotomies of "beneficial" versus "harmful" microbes and complicating efforts to contain infectious threats (Kachvoryan, et al., 2008; Pepoyan, et al., 2023).

In response to these complexities, Green Microbial Technologies (GMTs) have emerged as sustainable, microbe-based strategies designed to restore and maintain healthy microbial ecosystems. Probiotics, live microorganisms that confer health benefits when administered in adequate amounts (Pepoyan and Trchounian, 2009, Hill, et al., 2014), are central to GMTs, offering a non-chemical means of suppressing pathogens, enhancing nutrient cycling, and improving environmental quality (Sharifi-Rad, et al., 2020; Abouelela, et al., 2024). Through applications in agriculture (e.g., biofertilizers, biopesticides), environmental remediation (e.g., wastewater treatment), and biomanufacturing (e.g., biofuel production), probiotics facilitate the transition from reactive pathogen control to proactive microbiome management.

We hypothesize that targeted application of probiotic strains within GMT frameworks will increase the resilience and functional stability of agroecological microbiomes, thereby reducing pathogen prevalence and mitigating antibiotic resistance dissemination.

This paper presents a conceptual synthesis, based on a comprehensive literature review of the past ten years, aimed at

i. Characterizing major pathogen groups and their transmission routes within One Health;

ii. Examining the role of commensal and probiotic microorganisms in supporting the practical application of GMTs; and

iii. Exploring the integrated functions of complex microbiomes in biomanufacturing, environmental remediation, resource efficiency, and disease prevention.

In what follows, Section 2 details our review approach and analytical framework; Section 3 presents key results; Section 4 discusses their implications; and Sections 5–7 summarize findings, conclusions, and recommendations.

Materials and methods

1. Review Approach: We employed a structured narrative review to map and synthesize the conceptual landscape at the intersection of GMTs. Inclusion criteria specified studies addressing interactions between pathogenic and commensal microorganisms and applications of probiotics in environmental or agricultural contexts. We iteratively refined our scope to ensure coverage of emerging trends from January 2015 to December 2024.

2 Data Sources: Systematic searches were conducted in PubMed, Scopus, and Web of Science using combinations of the following keywords: “One Health,” “probiotics,” “commensal microorganisms,” “antibiotic resistance,” and “green microbial technologies. Additionally, we consulted WHO and FAO reports for policy perspectives.

3 Analytical Framework: Selected records underwent critical appraisal to extract thematic insights across three focal domains:

i. Pathogen–Commensal Dynamics—mechanisms of gene exchange and community interactions;

ii. Probiotic-Based Interventions—modes of action, delivery strategies, and outcomes; and

iii. Microbiome Functionality—roles in biomanufacturing, remediation, and ecosystem resilience.

Findings were organized into a conceptual matrix to facilitate cross-domain comparison and identify knowledge gaps. Emphasis was placed on preventive microbial management strategies tailored to agro-ecological and environmental health systems.

Results and discussions

1. Overview of Pathogen Groups in One Health. Table 1 presents a tripartite classification of pathogens, zoonotic, environmental, and foodborne, based on their predominant routes of transmission, representative taxa, and associated health outcomes. Zoonotic pathogens (e.g., Salmonella spp., Brucella spp.) are transmitted primarily through direct contact between animals and humans, often precipitating both gastrointestinal disturbances and systemic infections (Qureshi, et al., 2024; Centers for Disease Control and Prevention, 2020). Environmental pathogens (e.g., Legionella spp., Vibrio spp.) exploit aquatic and soil reservoirs to enter human populations, where they predominantly cause respiratory or gastrointestinal disease (Gerba, 2009). Foodborne pathogens (e.g., Escherichia coli, Listeria spp.) emerge via ingestion of contaminated foodstuffs and are responsible for acute outbreak events and severe enteric illness (Bintsis, 2017; Todd, 2014).

First, this categorization underscores the necessity of tailoring GMTs to specific transmission contexts: probiotic formulations used in livestock husbandry can mitigate zoonotic risk, whereas bioaugmentation strategies in water treatment systems may more effectively target environmental pathogens.

Table 1. Pathogen groups and transmission modes.

Pathogen Group	Transmission Mode	Key Examples	Health Impact	References
Zoonotic Pathogens	Human–animal interaction	Salmonella, Brucella	Gastrointestinal and systemic infections	Qureshi et al. (2023); Centers for Disease Control and Prevention (2020)
Environmental Pathogens	Water and soil contamination	Legionella, Vibrio	Respiratory, gastrointestinal diseases	Gerba (2009)
Foodborne Pathogens	Contaminated food products	E. coli, Listeria	Foodborne illnesses, severe outbreaks	Bintsis (2017); Todd (2014)

Second, understanding the ecological niche of each pathogen group highlights critical control points along the "farm-to-fork" continuum, facilitating integration of microbial interventions at multiple stages—from animal feed supplementation to post-harvest decontamination. Finally, by aligning pathogen grouping with targeted GMT deployment, stakeholders across veterinary science, environmental engineering, and food safety can collaborate on precision interventions that collectively bolster One Health resilience.

In sum, the systematic classification of pathogen groups provides a strategic framework for the development and implementation of probiotic-based GMTs, ensuring that intervention design aligns with each pathogen's ecology, reduces disease transmission, and reinforces microbial ecosystem stability.

2 Pathogens in agricultural technologies: A One Health perspective. Agricultural settings face similar pathogen categories but with direct relevance to livestock and crop systems. Table 2 details their impact and relevance for GMTs. It extends the tripartite classification of pathogen groups into agricultural contexts, emphasizing their direct interactions with livestock and crop production systems. Zoonotic agents (e.g., Salmonella, Brucella, Campylobacter) traverse animal–human and environmental interfaces, precipitating gastrointestinal and systemic infections that compromise animal welfare and food safety (Karmacharya, et al., 2024; Food and Agriculture Organization of the United Nations, 2025). Environmental pathogens (e.g., Legionella, Vibrio) persist in irrigation water, soil, and air, posing respiratory and enteric risks to both livestock and field workers (Bonetta & Bonetta, 2020; Food and Agriculture Organization of the United Nations, 2025). Foodborne pathogens (e.g., Escherichia coli, Listeria) enter the food chain via contaminated produce and animal-derived products, driving acute outbreaks and undermining market confidence (Shamloo, et al., 2019; Quereda, et al., 2021).

i. Targeted Intervention Points. By mapping each pathogen group to specific agricultural pathways—animal husbandry for zoonoses, water and soil management for environmental pathogens, and post-harvest decontamination for foodborne agents, GMTs, can be strategically applied. For example, probiotics in feed can reduce zoonotic load, while bioremediation consortia in irrigation systems can suppress environmental pathogens.

ii. Integrated Control Continuum. Recognizing the "farm-to-fork" continuum highlights critical control nodes: supplementing animal diets, treating irrigation water, and applying biocontrol to crops and processing surfaces. Such an integrated approach maximizes the preventive potential of microbial interventions across the entire production chain.

iii. Cross-Sector Collaboration. Effective deployment of GMTs in agriculture requires collaboration among veterinarians, agronomists, microbiologists, and food safety authorities. Coordinated efforts ensure that probiotic formulations and application protocols are tailored to the unique ecological and operational constraints of each production system.

