CURRENT CONCEPTS AND INNOVATIVE RESEARCH IN AGRICULTURE, FOREST AND WATER ISSUES



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Editor
Prof. Dr. NİGAR YARPUZ BOZDOĞAN



Current Concepts and Innovative Research in Agriculture, Forest and Water Issues

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CONTENT

1. Chapter **6**

Transforming Water Governance in Rapidly Urbanizing Regions: Strategies for Sustainable Management and Resilient Communities

Benson Rayson RUSIZI, İsmail Bülent GÜRBÜZ

2. Chapter **23**

Water Security Under Pressure: Sustainable Management Strategies for Rapidly Urbanizing Mediterranean Cities

Mohamed SIBIE, İsmail Bülent GÜRBÜZ

3. Chapter **38**

Energy Budget Calculation Methods in Crop Production (A literature review on energy balance)

Serap AKDEMİR

4. Chapter **55**

An Assessment of The Turkish Food Industry from a Sustainability Perspective

Şule TURHAN

5. Chapter **73**

Bee Products and Their Use in Apitherapy

Nuray ŞAHİNLER, Esra KOCABAŞ

6. Chapter **85**

Effects of Structural and Operational Features of a Flail-Type Forage Harvester on Chopping Length and Energy Consumption

Hüseyin SAUK, Mehmet Arif BEYHAN

7. Chapter **96**

Use of Digital Farming in Plant Production

Cenk PAŞA

8. Chapter **108**
Weed-Induced Losses in Pakistan: Economic Liability, Herbicide Reliance and Sustainable Solutions
Haroon KHAN, Ömer Süha USLU, Shah Alam KHAN, Osman GEDİK

9.Chapter **123**
Nanoparticles for Plant Production
Cenk PAŞA, Alper YARDAN

10.Chapter **141**
Agricultural Residue-Based Bio-Pellet Production: Resource Potential, Pelletization Technologies, Fuel Properties and Sustainability Perspectives
Doç.Dr.Emrah KUŞ

11.Chapter **167**
The Role of Plant Flora in the Sustainable Management of Clean Water Resources
Koray KAÇAN

12.Chapter **186**
How To Cope Wıth The Effects Of Global Warmıng On Agrıculture?
Erkan YASLIOGLU, Ercan ŞİMŞEK

13.Chapter **186**
Volume Calculation from Digital Elevation Models: A Practical Application Using QGIS
Mehmet ŞENER

14.Chapter **212**
The Relationship Between Animal Barns And Animal Productivity
Ercan ŞİMŞEK, Erkan YASLIOĞLU

Transforming Water Governance in Rapidly Urbanizing Regions: Strategies for Sustainable Management and Resilient Communities

Benson Rayson RUSIZI[1]
İsmail Bülent GÜRBÜZ [2]

1- Uludağ Üniversitesi Ziraat Fakültesi Tarım Ekonomisi Bölümü. bensonrayson@gmail.com ORCID No: 0009-0004-3342-1511
2- Doç. Dr.; Uludağ Üniversitesi Ziraat Fakültesi Tarım Ekonomisi Bölümü. bulent@uludag.edu.tr ORCID No: 0000-0001-5340-3725

ABSTRACT

Rapid urbanization presents profound challenges to water governance, demanding innovative strategies to ensure sustainable management and community resilience. This study examines the transformative strategies necessary to adapt water governance frameworks in rapidly urbanizing regions, where population growth, land-use changes, and climate variability intensify pressure on water resources. Reforming water governance in rapidly growing urban areas is crucial for achieving sustainable water management and fostering resilient communities. Integrated governance approaches foster collaboration across various levels of government, sectors, and stakeholders, breaking administrative boundaries to align water management with urban planning. Participatory decision-making, inclusive of public, private, and community actors, ensures equitable access, transparency, and accountability in water use and distribution. Considering water as a critical nexus resource linked with energy, food security, and economic growth encourages holistic approaches that optimize resource allocation and minimize conflicts. Addressing informal water provision systems in urban slums by integrating them within formal governance frameworks can preserve essential social and economic benefits while improving service quality and resilience. Ultimately, transforming water governance in rapidly urbanizing regions requires a paradigm shift from rigid, sectoral, and hierarchical models toward collaborative, integrated, and adaptive governance that supports sustainable urban water management goals. This transformation fosters resilient communities that can withstand disruptions, manage risks, and safeguard water resources for both current and future generations, thereby promoting environmental sustainability, social equity, and economic prosperity in a rapidly urbanizing landscape. This study synthesizes recent research and practical examples, emphasizing governance reforms, multi-level coordination, capacity building, and innovative financing as key elements for this change. It provides actionable insights to policymakers, practitioners, and communities engaged in urban water governance reform and sustainable urban development.

Keywords – Sustainability; Water Resources, Water Scarcity; Water Management; Resource Management.