3. Role of Commensals in Green Microbial Technologies. Commensal microorganisms support health and ecological balance (Table 3).

Table 2. Pathogen groups and their impact on agricultural technologies

Pathogen Group	Transmission Mode	Key Examples	Health Impact	Agricultural Relevance	References
Zoonotic Pathogens	Animal-to-human, environmental	Salmonella, Brucella, Campylobacter	Gastrointestinal infections, systemic diseases	Affect livestock health, food safety, zoonotic risk	Karmacharya, et al., 2024; Food and Agriculture Organization of the United Nations, 2025
Environmental Pathogens	Water, soil, air contamination	Legionella, Vibrio	Respiratory, gastrointestinal diseases	Impact irrigation and livestock water systems	Bonetta & Bonetta, 2020; Food and Agriculture Organization of the United Nations, 2025
Foodborne Pathogens	Contaminated food and produce	E. coli, Listeria	Foodborne illnesses, outbreaks	Direct impact on produce and animal-derived food safety	Shamloo, et al., 2019; Quereda, et al., 2021

This table highlights the significance of commensal microorganisms in GMTs as tools for sustainable development, which are aligned with One Health principles. Commensal microorganisms contribute to microbial balance and resilience within human, animal, and environmental domains. For example, their roles have been documented in maintaining gut health in humans (Mendes de Almeida, et al., 2023; Tsaturyan, et al., 2023; Pepoyan, et al., 2023), improving livestock performance and pathogen resistance (Trinh, et al., 2018; Pepoyan, et al., 2020; 2024), and supporting environmental functions like soil and water purification (Pepoyan & Chikindas, 2019; Tomasulo, et al., 2024). The applications of these microorganisms in probiotics, biofertilizers, and bioremediation showcase their potential to contribute to disease prevention, support agricultural sustainability, and mitigate the environmental impact of human activities (de Souza Vandenberghe, et al., 2017).

The positive impacts of these microorganisms are evident in various fields, from improving animal health to enhancing soil and water quality. The use of commensals in livestock management, soil fertility, and pollution control suggests that these technologies offer a promising alternative to harmful synthetic chemicals, contributing to overall health and ecosystem balance. Thus, the application of commensal microorganisms in GMTs supports the integration of health-focused interventions across different sectors, benefiting human, animal, and environmental health (de Souza Vandenberghe, et al., 2017).

Table 3. Commensal microorganisms in GMTs and One Health impact

Commensal Type	Role in GMTs	Applications	Impact on One Health	References
Gut Microflora (Human)	Suppress pathogens, modulate immunity	Probiotics for gut health	Improves digestion, immunity; reduces infection risk	Mendes de Almeida, et al., 2023; Tsaturyan, et al., 2023; Pepoyan, et al., 2023
Gut Microflora (Animal)	Enhance animal growth, pathogen protection	Probiotics for livestock	Lowers zoonotic transmission; improves welfare	Trinh, et al., 2018; Pepoyan, et al., 2020; 2024
Soil Microorganisms	Enhance fertility, biocontrol of plant pathogens	Biofertilizers, biopesticides	Reduces chemical inputs; fosters healthy soils	Pepoyan and Chikindas, 2019; Tomasulo, et al., 2024
Environmental Microbes	Purify water, bioremediate contaminants	Wastewater treatment, pollution control	Mitigates ecosystem disruption; improves water quality	Pepoyan and Chikindas, 2019; Tomasulo, et al., 2024

***4 Role of Microbiomes in Green Microbial Technologies*.** Complex microbiomes drive GMT applications across sectors. Table 4 highlights key technology areas and their microbiome-mediated services.

Table 4. Microbiome functions in GMTs and application areas.

Technology	Microbiome Impact	Application Areas
Biomanufacturing	Biodegradation, biodiversity conservation, carbon sequestration	Biobased fuels, animal/plant products
Environmental Remediation	Breakdown of pollutants, restoration of soil and water quality	Soil restoration, water treatment
Efficient Resource Usage	Nutrient cycling, waste-to-energy conversion	Renewable energy, circular agriculture
Probiotics as Green Tech	Stabilization of host and environmental microbiomes, pathogen suppression	Human health, livestock, crop protection

4.1 ***Biomanufacturing.*** Microbiomes are central to biomanufacturing, where they degrade complex organics and produce sustainable biobased products. Fermentation processes leverage microbial consortia to convert substrates into food ingredients and biofuels, reducing chemical inputs and environmental footprints.

4.2 Environmental Remediation. Certain microbes naturally metabolize heavy metals, pesticides, and hydrocarbons. Deploying these communities in bioremediation projects restores contaminated soils and waters, improving ecosystem health and reducing public exposure to toxins.

4.3 Efficient Resource Usage. Soil and waste microbiomes optimize nutrient cycling and energy recovery. Anaerobic digestion transforms organic waste into biogas, while soil microbes enhance crop productivity, enabling circular resource flows in agricultural systems.

4.4 Probiotics as Green Technology. Probiotics confer host and environmental benefits by reinforcing microbial barriers against pathogens, modulating immunity, and restoring ecological balance. Their use diminishes reliance on antibiotics in livestock, curbs resistance spread, and supports human gut health.

Key Findings

i. Pathogen Categorization Enables Targeted GMT Design. Grouping zoonotic, environmental, and foodborne pathogens informs selection of probiotic interventions tailored to specific transmission pathways.

ii. Commensal Microbes as Biocontrol Agents. Probiotic application in livestock and soil systems suppresses pathogens, enhances immunity, and reduces chemical inputs.

iii. Microbiome-Mediated Ecosystem Services. Complex microbial communities underpin biomanufacturing, remediation, and resource efficiency, offering scalable GMT solutions.

iv. Preventive Microbial Management. Proactive cultivation of resilient microbiomes shifts paradigms from reactive pathogen control to preventive ecosystem stewardship.

Conclusions

This conceptual synthesis underscores the pivotal role of probiotics and commensal microorganisms in advancing Green Microbial Technologies within a One Health framework. By categorizing pathogen groups and elucidating how beneficial microbes stabilize and functionalize microbiomes, we demonstrate that targeted probiotic interventions can simultaneously enhance public health, agricultural productivity, and environmental sustainability. Emphasizing preventive microbial management positions GMTs as resilient strategies to curb pathogen threats and antibiotic resistance across interconnected ecosystems.

Recommendations:

- *Empirical Validation:* Conduct field and laboratory trials to assess specific probiotic strains' efficacy in reducing pathogen loads and resistance gene prevalence.
- *Harmonizing Practices:* To promote reproducibility and wide-scale adoption, it is essential to develop scientifically grounded protocols that define optimal probiotic formulations, application routes, and outcome assessment criteria.
- *Interdisciplinary Collaboration:* Encourage partnerships among microbiologists, agronomists, environmental engineers, and public health experts to integrate GMTs into existing frameworks.
- *Resistance Surveillance:* Implement longitudinal monitoring of resistance gene flow in GMT-treated

communities and environments to guide adaptive management.