INTRODUCTION

Water forms the basis of sustainable development because it is the key element connecting all global issues, including energy, food, health, peace and security, and the elimination of poverty. (UN, 2018). Water lies at the center of sustainable development and is essential for socio-economic

progress, energy generation, food production, maintaining healthy ecosystems, and human survival. It plays a vital role in climate change adaptation, acting as the key connection between society, agriculture, and the environment (Gurbuz, 2024). Additionally, water is a matter of rights. As the global population continues to grow, it becomes increasingly important to balance the various competing commercial uses of water, ensuring communities have sufficient access to meet their needs (FAO, 2024). Water is the lifeblood of civilization, and nowhere is this more evident than in our cities, which are essential for human health, economic activity, and ecological balance. Yet, in the dawn of the urban century, this vital resource is under severe threat. The global urban population has skyrocketed from 751 million in 1950 to 4.4 billion today, and is expected to swell to 6.7 billion by 2050. The ability to secure, manage, and distribute water has been the cornerstone of urban development. Today, we are living through the most rapid period of urbanization in human history. Currently, 55% of the world's population resided in urban areas in 2018, and this proportion is expected to grow to 68% by 2025, adding another 2.5 billion people to cities. This massive demographic shift is concentrated primarily in Asia and Africa, regions often already facing significant water stress (UN, 2018). In recent years, many people have migrated from rural to urban areas, leading to rapid urbanization. It involves transforming landscapes worldwide, placing unprecedented pressure on water resources and infrastructure. More than half of the global population now resides in urban areas, a figure expected to grow, intensifying the demand for water and stressing the existing water management systems. Ensuring water sustainability within urban environments requires comprehensive strategies that address both supply and demand in the context of environmental, social, and economic challenges (Velenturf et al., 2021). Rapid urbanization refers to the swift growth and expansion of urban areas, driven primarily by rural-to-urban migration, natural population increase in urban areas, and administrative reclassification of rural areas as urban. This rapid urbanization, particularly pronounced in the developing world, concentrates water demand within a small geographical footprint, creating a complex web of challenges that existing water management systems are ill-equipped to handle. It is often linked to industrialization, economic development, and technological advancements that facilitate growth in infrastructure and transportation (Benna, 2019). This convergence of urbanization and water stress creates a perfect storm challenge. Traditional urban water management typically operates on a linear, supply-focused system: water is drawn from remote sources such as rivers and aquifers, treated to meet drinking water standards, delivered for consumption, then wastewater is collected and treated, often only partially, before being released back into the environment. The "take-make-dispose" method is becoming unsustainable, leading to excessive extraction that depletes groundwater and dries up rivers and lakes (Fam et al., 2021). In

many developed cities, old and centralized water systems often lose a significant amount of water due to leaks. Meanwhile, rapidly growing informal settlements in poorer countries often lack basic water and sanitation services altogether (UNDP, 2021). Additionally, climate change brings increased instability, causing more severe droughts and floods that challenge the strength of urban systems (IPCC, 2022 & Sitzenfrei et al., 2020). The traditional linear approach to urban water management, which involves sourcing water extraction, centralized treatment, distribution to consumers, wastewater collection, treatment, and eventual discharge into the environment, represents an outdated model characteristic of the 20th century. This model works well in stable situations but isn't suitable for today's fast-changing, resource-limited, and climate-affected world. While cities drive growth, they also bring challenges. The system consumes a significant amount of energy, wastes a substantial portion of the water due to leaky infrastructure known as non-revenue water, and overlooks the value of wastewater as a resource. As a result, cities become vulnerable, droughts can cause severe water shortages, heavy rains can flood overwhelmed sewers, and polluted runoff harms the natural environments cities rely on. The combined challenges of growing populations, aging infrastructure, and environmental changes have sparked a complete rethink of how cities manage their water. The concept of Sustainable Urban Water Management, emerges as a direct response to these systematic failures. It tries to mimic natural water cycles by encouraging conservation, reuse, and recovering resources. Sustainable Urban Water Management is not a single technology but a systemic approach that considers the entire urban water cycle within its social, economic, and environmental context (Brown et al., 2020). It aims to achieve multiple objectives simultaneously: water security, flood protection, pollution reduction, and enhanced urban livability. The concept of Sustainable Urban Water Management emerges as a direct response to these systemic failures. Sustainable water management is not a single technology or policy but a holistic philosophy and framework. It advocates for a shift from the linear model to a circular, "closed-loop" system that mimics natural water cycles. It integrates the management of water supply, wastewater, and stormwater, viewing them as interconnected components of a single system. Sustainable Water Management is essential to guaranteeing access to safe water and addressing the challenges posed by climate change, urbanization, and population growth (Walle et al., 2023). Rapid urbanization globally is increasing demands on water resources and straining existing water infrastructure and management systems. Urban populations are growing quickly, occupying more land and altering natural water cycles, which threatens water availability, quality, and sustainability. Effective Sustainable Water Management in these contexts is critical to ensure a reliable, equitable, and resilient water supply and sanitation, while protecting ecosystems. Sustainable Urban Water

Management integrates environmental, social, and economic goals, balancing usage and conservation (UN Habitat, 2024). This paper examines the challenges posed by rapid urbanization to water management, discusses sustainable solutions and strategies, and concludes with recommendations for policy and practice. Sustainable water management in urban areas is becoming increasingly important due to rapid urbanization, climate change, and increasing strain on natural resources. As cities grow and populations rise, water demand intensifies, creating challenges in maintaining a sustainable and dependable water supply (Siddique, 2022). The sustainability of water use is increasingly threatened by climate change, population growth, and urbanization. Since water management is closely linked to public health, food security, human rights, ecosystem services, and education, strengthening water management systems has become a vital development objective for many nations.