- Policy Integration: Advocate for inclusion of probiotic-based GMT strategies in national and international One Health policies, highlighting preventive microbial stewardship as key to sustainable biosecurity and environmental health.

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How to Meet the Challenges in Agriculture as a Life Science University

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ABSTRACT

Agricultural systems across the globe are experiencing unprecedented pressure due to population growth, climate change, resource scarcity, and the demands of digital transformation. Life science universities stand at the heart of addressing these challenges through education, research, and societal engagement. This article outlines the role of the University of Applied Sciences Weihenstephan-Triesdorf (HSWT) in Germany as a model institution responding proactively to these trends. Through strategic investments, interdisciplinary research centers, and the development of innovative degree programs, HSWT exemplifies how academic institutions can become engines of sustainable change under the "twin transition" — the simultaneous pursuit of digital transformation and environmental sustainability.

Introduction

Universities in a Time of Transformation

In the 21st century, universities are being called upon to play a greater role in solving global challenges. The transition from traditional academic institutions to active agents of transformation is particularly important for life science universities. As the world grapples with crises like climate change, biodiversity loss, food insecurity, and energy shortages, the agricultural sector must evolve quickly.

Universities not only generate the knowledge required to tackle these issues, but they also educate the future professionals who will implement change. The Green Agriculture Conference in Yerevan, Armenia, 2025, underscores the urgency and highlights HSWT as a pioneering institution. The following sections describe how HSWT is building capacity, expanding knowledge, and creating tools for a more sustainable agricultural future.

Materials and methods

HSWT: A Profile of Applied Excellence

Founded in 1971 with a mission to offer practical, applied education, HSWT has become a cornerstone of agricultural and environmental innovation in Germany. Spread across two main campuses in Weihenstephan and Triesdorf, the university hosts (https://www.hswt.de/en/):

- Over 6,000 students
- 1,600 to 1,900 new enrollments annually
- 650+ international students
- 170 full professors and over 400 adjunct staff
- Seven faculties and seven specialized research facilities

HSWT also offers:

- 20 Bachelor‘s programs
- 18 Master‘s programs
- 14 work-study programs
- Continuing education, including certifications and short courses

Research facilities include specialized institutes in ecology, digital agriculture, horticulture, food technology, smart indoor farming, and biomass research (https://www.hswt.de/en/research/research-profile/research-institutions). Innovation hubs like the Food Startup Incubator (https://www.hswt.de/en/research/research-profile/research-institutions/institute-for-food-technology/food-startup-incubator-weihenstephan-fsiws) and the newly formed SUN (Startup, Entrepreneurship, Succession) center are helping bridge academia and enterprise (https://fsiws.com/en/new-gruendungszentrum-startup-entrepreneurship-and-follow-up-center-sun/).

The Agricultural Challenge Landscape

Agriculture today is at a crossroads. Major global forces include:

- *Population Growth:* The world population is expected to exceed 9 billion by 2050, increasing food demand by at least 60%.
- *Climate Change:* Droughts, floods, and rising temperatures threaten crop yields, livestock, and biodiversity.
- *Globalization:* International trade, supply chains, and economic interdependence bring both opportunities and vulnerabilities.
- *Resource Scarcity:* Water, soil, and energy are becoming limiting factors.
- *Technological Disruption:* Automation, AI, robotics, and IoT are transforming how farms are managed.

These interconnected challenges require complex, interdisciplinary solutions – the very type that life science universities are well-positioned to provide.

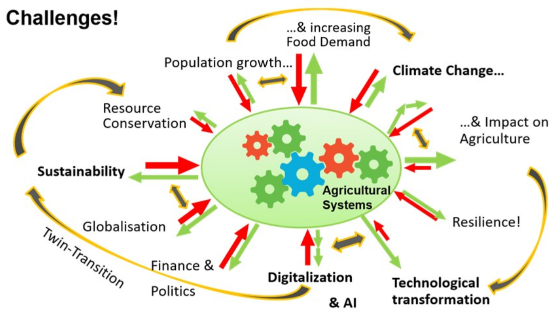

Figure. The challenges in agriculture and their interactions.

The Twin Transition: Digital and Green Integration

The “twin transition” merges two vital shifts:

Digitalization: Using digital technologies to optimize operations, monitor systems, and predict outcomes.

Green Transformation: Transitioning to environmentally sustainable practices that reduce emissions and conserve resources.

Examples at HSWT include:

- Precision agriculture using drones and satellite imaging
- AI algorithms for crop health monitoring
- Smart irrigation systems that conserve water
- Biodiversity-friendly farming practices

This dual approach not only increases efficiency but also helps mitigate agriculture’s environmental footprint. Students trained under this paradigm become change agents in both digital and ecological domains.

Results and discussions

Strategic Response: The Hightech Agenda Bayern

To meet these challenges, the Bavarian government launched the Hightech Agenda Bayern (https://www.hightechagenda.de/en/), an unprecedented investment program totaling €5.5 billion. Its key elements include:

- Creation of 1,000 professorships in future-oriented fields such as AI, sustainability, and clean tech
- €600 million investment in infrastructure modernization
- 46 new Technology Transfer Centers (TTZs) for regional knowledge exchange

- 19 digital startup centers to foster entrepreneurship
- Support for SMEs in digital transformation

HSWT is a major beneficiary, enabling it to expand its academic offerings, upgrade labs, and collaborate more closely with regional industries.

Climate Change and Agricultural Resilience

To address climate change, HSWT has strategically introduced:

New Professorships (2020-2025):

- Agricultural Systems and Climate Change
- Sustainable and Resilient Farming
- Novel Grain Crop Breeding
- Climate Change Hydrology and Advanced Irrigation
- Forestry and Climate Change

New Degree Programs:

- MSc Climate Change Management (English) https://www.hswt.de/studium/studienangebot/master/climate-change-management
- MSc Sustainable Regional Development (English) https://www.hswt.de/en/study/study-offer/master/sustainable-regional-development
- MSc Resilient Horticulture (English) https://www.hswt.de/en/study/study-offer/master/resilient-horticulture
- BSc Climate Change Mitigation and Adaptation (German)
- BSc Green Urban Planning (German)
- BSc Energy and Water Management (German)

Specialized Research Centers:

- *Peatland Science Centre (PSC):* Focuses on peatland conservation, carbon storage, and biodiversity https://www.hswt.de/en/research/research-profile/research-institutions/institute-of-ecology-and-landscape/peatland-science-centre
- *B.Life Centre:* Integrates social and scientific dimensions of climate adaptation https://www.hswt.de/en/about/university-profile/sustainability-environmental-management/blife-centre

These initiatives promote a deeper understanding of climate impacts and foster practical solutions for resilience.

Digitalization and Technological Transformation in Agriculture

Parallel to climate strategies, HSWT also prioritizes digital transformation through:

Professorships in:

- Smart Farming
- Digital Farm Management
- Green Digital Engineering
- Data Science for Life Sciences
- IoT in Agriculture and Environment

Degree Programs:

- MSc Digital Farming (English) https://www.hswt.de/en/study/study-offer/master/digital-farming
- MSc Green Digital Engineering (German)
- BSc Applied Informatics (English) https://www.hswt.de/en/study/study-offer/bachelor/applied-informatics

Clusters and Centers:

- *KoDA* (Competence Center for Digital Agriculture): A hub for data-driven innovation https://www.hswt.de/en/research/research-profile/research-institutions/competence-centre-for-digital-agribusiness-koda
- *Cluster Green AI:* Fosters robotics, machine learning, and digital twins for farming.