DISCUSSION

The rapid expansion of urban areas places direct pressure on water resources through increased demand from residential, commercial, and industrial sectors. Urbanization often leads to pollution via untreated wastewater discharge and runoff, exacerbating water quality issues. Furthermore, aging infrastructure leads to water losses, reducing efficiency. Climate change compounds these pressures through altered precipitation patterns and extreme weather events, causing floods and droughts (Smith & Jones 2021). Sustainable urban water management in urban contexts requires a multidisciplinary approach that integrates technological, institutional, and social measures. Water conservation techniques such as efficient fixtures and irrigation, rainwater harvesting, and reuse of treated wastewater are essential to reducing demand (Lee et al., 2022). Infrastructure modernization to reduce leaks and improve treatment capacity enhances resilience. Policies need to promote integrated water resources management that considers water use within the entire urban ecosystem. Governance frameworks, inclusive of stakeholder engagement, ensure equitable access and accountability. Data-driven decision-making, utilizing sensors, geographical information systems, and machine learning, can optimize water distribution and identify vulnerabilities (Yavuz et al., 2025). Community participation and public awareness campaigns are crucial for achieving sustainable behavioral change and promoting water conservation practices. In designing urban

spaces, green infrastructure such as permeable pavements, green roofs, and constructed wetlands supports natural water infiltration and reduces stormwater runoff. Incorporating climate adaptation measures into urban planning helps protect water sources and infrastructure from climate-related risks. Transitioning from traditional to sustainable urban water management requires a comprehensive approach. This discussion focuses on the key elements of sustainable urban water management, examining the specific strategies involved, the challenges they bring, and the opportunities they offer.

Technological and Infrastructural Innovation

The physical infrastructure of water management is undergoing a significant transformation, shifting from traditional, centralized grey systems to hybrid, decentralized, and intelligent networks.

The integration of Information and Communication Technology is transforming water management practices. Real-time consumption data obtained from smart meters facilitates demand management and rapid leak detection. Furthermore, sensors deployed across distribution networks and sewer systems enable continuous monitoring of pressure, flow, and water quality, supporting predictive maintenance and enhancing the capacity for rapid response to contamination incidents. By integrating these technologies into water management, cities can enhance resource efficiency, reduce losses, and improve overall system resilience, aligning with the holistic and adaptive goals of Sustainable Urban Water Management. For instance, the city of Barcelona has implemented a smart water grid that reduced non-revenue water by millions of cubic meters annually (Domènech et al., 2020). The substantial initial investment required for deploying sensors and establishing data management systems poses a significant barrier for many municipalities, particularly in developing regions of the Global South. Additionally, critical challenges include concerns over data security and privacy, as well as the need for a proficient workforce capable of handling and analyzing complex data streams. However, the potential for efficiency improvements is substantial. Reduced non-revenue water, lower energy consumption for pumping, and extended infrastructure lifespans offer a strong return on investment (Lunda et al., 2018). Digital twins, which are virtual models of real water systems, offer a secure environment for experimenting with solutions and enhancing resilience to extreme events. (Barton et al., 2020).

Unlike traditional grey infrastructure (pipes, concrete channels), Green Infrastructure uses natural or semi-natural systems to manage water. This includes green roofs, permeable pavements, rain gardens, and artificial wetlands. Green Infrastructure mitigates urban flooding by absorbing and infiltrating stormwater at its source, reduces the burden on combined sewer

systems, and improves water quality through natural filtration (Fletcher et al., 2015). A primary challenge is that Green Infrastructure is viewed as an unproven solution compared to Grey Infrastructure. In densely populated urban areas, it may also face conflicts over land use, and the long-term maintenance requirements are often underestimated or underfunded. (O'Donnell et al., 2020). Moreover, Green Infrastructure offers numerous benefits that extend beyond water management. It reduces the urban heat island effect, enhances urban biodiversity, captures carbon, and provides recreational and visual enhancements for communities, thereby increasing property values and public well-being. Cities like Philadelphia and Singapore have demonstrated the large-scale viability of Green Infrastructure as a core urban water strategy.

Decentralized and Circular System

A cornerstone of Sustainable Urban Water Management is closing the water loop. Decentralized systems handle water and wastewater treatment near to their source. This includes harvesting rainwater from rooftops, recycling greywater from showers and sinks for toilet flushing or irrigation, and treating blackwater on-site using artificial wetlands (Lens et al., 2020). At a larger scale, Water Reclamation and reuse involve treating wastewater to a high standard for non-potable uses (such as industrial cooling, agricultural irrigation, and urban landscaping) or, increasingly, for indirect or direct potable reuse. Public perception remains a significant barrier to the adoption of potable reuse. Regulatory frameworks for water reuse are often underdeveloped or too strict (Menzies, 2021). Managing a distributed network of small-scale treatment systems presents new operational and regulatory complexities compared to a single, large plant. However, Decentralization improves resilience by minimizing reliance on one central system that may be vulnerable. Water reuse drastically reduces the extraction of freshwater from ecosystems and the volume of wastewater discharged, thereby protecting environmental flows. Moreover, wastewater is increasingly viewed not as waste, but as a resource from which energy (via biogas), nutrients (such as phosphorus and nitrogen), and even bioplastics can be recovered, thereby creating a circular economy model. Economic instruments serve as effective mechanisms to promote sustainable water use and finance essential infrastructure improvements.

Water Pricing and Tariff Designs

The actual cost of water, including extraction, treatment, delivery, wastewater collection, and environmental impacts, is rarely reflected in its price. Implementing cost-reflective pricing, often through increasing block tariffs (where the per-unit price increases with consumption), can provide a clear signal for conservation (Grafton et al., 2020). In other side, water is commonly seen as a social benefit and a fundamental human right, which

makes raising prices a politically delicate issue. It is essential to safeguard low-income families by implementing carefully designed subsidies to maintain affordability and fairness. (Nauges & Whittington, 2017). But well-designed tariff systems provide utilities with consistent revenue, allowing for investment in maintenance, upgrades, and service expansion. Effective public communication campaigns are crucial to gaining support by highlighting the benefits of dependable, high-quality water services.

Innovative Financing and Public-Private Partnerships

The investment needed for Sustainable Urban Water Management is substantial and often beyond what municipal budgets can cover. Green bonds, which finance environmentally friendly projects, are becoming an increasingly important source of funding (CBI, 2021). Payments for Ecosystem Services channel money from water consumers to upstream landowners to preserve forests and wetlands that safeguard water quality (Salzman et al., 2018). Quantifying the multiple benefits of Sustainable Urban Water Management projects, such as the economic value of flood risk reduction or improved public health) can be difficult, making it hard to compete for funding against traditional projects with narrower cost-benefit analyses. (Liu et al., 2020). An increasing amount of impact investment capital is targeting projects that deliver social and environmental benefits. Showing the long-term economic sustainability and risk reduction advantages of Sustainable Urban Water Management can help draw this funding. Blended finance, which utilizes public funds to mitigate risk for private investors, is a promising approach, particularly for the Global South. (World Bank, 2019).

Integrated Water Resources Management and Nexus Frameworks

Urban water systems cannot be managed in isolation. The Integrated Water Resources Management approach promotes the coordinated development and management of water, land, and related resources. This is extended by the Water-Energy-Food Nexus perspective, which recognizes the deep interlinkages between these sectors. For example, pumping and treating water consumes significant energy (energy for water), while thermoelectric power generation is a major water user (water for energy). Urban agriculture links water use and food security. Institutional fragmentation poses a significant challenge. Water utilities, energy providers, urban planning departments, and agricultural agencies often operate with separate mandates, budgets, and data systems, hindering coordinated action. (Pahl-Wostl, 2015). Furthermore, implementing a nexus approach can reveal opportunities and compromises, resulting in more efficient and sustainable resource management. (Al-Saidi & Elagib, 2017). For example, employing reclaimed water for cooling power plants can preserve freshwater for alternative purposes. Collaborative governance structures, like

metropolitan water boards that span multiple municipalities, can facilitate water management at the basin level, balancing urban and rural needs (OECD, 2015). The unpredictable nature of climate change calls for moving away from fixed, long-term towards adaptive management. This approach treats strategies as (learning-by-doing) trials, tracking results and modifying policies and actions as needed. It also demands flexible regulations that support innovation, like performance-based water standards. (Hering et al., 2016). Resistance within bureaucracies and cautious political environments can hinder innovation. Extended infrastructure planning timelines frequently conflict with the shorter durations of political election cycles. Nevertheless, Adaptive Management enhances institutions' ability to learn and become more resilient (Cosens & Gunderson, 2018). Cities can act as a living laboratory for testing innovative water management solutions. (McCormick & Hartmann, 2017). Creating networks of cities, such as C40 Cities, facilitates the exchange of best practices and collective problem-solving. The effectiveness of sustainable urban water management depends on individuals, their willingness to adopt it, participation, and daily habits. Top-down approaches to water project implementation frequently fall short. Meaningful public involvement in planning and designing water systems helps build trust, encourages ownership, and results in solutions that are better suited to local contexts and socially resilient (Hoolohan & Browne, 2020). Collaborative design efforts that involve residents, community organizations, and local businesses are particularly effective in developing green infrastructure in public areas. Public involvement often requires a significant amount of time and resources. It can also be influenced by special interest groups or the loudest voices, which may exclude disadvantaged and vulnerable populations. (Sultana, 2020). Inclusive processes can reveal local knowledge and preferences, resulting in greater acceptance and sustained care of water infrastructure. Digital platforms can broaden participation and gather feedback at large scale. A well-informed public is essential for fostering a water-saving culture. Educational programs in schools and media campaigns can increase understanding of water's importance and the need to save it. At the same time, fairness must remain a key focus. Rapid urban growth often worsens inequalities, as residents in informal settlements pay high prices for purchased water while affluent areas receive subsidized piped water (Graham et al., 2019). Breaking through indifference and established behaviors is challenging. Achieving an equitable distribution of the costs and advantages of Sustainable Urban Water Management represents a significant social justice issue. Presenting water conservation as a collective responsibility can be to be more impactful than focusing solely on individual efforts. (Russell & Knoeri, 2020). Designing programs that assist vulnerable groups, such as offering subsidies for water-saving devices or guaranteeing

legal water access to informal settlements, is both a moral obligation and vital for maintaining urban stability and public health.

Water Scarcity and Climate Change: Impacts on Animal Husbandry

The interconnections between water management, animal husbandry, and climate change are becoming increasingly evident (Gurbuz & Ozkan, 2019; Gurbuz & Ozkan 2021). Climate change exacerbates the problems associated with water scarcity by altering precipitation patterns, increasing the frequency of droughts, and reducing the availability of freshwater resources. For example, in many parts of the world, higher temperatures and irregular rainfall patterns have led to reduced crop yields, which in turn affect the availability and cost of animal feed. The impact of climate change on animal husbandry extends beyond the availability of water. It also affects animal health and productivity. Livestock are particularly vulnerable to heat stress, which can reduce milk production, weight gain, and reproductive performance. In regions where water is already scarce, the increased pressure on water resources can lead to conflicts over access and allocation, further complicating the future of animal husbandry. To address these challenges, technological innovation plays a critical role in improving the efficiency of water use in animal husbandry. Precision agriculture technologies, such as satellite monitoring, automated irrigation systems, and data analytics, have the potential to optimize water usage in both crop and livestock management. For example, sensors can monitor soil moisture levels and provide real-time data on water requirements, helping farmers make more informed decisions about irrigation and feed production. In animal husbandry, specifically, water-efficient systems, such as water recirculation systems in dairy farms, are increasingly being adopted to reduce water waste. Advances in genetic breeding also hold promise for developing more water-efficient livestock breeds that require less water to produce the same amount of meat or milk. Furthermore, researchers are exploring alternative feed ingredients, such as algae and insects, which have lower water footprints than traditional feed crops.