These efforts equip students with hands-on skills in precision agriculture, cloud computing, and AI applications.

Interdisciplinary and Intersectoral Knowledge Transfer

Real-world transformation depends on more than research – it needs action. HSWT embraces this by:

- Creating interdisciplinary platforms for students, researchers, and professionals
- Hosting "real-world laboratories" to test innovations in live environments
- Offering continuing education and certification for lifelong learning
- Actively involving stakeholders in curriculum development

Transfer isn't one-way: HSWT listens to the needs of industry and communities and co-creates solutions.

Networking and Global Collaboration

Agricultural challenges are global, and so must be the responses. HSWT engages in:

- International research collaborations and EU-funded projects
- Exchange programs with universities on all continents
- Shared innovation platforms for policy dialogue and best practices
- Capacity-building programs for developing countries

Standardizing data, sharing methodologies, and learning from others are essential to accelerate progress.

The Vision: Centre for Systemic Agricultural Sciences

As a next step, HSWT is developing a Centre for Systemic Agricultural Sciences (working title). An agricultural centre in Weihenstephan, also connected with Triesdorf, where the University of Applied Sciences Weihenstephan-Triesdorf (HSWT), the Technical University of Munich (TUM), and the Bavarian State Research Center for Agriculture (LfL) collaborate closely, offers several key advantages, especially when viewed through the lens of agricultural systems science:

Interdisciplinary Synergy and Complementary Expertise

Each institution brings its unique strengths to the table, fostering a truly interdisciplinary approach:

- *HSWT* excels in applied research, focusing on practical, hands-on agricultural innovation and technology transfer.
- *TUM* is renowned for its cutting-edge basic research and academic rigor in life sciences, agronomy, and environmental sciences.
- *LfL* provides a bridge between research and agricultural policy, offering practical implementation insights and ensuring that findings contribute to regional agricultural development. Together, these complementary roles create a holistic research ecosystem that addresses challenges at every stage, from basic research to field application.

Systems Thinking Approach to Agriculture

By integrating the expertise of these institutions, the center can adopt a systems-level perspective on agriculture. Agricultural systems science aims to understand and optimize the interconnected components of agriculture, including soil health, plant breeding, crop production, resource efficiency, biodiversity, and sustainability. The combined knowledge allows for the development of innovative, systemic solutions to complex agricultural challenges such as climate change, sustainable food production, and digitalization in farming.

Innovation and Technology Transfer

The close collaboration between academic researchers, applied scientists, and government researchers ensures that innovations in precision farming, plant genetics, and sustainable agricultural practices are efficiently translated from research to real-world applications. Farmers and agricultural businesses can benefit more directly from cutting-edge research.

Efficient Use of Resources and Infrastructure

Sharing resources—such as laboratories, experimental fields, greenhouses, and data infrastructure—promotes efficiency and cost savings. It also fosters joint projects that would be difficult to implement independently.

Strengthened Regional and Global Impact

The agricultural center can enhance the global reputation of Weihenstephan as a hub for agricultural excellence, while also addressing region-specific challenges. This dual focus strengthens both local agriculture and the international competitiveness of Bavarian agricultural research.

Enhanced Educational Opportunities

Students and young researchers benefit from exposure to a broad spectrum of agricultural sciences, gaining access to diverse research methodologies, practical applications, and cross-institutional learning. This fosters a new generation of experts equipped with the interdisciplinary skills needed to tackle the future challenges of agriculture.

A tightly integrated agricultural center in Weihenstephan creates a powerful platform for addressing complex agricultural challenges through collaboration, innovation, and systems-based thinking. By pooling the strengths of HSWT, TUM, and LfL, the center not only drives sustainable agricultural development but also strengthens Bavaria's position as a leader in agricultural research and education.

Together, we will create a European agricultural centre with well over 100 professorships in the agricultural sector. It is expected to be launched in 2027, in the area of teaching, with its own degree programmes and in the area of research.

Outlook: The Role of Universities in Shaping the Future

Universities must not only react to global change – they must anticipate and shape it. Their responsibilities include:

- Educating future leaders with practical and ethical tools
- Uniting digital progress and ecological stewardship
- Serving as think tanks and testbeds for innovation
- Engaging with citizens, governments, and businesses

Life science universities, in particular, hold the key to balancing productivity and sustainability – a task that will define the coming decades.

Conclusion

The agricultural sector is undergoing a historic transformation. Life science universities like HSWT demonstrate that academic institutions can – and must – be proactive leaders in this change. By embedding sustainability and digital innovation into their mission, they help build the resilient food systems of the future. HSWT's example illustrates that with strategic foresight, interdisciplinary thinking, and strong partnerships, universities can serve as true engines of change in a complex and rapidly evolving world.

Declarations of interest

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Capacity Development for Green Agriculture in Armenia: An AKIS-Based Assessment and Strategic Roadmap

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ABSTRACT

This study contributes to the European Union›s Green Agriculture Initiative in Armenia (EU-GAIA), a development project aimed at fostering sustainable, inclusive, and market-oriented agribusiness in the northern regions of Armenia. Implemented by the Austrian Development Agency, the project supports the transition to green agriculture (GA) through capacity building, policy development, and stakeholder engagement. Employing the Agricultural Knowledge and Innovation System (AKIS) framework, this research identifies capacity needs, institutional challenges, and knowledge gaps among key stakeholders. The study combines a systematic review with 68 in-depth stakeholder interviews and a tailored questionnaire-based self-assessment to develop a capacity development roadmap. Findings reveal critical weaknesses in research collaboration, extension services, market incentives, and policy enforcement. The paper presents a detailed strategy for short- and long-term capacity building, including the establishment of Centres of Excellence, curriculum reforms, legal frameworks, and stakeholder networking mechanisms. The results offer actionable insights for policymakers, development agencies, and academic institutions committed to sustainable agricultural transformation.

Introduction

Green agriculture (GA) is a transformative approach that aims to reconcile food production with environmental sustainability and rural development. It emphasizes resource-efficient practices, emissions reduction, and improved soil health, while contributing to climate resilience and economic inclusiveness. Armenia's agricultural sector, characterized by smallholder dominance and regional disparities, faces mounting challenges related to soil degradation, limited innovation, and market inefficiencies. The EU-GAIA project seeks to address these challenges by enabling systemic change in the sector through capacity development, institutional alignment, and multi-stakeholder collaboration. This paper presents the findings of a comprehensive capacity needs assessment, with the aim of designing a coherent capacity development strategy based on the AKIS framework.

Background on the Armenian Agricultural Sector

The agricultural sector in Armenia is regarded as one of the most important sectors of the economy, contributing about 15% to the country's GDP and employing approximately 40% of the population (FAO, 2020). Agriculture is also the main source of economic activity in rural areas and is significantly female-driven, with nearly 56% of farmers being women. The farm structure in Armenia, like in many other countries in the region, is dominated by a large number of small-scale farms with fragmented land holdings. The average farm size is about 1.48 hectares (ICARE and IFOAM, 2017). According to 2014 census data, the 317,346 family farms contribute to more than 97% of total agricultural output.

Despite its economic and social importance, the sector remains at a low level of development, facing challenges such as geographic isolation, being landlocked with limited access to export markets, and a dependency on the Russian market. Key areas for improvement include the need for innovation, production efficiency, and a clearer legal framework. These limitations hinder sustainable development and resilience in the sector.

The Case for Green Agriculture in Armenia

In response to environmental degradation and climate challenges, the concept of Green Agriculture (GA) has been proposed to ensure food security while preserving ecosystem services for current and future generations (ICARE and IFOAM, 2017). The Republic of Armenia has favorable geographic and natural conditions conducive to GA. Recognizing this, the Ministry of Economy has prioritized GA through its integration into governmental policy and regulatory frameworks.

GA is often used interchangeably with terms such as sustainable agriculture or sustainable food systems. According to the HLPE (2014), a sustainable food system "delivers food security and nutrition for all in such a way that the economic, social and environmental bases to generate food security and nutrition for future generations are not compromised." The European Environment Agency (EEA, 2027) similarly emphasizes that sustainability must ensure both human and ecosystem health. GA draws upon principles from organic, ecological, biodynamic, and conservation agriculture. The FAO defines organic agriculture as a system that sustains the health of soils, ecosystems, and people by relying on ecological processes and biodiversity rather than external inputs (FAO, 2009; Gomiero, et al., 2011).

In summary, Green Agriculture can be defined as the production of sufficient, healthy, and high-quality food without depleting natural resources, using farming practices that conserve resources, reduce emissions and waste, and improve soil quality.

Materials and methods

Conceptual Framework

The Agricultural Knowledge and Innovation System (AKIS) framework provides a structured approach to assess and enhance interactions among education, research, advisory services, and market actors. It is increasingly adopted in the EU and its partner countries as a guiding concept for aligning agricultural innovation with societal goals.

Agricultural Knowledge ու Innovation System

The concepts of AKIS are used in this study to 1) identify and assess the capacity needs revealing the existing capacity needs, challenges and knowledge gaps of relevant stakeholders in terms of green, sustainable agriculture and 2) to develop a plan for a capacity development strategy, identifying both short and long-term requirements of relevant stakeholders.

AKIS is a useful concept to describe a system of innovation, with emphasis on the organizations and stakeholders involved, the links and interactions between them, the institutional infrastructure with its incentives and budget mechanisms (SCAR AKIS, 2012, 2016, 2019). AKIS is the combined organization and knowledge flows between persons, organizations and institutions who use and produce knowledge for agriculture and interrelated fields (Figure 1).

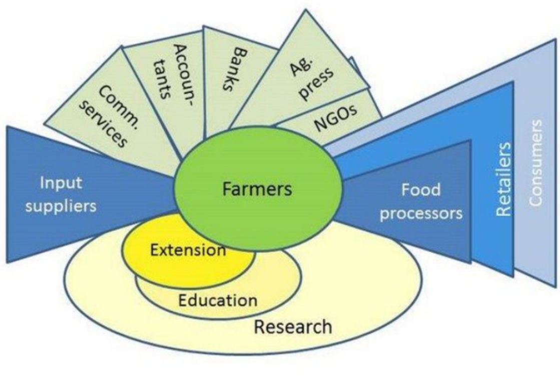


Figure 1. Visualization of the Agricultural Knowledge and Innovation System. *Source:* SCAR-AKIS.org.

AKIS actors use and produce knowledge for agriculture and interrelated fields (value chains, rural actors, consumers, etc.). Although different components of AKIS, extension/advise, education and research, are often stressed, it is important to realize that there are many more actors in the food chain which directly influence the decision making of farmers and their innovations (Figure 2).

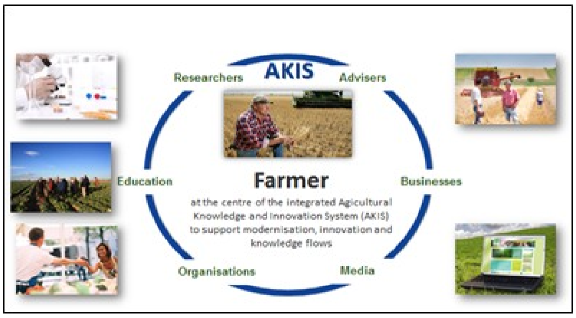


Figure 2. Relations and interaction between AKIS actors. *Source: AKIS, 2019.*

Seven key functions for AKIS

In particularly, when developing capacity development strategy, the 7 key functions for AKIS framework is utilised (Table).

Research Design and Data Collection

The study was conducted from November 2020 to March 2021 in Armenia. It involved five main components:

- Stakeholder mapping and identification (124 stakeholders including ministries, NGOs, universities, and the private sector)
- Development of tailored self-assessment questionnaires
- Review of relevant literature, including the EU Green Deal and CAP policy documents
- Conducting 68 semi-structured interviews (24% women-led organizations)
- Qualitative coding and synthesis of data into capacity themes

Results and discussions

Interviews

The interviews were conducted through phone calls, using online platforms or organizing personal meetings. Personal meetings took place mainly in regions, taking into consideration several factors: availability of internet and knowledge of online platforms, willingness of stakeholders as well as their business life. The tailor-

Table. Seven key functions for AKIS*

Education, technical training, research and data collection	Fundamental to the transformation process and involves the learning processes related to developing and utilizing new knowledge of a technology or set of practices. The development of new knowledge can occur through formal research (e.g. at universities and governmental and non-governmental research centers), the private sector (e.g. agri-business) or at the individual level (e.g. farmers).
Knowledge diffusion through networks	The exchange of information through networks, where research and development (R&D) meets government and markets. Policy decisions should be guided by the latest technological research, and R&D agendas should be adapted to changing environmental, market and social conditions.
Development of a vision for the agricultural sector	Refers to the creation of a vision for the AKIS and mobilization of incentive structures to promote that vision. Incentive structures may change in response to factor prices and regulatory pressures (e.g. product prices, taxes and subsidies), expectations in market growth potential, new knowledge, expression of interest by customers, cultural changes and external events.
Entrepreneurial activities	Turn the potential of new knowledge, networks and markets into concrete actions to develop and capitalize business opportunities.
Market formation	Is about creating demand for the outputs of the development process. New technologies or practices often have difficulty competing with the status quo, so a market must be created via institutional change. Market creation can occur through changes in regulation and taxes and/or investment in infrastructure complimentary to the innovation.
Creation of legitimacy	It is necessary to overcome resistance to a new technology or set of practices from the existing production, trade and consumption systems. It must be considered appropriate and desirable by incumbent actors for resources to be mobilized rather than blocked.
Resource mobilization	Is closely linked to the creation of legitimacy and concerns financing investment in innovation in the form of access to credit, seed funding, venture capital, investment in human and social capital and the development of complementary products, services, infrastructure, etc.