Policy and Regulatory Frameworks for Sustainable Water Management

In addition to technological advancements, effective policy and regulatory frameworks are essential for ensuring the sustainable management of water in animal husbandry. Governments must implement policies that encourage water conservation practices, such as providing incentives for water-efficient technologies, imposing water-use regulations, and promoting sustainable farming practices. One potential avenue for policy intervention is the establishment of water pricing mechanisms that reflect the true cost of water. This would incentivize farmers and livestock producers to adopt more sustainable water management practices, as well as discourage wasteful consumption. Additionally, policymakers must address the broader issue of

water rights and allocation, especially in water-scarce regions. Ensuring equitable access to water resources for all users human, agricultural, and industrial will be essential for maintaining social and environmental stability. International cooperation is also crucial, as water scarcity is a global issue that transcends national borders. Transboundary water management agreements, such as those established under the United Nations, provide a framework for countries to collaboratively manage shared water resources and prevent conflicts over water access. The future of animal husbandry in the context of water management will likely involve a combination of technological innovation, policy reform, and shifts in consumer behavior. While the traditional model of intensive animal farming, which relies heavily on water-intensive feed crops and large-scale operations, is unlikely to be sustainable in the long term, alternative practices may emerge to reduce the environmental impact of livestock production.

One promising avenue is the development of plant-based and lab-grown meat alternatives. These innovations, which do not require the rearing of animals, have the potential to significantly reduce the water footprint of food production. Plant-based diets, which require less water to produce compared to animal-based foods, are also gaining popularity as consumers become more aware of the environmental consequences of their food choices (Gurbuz & Kadağan 2022). Moreover, regenerative agriculture practices, which prioritize soil health and water conservation, could offer a more sustainable approach to livestock farming. By incorporating rotational grazing, agroforestry, and other regenerative practices, farmers can restore water cycles, enhance soil moisture retention, and reduce their overall water usage. Despite these possibilities, the shift toward more sustainable models of animal husbandry is not without challenges. Changing consumer preferences, cultural norms, and economic interests will all play a role in determining the pace of transition. Additionally, the upfront costs of adopting new technologies and practices may be a barrier for small-scale farmers in developing regions, further complicating the global transition to sustainable water management in animal husbandry. Water management in animal husbandry is a critical issue that must be addressed to ensure the long-term sustainability of both food production and water resources. As climate change, population growth, and resource scarcity place increasing pressure on global water supplies, the need for more efficient and equitable water management practices in agriculture becomes more urgent. Technological innovations, such as precision agriculture and water-efficient livestock systems, offer promising solutions, but they must be supported by strong policy frameworks and international cooperation. Ultimately, the future of animal husbandry will depend on a combination of technological advancements, regulatory reforms, and shifts in consumer behavior toward more sustainable food production systems. While the challenges are

significant, the potential for creating a more water-efficient and environmentally sustainable future for animal husbandry remains within reach, provided that concerted efforts are made to address these complex issues.

RESULTS

Sustainable Water Management is essential amid rapid rural-to-urban transitions and mounting challenges like climate change. Urbanization increases water demand, which often exceeds supply, causing shortages and intensifying competition among urban, agricultural, and industrial uses. This threatens water availability, quality, and ecosystem health, with pollution from wastewater, industrial effluents, and altered land use further degrading resources. Despite growing awareness, key research gaps remain in developing integrated, adaptive management approaches that fully address socio-economic, ecological, and governance complexities in these rapidly changing rural-urban areas. To overcome these challenges, policy frameworks must move beyond incremental reforms toward transformative strategies emphasizing equitable water allocation, sustainable infrastructure, and resilience-based planning. Future research should prioritize interdisciplinary models incorporating community engagement, cross-sector collaboration, and innovative ecological designs. Aligning urban planning, climate adaptation, and ecosystem preservation through adaptive governance will support progress toward Sustainable Development Goals 6 (Clean Water and Sanitation) and 11 (Sustainable Cities and Communities). By treating water as a shared, cyclical resource rather than a mere commodity, sustainable pathways can be forged to safeguard water security, social equity, and environmental integrity in the face of ongoing rural-urbanization. Future research should explore gaps in integrated governance models, real-time data monitoring, community engagement, infrastructure resilience, pollution control, and land-use planning, while policy frameworks must prioritize Integrated Water Resource Management (IWRM), water reuse, decentralized governance, green infrastructure, pollution accountability, and climate-adaptive planning. Transformative and inclusive approaches are urgently needed to secure water availability, social equity, and environmental sustainability for current and future populations.

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Water Security Under Pressure: Sustainable Management Strategies for Rapidly Urbanizing Mediterranean Cities

Mohamed SIBIE[1]
İsmail Bülent GÜRBÜZ [2]

1- Uludağ Üniversitesi Ziraat Fakültesi Tarım Ekonomisi Bölümü. sibiem6@gmail.com ORCID No: 0009-0002-1127-8713
2- Doç. Dr.; Uludağ Üniversitesi Ziraat Fakültesi Tarım Ekonomisi Bölümü. bulent@uludag.edu.tr ORCID No: 0000-0001-5340-3725