**Source: Sixt u. Poppe, 2019.*

made questionnaires with open-ended questions have been used during the interviews, creating a basis for detailed discussion and expression of views without any limitations. In average, interviews took around 1 hour, though sometimes it extended to two hours. During interviews respondents were asked to evaluate and answer questions from their personal and organizational perspectives, having in mind their needs and development perspectives. The interviews involved all types of stakeholders. The private sector respondents and respondents presenting their own organization (for example NGOs) answered to the questions mainly from their personal perspective. Other respondents tried to differentiate their personal and organizational needs/issues, which, not always was successful. The number of interviews per stakeholder group is as follows (Figure 3):

- State bodies (Ministries and other state institutions) - 11
- Regional authorities - 5
- Education and Research institutions/colleges - 15
- Extension services/advisors - 9
- Non-Governmental organizations - 7
- Associations/unions - 5
- International Organizations - 5
- Private sector organizations/farmers - 10
- Local organic certification provider - 1

41% of the interviewed stakeholders are in regions of Armenia.

Analysis of the Seven AKIS Functions for Green Agriculture

The Armenian agricultural sector is characterized by structural weaknesses, which hinder the development of GA. Major gaps include limited alignment between education/training and sectoral needs, weak public extension services, low engagement of smallholders,

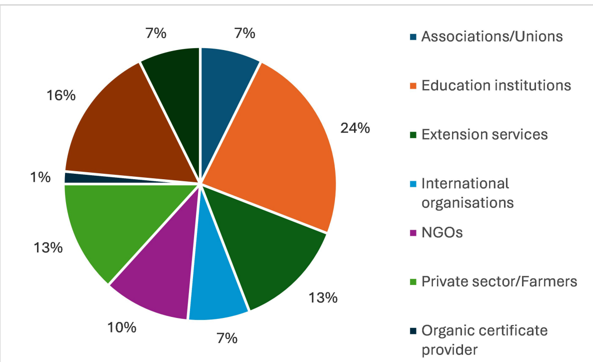


Figure 3. Legal forms of interviewed stakeholders

and fragmented vision among stakeholders. This section assesses Armenia's AKIS performance using the seven-function framework (see Table 1), based on interviews and literature.

1. Education, Training, and Research

Current education and research systems do not adequately support GA development. Agricultural education is unattractive to youth due to outdated methods, weak sector development, and limited profitability. Key challenges include:

- *Weak Coordination:* Limited collaboration between universities, research institutes, NGOs, and the private sector leads to duplication and inefficiencies. NGOs are the most active in knowledge transfer, often driven by donor-funded projects, while government involvement remains low.
- *Misaligned research agendas:* Public research institutions are poorly connected to farmer needs. There is a lack of systematic transfer of sector challenges into research priorities and back into practice. Though demo plots (e.g. by ANAU) exist, scaling innovations remains a challenge for smallholder-dominated agriculture.
- *Underdeveloped capacity and Infrastructure:* Extension services lack GA expertise and quality monitoring mechanisms. Most extension staff have limited knowledge of international programs and innovative farming practices. Education programs lack digital platforms (e.g., MOOC/Moodle) and data analytics integration.

Curricula need redesign to integrate sustainability principles across subjects. Enhanced collaboration with the private sector is needed to update training content and delivery. Investments are required in demonstration facilities, tech parks, and innovative laboratories to support hands-on learning. Advisory services need systemic upgrades through continuous training, peer learning, performance-based incentives, and stronger linkages with education and research institutions.

2. Knowledge Diffusio

Knowledge diffusion in Armenia's agricultural sector remains limited and fragmented, posing a barrier to the advancement of GA. Three key challenges were identified:

- Weak stakeholder collaboration: Existing multi-stakeholder platforms (e.g., regional alliances, public councils, donor-funded working groups) are underutilized for GA promotion. Stakeholder engagement, particularly from government institutions, remains limited, and the institutional capacity of associations and sectoral unions to advocate for GA is weak. Increased cooperation, peer learning, and capacity-building initiatives are needed.

- *Lack of a centralized GA knowledge hub:* There is no integrated system for collecting and disseminating GA-related knowledge. A centralized knowledge platform (e.g., website or offline depository) is needed to aggregate research, best practices, regional data, and innovation examples. It could also serve to connect stakeholder networks. Armenia's Digital Agriculture Strategy offers a potential entry point for this development.
- *Limited public awareness and visibility:* Awareness of GA remains low among farmers, communities, and local authorities. Media campaigns, educational programs, school-based environmental activities, and demonstration sites could help build broader understanding. Local authorities should be empowered to act as GA ambassadors, promoting sustainable practices at the community level.

3. Development of a Common Vision on Green Agriculture

Armenia lacks a unified national vision for GA. Fragmented priorities among public institutions, weak coordination with private actors, and the absence of organized leadership hinder the sector's strategic direction. Conflicting goals and limited information exchange further constrain the development of GA.

A shared, long-term vision is needed—one that aligns public, private, and civil society actors. Key recommendations include:

- Inclusive stakeholder engagement through continuous dialogue (e.g., forums, working groups), with a leading institution coordinating the process—potentially the Ministry of Economy after the EU-GAIA project.
- Clarity on GA definitions and principles, emphasizing environmental protection and sustainability (e.g., "less harm, more value recovery").
- Local government involvement in developing region-specific strategies for natural resource protection.
- Integration of GA into national strategies, such as the 2020–2030 agricultural development policy, alongside the development of a dedicated GA strategy. A phased approach—starting with a letter of intent—can help build momentum and commitment.

4. Entrepreneurial Activities

The Armenian agricultural sector lacks a strong culture of innovation, due to both internal (institutional and capacity-related) and external (regional instability) factors. Farmers and entrepreneurs tend to be risk-averse and require incentives to adopt GA practices. These may include financial support, guaranteed markets for green products, and simplified procedures. Private sector engagement in GA depends on profitability, visible success stories, and a supportive regulatory environment. Currently, public-private partnerships (PPPs) are underdeveloped, though they hold potential for facilitating the transition to GA if adequately financed and structured.

5. Creation of Legitimacy

Establishing legitimacy for GA in Armenia requires a clear legal framework. Respondents emphasized the need for GA to be integrated into national agricultural strategies and supported by regional action plans. Legislative updates are needed across multiple areas, including environmental standards, enforcement mechanisms, and incentives for sustainable practices. The lack of enforcement of existing laws—such as those regulating organic labeling and residue burning—undermines trust and progress. The development of comprehensive GA legislation, supported by the findings of the 2020 EU-GAIA policy review, is a critical step forward.

6. Market Formation

Market development is vital for GA adoption. Export opportunities are limited due to compliance issues with international standards. Farmers and businesses require state support to understand and access these markets. Policy instruments such as tax incentives, quality-based subsidies, and labeling regulations can stimulate market demand for green products. Branding, certification, and targeted marketing strategies are essential tools for promoting consumer awareness and creating value chains based on sustainability principles.

7. Resource Mobilization

Sustainable resource mobilization is currently inadequate. There is limited public financing for GA, and private sector engagement in training or innovation support is minimal. Key gaps include the absence of data systems for climate and market intelligence and limited integration of research, extension, and education. Innovation hubs such as Living Labs or Centers of Excellence could fill this void, fostering collaboration and knowledge exchange. However, these require significant investment and capacity development, particularly among educators and researchers, to bridge the knowledge gap with the private sector.