ABSTRACT

Rapidly expanding Mediterranean cities confront escalating freshwater deficits driven by converging anthropogenic and climatic pressures. This paper investigates sustainable water resource governance in urban environments experiencing accelerated demographic and industrial growth, with particular examination of northwestern Turkish municipalities. Analysis synthesizes contemporary peer-reviewed literature spanning hydrology, institutional economics, environmental management, and technological innovation. Findings reveal that conventional supply-augmentation infrastructure strategies prove inadequate for addressing structural rather than conjunctural scarcity conditions. Mediterranean urban regions face temperature increases of two to four degrees Celsius alongside precipitation declines of ten to twenty percent by century's end, substantially reducing reservoir yields while urban expansion converts permeable surfaces to impervious infrastructure, diminishing aquifer recharge capacity. Institutional fragmentation among municipal, regional, and national water authorities generates coordination failures and duplicative investments. Economic instruments including progressive tariff structures, tradable allocation permits, and payments for ecosystem services offer efficiency gains while protecting vulnerable populations from prohibitive costs. Technological solutions encompassing wastewater reclamation, distributed stormwater capture, intelligent metering systems, and nature-based watershed restoration expand available supplies while enhancing system resilience. Effective responses require transitioning from reactive infrastructure development toward integrated adaptive management combining institutional reform, economic incentives, technological deployment, and environmental stewardship. Policymakers confront substantial political, administrative, and cultural barriers necessitating sustained commitment over decadal timeframes. Future research priorities include detailed hydrological modeling under climate scenarios, empirical evaluation of policy instrument effectiveness, social acceptance studies, and water-energy-food nexus analysis. Successfully navigating urban water insecurity demands comprehensive approaches balancing competing sectoral demands while preserving ecological integrity for current and future generations.

Keywords – Water Scarcity; Urban Water Management; Integrated Water Resources Management; Institutional Governance; Sustainable Development.

INTRODUCTION

Water is one of the most critical resources for sustaining life and ensuring socio-economic development (Gurbuz, 2024). Yet, across the world, freshwater scarcity is increasing due to the combined pressures of rapid urbanization, population growth, industrialization, and climate change (Grafton et al., 2018). In recent decades, many regions especially those with Mediterranean climates have faced heightened water stress due to declining precipitation and overexploitation of water resources (Cramer et al., 2018). Türkiye represents a particularly compelling example where urban growth and agricultural dependence create complex water-management challenges (Er &Gurbuz 2022).

Bursa, located in northwestern Türkiye, serves as both an industrial powerhouse and an agricultural hub. Rapid population growth and industrialization have led to increasing water demand across domestic, agricultural, and industrial sectors(Ozkan et al., 2020) . The city depends mainly on the Doğancı and Nilüfer Dams, yet these reservoirs have experienced drastic depletion. Recent observations show the Doğancı Dam fell below seven percent of capacity, while the Nilüfer Dam nearly dried completely. Meanwhile, groundwater wells that once reached ten meters depth must now be drilled to depths exceeding 250 meters, indicating severe aquifer depletion (Yılmaz et al., 2017). The water scarcity observed in Bursa results from interconnected climatic, environmental, and anthropogenic pressures. Reduced rainfall combined with higher evaporation rates stemming from climate change diminish reservoir inflows substantially (Lionello & Scarascia, 2018). Urban expansion reduces infiltration capacity and increases surface runoff, thereby weakening groundwater recharge mechanisms (Fletcher et al., 2015). Agriculture, responsible for roughly 74 percent of Türkiye's total water consumption, competes intensely with domestic and industrial demand (Topcu & Kavvas, 2016). When combined with fragmented governance structures, these forces endanger long-term water security across the region (Kibaroğlu & Başkan, 2017). This paper examines sustainable water management challenges in rapidly urbanizing Mediterranean contexts, identifying causes of water stress, institutional and policy obstacles, and viable economic, environmental, and technological responses. The analysis synthesizes recent research to develop comprehensive recommendations for integrated water-resource management and climate-adaptation strategies applicable to similar urban regions facing water scarcity.

RESULTS AND DISCUSSION

Urbanization, Climate Change, and Water Stress

Urban population growth and industrial expansion exert immense pressure on existing water infrastructure. The Marmara region has experienced declining rainfall patterns and higher temperature averages for two decades (Ozturk et al., 2015). Climate modeling indicates temperature increases between two and four degrees Celsius alongside precipitation reductions of ten to twenty percent by the year 2100 (Şen, 2015). These projected conditions will substantially reduce reservoir inflows and intensify drought frequency and severity (Marcos-Garcia et al., 2017). Urban expansion further converts permeable land surfaces to impervious asphalt and concrete, dramatically reducing aquifer recharge capacity (Fletcher et al., 2015; Gürbüz & Özkan, 2021; Gül et al., 2024).

Industrial sectors including textiles, automotive manufacturing, and food processing depend heavily on water resources while simultaneously discharging effluents that degrade river water quality (Alp & Çığgın, 2016). Without effective wastewater treatment infrastructure and enforcement, water quality deteriorates progressively, exacerbating overall scarcity conditions (Coskun & Akbaş, 2024). Urban heat island effects compound these challenges by increasing evapotranspiration rates within city boundaries compared to surrounding rural areas (Grimmond et al., 2017).

Research demonstrates that Mediterranean urban areas face structural rather than merely seasonal water scarcity, meaning that temporary interventions prove insufficient for addressing fundamental supply-demand imbalances (Salvati et al., 2016). The convergence of climate variability, land-use change, and increasing consumption creates persistent vulnerability requiring comprehensive management responses (McDonald et al., 2016).

Institutional and Policy Challenges

Water governance typically involves multiple agencies including municipal water administrations, state hydraulic works departments, and agricultural ministries, yet weak coordination creates duplication and operational inefficiency (Burak, 2015). Historically, water policy emphasized supply-side infrastructure projects including dams and pipeline networks rather than demand management strategies (Tortajada, 2016). Non-revenue water losses stemming from leakage and illegal connections can reach forty-five percent in some municipal systems (Karadirek et al., 2016).

Integrated Water Resources Management provides a holistic framework for balancing competing water uses across sectors (Global Water Partnership, 2015). Successful implementation requires clear legal frameworks, systematic data sharing among agencies, and meaningful stakeholder participation in decision-making processes (Medema et al., 2016; Pahl-Wostl et al., 2018). Stronger community involvement could

enhance accountability while promoting water conservation behaviors. However, top-down institutional cultures often limit genuine public participation in water planning (Agyenim & Gupta, 2018).

Legal frameworks governing water rights and allocation frequently remain fragmented, with responsibilities distributed across multiple statutes enacted during different historical periods (Kibaroğlu, 2015). This legal complexity hinders effective coordination and creates uncertainty for water users and resource managers. International experience suggests that comprehensive water codes with clear authority hierarchies and dispute resolution mechanisms prove essential for effective governance (Salman, 2015).

Economic Impacts and Opportunities

Water scarcity raises both agricultural and industrial production costs substantially. Farmers face increasingly expensive deep-well irrigation as shallow aquifers become depleted (Topcu & Kavvas, 2016), while industries risk production losses and potential facility relocations (Coskun & Akbaş, 2024). Economic instruments including tiered tariffs, volumetric pricing systems, and water trading markets can encourage more efficient resource use (Grafton et al., 2018; Montginoul & Vestier, 2018). Progressive tariff structures conserve water while protecting low-income users from prohibitive costs (Massarutto, 2015).

Payment-for-Ecosystem-Services schemes reward upstream landowners for maintaining forest cover and implementing soil conservation practices that benefit downstream water users (Abell et al., 2017; Salzman et al., 2018). Modern irrigation technologies including drip systems and soil moisture sensors can reduce agricultural water consumption by approximately forty percent compared to traditional flood irrigation (Jägermeyr et al., 2016). However, pricing reforms must account for equity considerations to avoid disproportionately burdening vulnerable populations (Johansson et al., 2016).

Water markets offering tradable allocation permits provide another economic tool for efficient resource distribution, allowing voluntary transfers between users while maintaining environmental protections (Grafton et al., 2019). Establishing functional water markets requires secure property rights, clear regulatory frameworks, and mechanisms preventing market concentration that could disadvantage smaller users (Wheeler et al., 2020). Economic valuation studies consistently demonstrate that urban water uses generate substantially higher economic returns compared to agricultural applications, suggesting potential welfare gains from carefully managed reallocation (Garrick et al., 2019).

Environmental and Technological Solutions

Sedimentation and watershed degradation progressively reduce reservoir storage capacity; national losses approach five hundred million cubic meters annually (Demirci & Cürebal, 2016). Reforestation programs, erosion control measures, and wetland restoration improve catchment water retention capacity (Gül et al., 2024). Watershed management programs combining structural measures like terracing with biological interventions including reforestation can reduce erosion rates by sixty to eighty percent (Garg et al., 2016).

Technological innovations including wastewater reuse systems, rainwater harvesting infrastructure, and smart-meter monitoring networks expand available supply while improving efficiency (Angelakis et al., 2018; Garrido-Baserba et al., 2024). Urban rainwater harvesting mitigates flood risks while supplementing municipal supply, potentially providing ten to fifty percent of household water needs depending on rainfall patterns and collection infrastructure (Flynn & Davidson, 2016). Advanced treatment technologies including membrane bioreactors and reverse osmosis produce water quality suitable for virtually any non-potable application (Tal, 2018).

Digital management tools including artificial intelligence-based leak detection systems and geographic information system monitoring enable adaptive, data-driven management approaches (Abu-Mahfouz et al., 2019; Mohapatra et al., 2021). Real-time monitoring networks tracking precipitation, streamflow, groundwater levels, and water quality provide early warning of emerging problems while supporting evidence-based policy decisions (Hrachowitz et al., 2016). Nature-based solutions including green infrastructure such as bioswales, rain gardens, and permeable pavements reduce urban runoff volumes by fifty to ninety percent while improving water quality and providing additional benefits including urban cooling and biodiversity habitat (Browder et al., 2019).

Forest and wetland conservation in headwater areas provides critical ecosystem services including water flow regulation, flood attenuation, and natural water purification (Bradshaw et al., 2016). Economic valuations consistently demonstrate that watershed protection benefits substantially exceed costs, particularly when accounting for avoided water treatment expenses and flood damage (Bennett et al., 2016). However, implementing watershed-scale conservation requires overcoming collective action challenges and ensuring upstream communities receive equitable compensation for foregone development opportunities (Goldman-Benner et al., 2016).

Integrated Management Approaches

Long-term water sustainability depends on holistic strategies combining governance reform, economic incentives, technological innovation, and environmental protection. Institutional coordination through

basin-level water councils with representation from diverse stakeholder groups facilitates dialogue and consensus-building (Warner et al., 2018). Clear delineation of roles and responsibilities, supported by formal agreements between agencies, reduces institutional friction and improves crisis response capabilities (Agyenim & Gupta, 2018).

Demand management through water-saving technologies, universal metering, and public awareness campaigns can reduce consumption by twenty to forty percent (Boyle et al., 2016). Public education programs highlighting connections between water and energy use while providing practical conservation guidance demonstrate significant impact on residential consumption patterns (Willis et al., 2017). Behavioral interventions including social norm messaging and personalized consumption feedback amplify effects of pricing and technology-based approaches (Ferraro & Price, 2016).