Conclusion

Armenia's transition toward Green Agriculture (GA) is challenged by structural weaknesses across its Agricultural Knowledge and Innovation System (AKIS). These include misaligned education and research agendas, under-resourced extension services, fragmented stakeholder collaboration, and limited policy and market support. A lack of entrepreneurial culture and an underdeveloped legal and institutional framework further constrain progress. Resource mobilization remains inadequate, and there is no unified national vision to guide transformation.

Despite these challenges, positive developments are emerging. Stakeholder awareness of sustainability is growing, supported by EU-funded initiatives like the GAIA project, which have initiated policy dialogue, demonstration activities, and capacity-building. Armenia's Digital Agriculture Strategy provides a promising platform for centralized knowledge sharing. Efforts to modernize curricula, expand demonstration plots, and promote branding and certification of green products show early signs of momentum. There is also increasing recognition of the value of public-private partnerships and innovation hubs such as Living Labs and Centers of Excellence.

To build on these foundations, Armenia must continue to align education, research, and extension systems with sectoral needs, promote stakeholder coordination, invest in infrastructure and training, and establish a coherent legal and strategic framework for GA. Strengthening market incentives and resource mobilization—through supportive policies and institutional leadership—will be essential for enabling a sustainable agricultural transition.

Below, we present a set of short-term and long-term recommendations to guide future action. The highlighted recommendations can be considered as the main building blocks for further implementation of the GA capacity building in Armenia.

Short-Term Measures

Centre of Excellence: Establish a dedicated Centre of Excellence to raise awareness and showcase GA progress. It can host demonstrations, school activities, and public campaigns. This center would serve as a hub for capacity building and outreach.

GA Curriculum: Integrate GA principles into educational programs, not only in agriculture but also in business, environmental, and ecological studies. Close cooperation with the private sector is essential to update curricula and align professions with evolving sector needs.

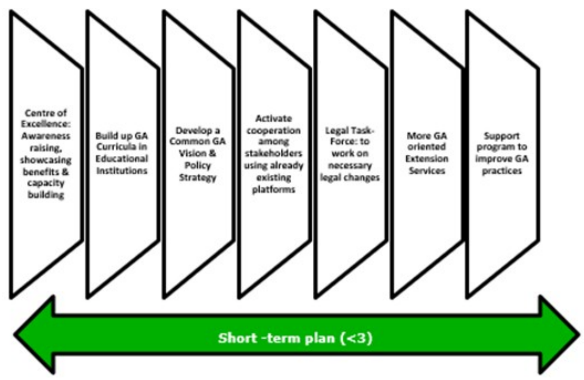
Common Vision and policies: Develop a shared national GA vision supported by clear policies and market incentives—such as green labelling, tax benefits, or subsidies—to build public commitment and demonstrate government leadership.

Stakeholder Cooperation: Strengthen collaboration through existing platforms like working groups or public councils. Facilitate joint action among farmers, researchers, and extension services, with strong government involvement.

Extension Services Reform: Reorient extension services to support GA through new performance indicators, regular advisor training, and adoption of international best practices. Services must offer timely, tailored, and practical guidance to farmers.

Legal Taskforce: Establish a taskforce to revise laws and prioritize GA-related legal reforms. Many existing regulations are outdated, unenforced, or not aligned with GA needs.

Support Program for GA Adoption: Launch a state-funded program to stimulate GA through incentives for producers, export readiness support, and consumer awareness (e.g., food safety as part of green branding). Special focus should be placed on empowering youth and women through targeted capacity building.



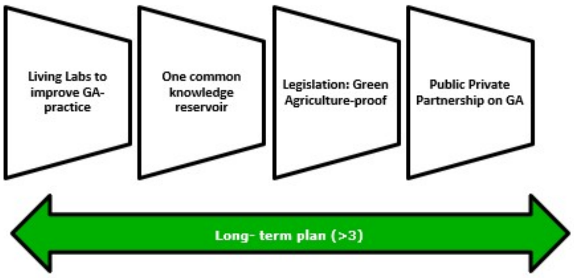
Long-Term Measures

Living Labs for GA: Evolve the Centre of Excellence into Living Labs to test, refine, and promote practical GA solutions. This includes strengthening laboratory facilities in research and educational institutions.

Central Knowledge Hub: Create a national GA knowledge platform with three key functions: (1) centralizing tools, research, and materials; (2) offering an open-source agricultural innovation database; and (3) connecting existing stakeholder networks. This hub could be developed under the Ministry of Economy's digital infrastructure.

GA-Aligned Legislation: Complete and enforce the work of the Legal Taskforce by integrating GA provisions into relevant laws and ensuring effective implementation and compliance mechanisms.

Public–Private Partnerships (PPPs): Establish PPPs to sustain awareness-raising efforts, encourage innovation, and engage farmers and youth in shaping the future of agriculture. These partnerships can serve as platforms for dialogue and adaptation to sectoral changes.



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Innovative Approaches to Knowledge Transfer and Experience Sharing in Armenian Agriculture

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ABSTRACT

As Armenia seeks to transition toward more sustainable and climate-resilient agricultural practices, the success of this transformation depends significantly on how knowledge is generated, shared, and applied among agricultural stakeholders. This paper explores critical gaps in the current educational system for agricultural professionals in Armenia, contrasts these with international best practices, and proposes a two-part strategy that integrates curriculum reform, experiential learning, and digital tools. A five-step model for training veterinarians and farmers is presented, along with practical innovations such as mobile applications, video tutorials, and a national online platform for agricultural education. By emphasizing participatory learning, localized content, and lifelong education, this framework seeks to empower individuals and communities, enabling Armenia's agricultural sector to thrive in the face of future challenge.

Introduction

Agriculture remains a vital component of Armenia's economy and national identity. However, achieving sustainable development in this sector requires more than advanced technology or foreign investment. It requires a strategic transformation in how agricultural knowledge is produced, transferred, and embedded in practice. The importance of knowledge transfer in agriculture cannot be overstated; it serves as a bridge between traditional practices and scientific innovation, enabling communities to adapt to climate variability, improve productivity, and strengthen resilience.

This article argues that while Armenia has a foundational education system in agriculture, it falls short in delivering practice-oriented, continuously updated knowledge to students and professionals alike. We propose a forward-looking model that centers on human capacity—students, educators, veterinarians, and farmers—as the key to transforming Armenian agriculture from the ground up. Contemporary models of knowledge transfer emphasize experiential learning, Trainer of Trainers (ToT), peer-to-peer dissemination, and technology-enabled platforms that make knowledge more accessible and actionable.

Materials and methods

1. Limitations of the Formal System

Conventional agricultural education in Armenia often prioritizes theory over practice. For instance, veterinary training programs at Armenian universities lag behind their European counterparts in both structure and content. While graduates may possess theoretical knowledge, they frequently lack the hands-on experience required in real-world farm settings. A diploma or certificate alone is not a guarantee of professional competence—a reality underscored by the observed disparity between Armenian and Bavarian veterinary education models.

Armenia's agricultural universities and colleges produce numerous graduates each year. However, the effectiveness of this education in preparing professionals for modern agricultural challenges is debatable. A diploma or certificate often does not equate to practical knowledge or skill. The curricula are heavily loaded with non-specialized subjects, while practical training hours are minimal. For example, veterinary students at the Armenian National Agrarian University receive only one semester of practical training (120 hours), in contrast to approximately 1,200 hours in German programs like that of LMU Munich.

Moreover, core subjects such as language, political science, and philosophy dominate the early semesters in Armenia, leaving students underprepared for real-world veterinary and agricultural challenges.

2. Learning versus Memorizing

The "Learning Pyramid" model demonstrates that traditional lecture-based instruction results in low knowledge retention (~10%), while participatory methods such as practical application and peer teaching result in retention rates of up to 90%. Armenian education still favors passive learning, thereby failing to prepare professionals for on-farm problem-solving and innovation.

In the context of modern agricultural education and capacity-building, traditional pedagogical models often fall short in equipping learners with the practical, experience-based knowledge required for fieldwork and technical problem-solving. To address this gap, a modified and contextually adapted version of the Learning Pyramid has been proposed as a guiding framework for both initial and continuous education of agricultural specialists. This model emphasizes a progressive shift from passive to active learning methods—starting with foundational theoretical instruction (e.g., reading and lectures) and moving toward higher-retention activities such as observation, demonstration, simulation, and ultimately, "learning by doing" trough ToT and peer-teaching.

In its adapted form for agricultural use, the learning pyramid prioritizes practical application in real-world settings—such as internships on working farms, guided fieldwork with livestock or crops, and problem-solving workshops with real case studies. Crucially, the model also integrates digital learning platforms, including video tutorials, AI-enhanced translation tools, and mobile applications, to ensure accessibility across Armenia's diverse and often rural agricultural communities. When learners engage not only in practice but also in teaching peers and contributing to forums or discussion groups, retention rates approach 90%, according to educational research.

Such an approach is particularly relevant for the Armenian agricultural sector, where educational reforms are urgently needed to replace outdated, theory-heavy curricula with skills-based training. Therefore, an adapted learning pyramid serves not only as a pedagogical tool but as a strategic framework for building a resilient, competent, and future-ready agricultural workforce.

Chapter. Modified Learning Pyramid for agricultural education in Armenia. *Source: National Training Laboratories. (n.d.). Learning Pyramid. Bethel, ME.*

3. Two-Part Strategic Framework for Reform

- Part 1: Reforming Student Education

To modernize agricultural education, the following reforms are proposed:

Curriculum Update: Prioritize profession-specific subjects from the first semester onward.

Practical Internships: Partner with farms and agribusinesses to embed hands-on learning.

Modern Teaching Materials: Replace outdated textbooks with current, relevant content.

Educational Videos: Use visual learning tools to improve retention and accessibility.

- Part 2: Lifelong Learning for Professionals

The rapid evolution of agricultural practices means knowledge becomes outdated quickly. Agricultural universities must evolve into centers for continuous learning, offering:

- Short courses and seminars.
- Modular content delivery.
- Remote access to training materials.

4. Five-Step Model for Veterinary Training and Dissemination

To address the deficiencies in the current system, a five-step phased strategy was developed for knowledge transfer and professional development in veterinary science:

Step 1: Selection of Regional Trainers (Multipliers, ToT)

Veterinarians from across Armenia are selected based on their motivation and capacity to train others.

Step 2: International Training in Germany

Selected participants undergo intensive, hands-on training at the Triesdorf Agricultural Training Center in Bavaria, focusing on cattle husbandry, disease detection, nutrition, and treatment techniques.

- *Step 3:* Localization of Learning Content

Materials are adapted to the Armenian agricultural context, translated, and integrated into training formats suited for adult learners and farmers.

Step 4: Digital Dissemination

Content is made accessible via the Armenian Agricultural Education (AAE or similar) Platform, a digital hub designed for open access learning and international collaboration.

Step 5: Regional Capacity Building

Trained veterinarians conduct workshops, seminars, and field trainings across Armenian regions, creating a multiplier effect and fostering local ownership.

5. Technological Tools Supporting Knowledge Transfer

5.1 The “Cow & Calf” Handbook

This Armenian-translated manual provides visual guides and practical advice for recognizing and treating cattle diseases. It is an essential reference for both veterinarians and livestock farmers and a comprehensive guide covering disease symptoms, causes, emergency response, and preventive measures, translated for Armenian audiences.

5.2 “Fit for Cows” Smartphone Application

This mobile application, developed in Germany and currently being translated into Armenian, enables farmers to identify behavioral signals and symptoms in cattle for early disease detection.

5.3 Educational Veterinary Video Tutorials

A series of short, practical video guides (e.g., on hoof care and disease prevention) address specific Armenian veterinary challenges. These videos serve as supplementary learning tools, especially in rural areas.

Results and discussions

Although still in early phases of implementation, pilot training sessions have demonstrated:

- Enhanced practical knowledge among trainees.
- Increased confidence in disease detection and treatment.
- High demand for region-specific training sessions across provinces.
- Strengthened networks between local veterinarians and international experts.

The scalable and adaptable nature of the five-step model positions it as a replicable framework for other sectors within Armenian agriculture (e.g., horticulture, agribusiness, water management).

To ensure long-term impact, the following actions are recommended to create an Armenian Agricultural Education (AAE) platform serves as a central pillar in the dissemination ecosystem. Its functionalities include:

- Access to manuals, video content, and translated German educational resources.
- AI-based translation to facilitate cross-border dialogue and knowledge flow.
- Discussion forums for peer engagement and expert consultation.
- Integration of mobile-responsive learning tools.

This platform not only democratizes access to knowledge but also fosters long-term partnerships between Armenian professionals and European institutions.

Conclusion

The path toward sustainable, green agriculture in Armenia lies not only in policy or investment but in people—how they learn, apply, and share agricultural knowledge. The transformation of Armenia's agricultural sector begins with educational reform and extends through lifelong learning, digital access, and participatory practice. By implementing the proposed strategies and tools, Armenia has the potential to become a regional leader in knowledge-driven, sustainable agriculture.

This initiative highlights the importance of:

- *Local empowerment:* Giving Armenian professionals the tools and autonomy to lead training efforts ensures sustainability.
- *International cooperation:* Germany's contribution through infrastructure, expertise, and digital tools exemplifies the benefits of global partnerships.
- *Hybrid learning:* Combining digital platforms with in-person training strikes a balance between scalability and depth of knowledge.

However, challenges remain, including ensuring consistent internet access in rural areas, maintaining updated content, and securing long-term institutional funding.

To foster sustainable growth in Armenian agriculture, a shift from static education to dynamic, practice-based learning is essential. The five-step model, enhanced by digital platforms and international collaboration, provides a resilient framework for transforming veterinary and agricultural education. By investing in human capital—students, farmers, and veterinarians alike—Armenia can cultivate a knowledgeable, skilled, and adaptive agricultural workforce capable of meeting the demands of the 21st century.

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Declarations of interest

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