Supply diversification through wastewater reuse, stormwater harvesting, and managed aquifer recharge enhances water security and system resilience (Garrido-Baserba et al., 2024). Portfolio approaches developing multiple supply sources reduce vulnerability to individual source failures while providing operational flexibility (Paton et al., 2016). Managed aquifer recharge schemes storing treated wastewater or stormwater underground during wet periods for extraction during droughts represent increasingly cost-effective adaptation strategies (Dillon et al., 2019).

Watershed conservation through forest restoration and critical recharge zone protection ensures long-term supply sustainability while delivering multiple co-benefits (Garg et al., 2016). Payment for ecosystem services schemes create sustainable financing for watershed protection by linking downstream water users to upstream conservation providers (Goldman-Benner et al., 2016). Land-use planning restricting development in critical recharge areas and riparian corridors protects water resources while maintaining ecological functions (Abell et al., 2017).

Climate adaptation planning incorporating climate projections into infrastructure design and policy development ensures continued effectiveness under changing conditions (Marcos-Garcia et al., 2017). Adaptation measures including increased storage capacity, supply diversification, and demand reduction build resilience to droughts and other climate impacts (Mukheibir, 2016). Flexible adaptive management approaches allowing course corrections as conditions evolve prove essential given deep uncertainties surrounding future climate and socioeconomic trajectories (Pahl-Wostl, 2015).

Legal and regulatory reform updating water laws to clarify rights, streamline permitting processes, and establish clear enforcement mechanisms supports effective governance (Salman, 2015). Water allocation frameworks balancing consumptive uses with environmental flow requirements protect aquatic ecosystems while ensuring human needs

receive adequate provision (Poff et al., 2016). Groundwater governance regimes preventing overextraction through permitting systems, universal metering, and sustainable yield limits prove essential where groundwater provides significant supply (Foster & Garduño, 2016).

RESULTS

The water crisis facing rapidly urbanizing Mediterranean regions represents one of the most pressing sustainability challenges of the twenty-first century. This analysis demonstrates that effective responses require fundamental shifts from reactive infrastructure development toward proactive integrated management combining institutional reform, economic incentives, technological innovation, and environmental stewardship. The convergence of climate change, urban expansion, and increasing consumption creates structural rather than temporary scarcity, demanding comprehensive long-term solutions rather than short-term fixes.

Policymakers must prioritize several critical actions to achieve water security. First, establishing effective coordination mechanisms among water agencies through basin-level councils with clear mandates and adequate authority can overcome institutional fragmentation that currently hampers coherent water planning. Second, implementing progressive water pricing structures that balance conservation incentives with equity protection ensures efficient use while maintaining affordability for vulnerable populations. Third, investing in diversified supply portfolios including wastewater reuse, rainwater harvesting, and managed aquifer recharge reduces dependence on increasingly unreliable traditional sources. Fourth, protecting and restoring watersheds through payment for ecosystem services programs and land-use regulations preserves natural water infrastructure at costs substantially below engineered alternatives.

However, policymakers face significant constraints in implementing these recommendations. Political opposition to water pricing reforms from agricultural lobbies and industrial interests often delays or dilutes necessary policy changes. Limited administrative capacity at municipal levels hinders effective implementation even when national policies support integrated management. Fragmented legal frameworks create uncertainty about authority and responsibilities, slowing coordinated action. Public resistance to water reuse despite technological advances capable of producing high-

quality treated water presents another barrier requiring sustained educational efforts to overcome cultural attitudes.

Several critical research gaps emerged during this analysis that future studies should address. This paper could not examine specific hydrological modeling of climate change impacts on local water sources due to data limitations and the scope of desk research. Future work incorporating detailed watershed modeling using high-resolution climate scenarios would provide more precise estimates of future water availability under different emissions pathways. Additionally, this analysis lacked primary data on actual water consumption patterns across different user sectors, relying instead on national averages that may not reflect local conditions. Detailed consumption surveys combined with smart meter data could reveal opportunities for targeted efficiency improvements.

Economic analysis of different policy instruments also requires deeper investigation through original research. While this paper synthesized existing literature on pricing mechanisms and water markets, empirical studies evaluating actual implementation outcomes in similar Mediterranean contexts would strengthen evidence for policy recommendations. Similarly, social acceptance studies examining public attitudes toward water reuse and conservation measures would help design more effective behavior change programs. Future research should employ mixed methods combining quantitative modeling with qualitative stakeholder analysis to develop context-appropriate solutions.

Institutional analysis would benefit from detailed case studies examining coordination mechanisms that successfully overcame bureaucratic fragmentation in comparable settings. This paper identified institutional challenges but could not analyze specific reform processes and their outcomes due to limited documentation of Turkish water governance reforms. Comparative institutional analysis examining successful and unsuccessful reform attempts would generate practical insights for policymakers navigating political and administrative obstacles.

The environmental dimension requires additional research on nature-based solutions effectiveness under varying climatic and hydrological conditions. While watershed restoration benefits are well-documented generally, site-specific studies quantifying outcomes in Mediterranean landscapes would improve implementation guidance. Long-term monitoring of green infrastructure performance in reducing urban runoff and improving water quality would help refine design standards and maintenance protocols.

Future researchers should also investigate water-energy-food nexus interactions more thoroughly. This paper focused primarily on water security but these sectors remain deeply interconnected through irrigation energy requirements, hydropower generation, and food production water demands. Integrated nexus analysis could identify synergies and trade-offs not

apparent in sectoral approaches, potentially revealing more efficient resource allocation strategies.

Climate adaptation strategies require ongoing research as climate models improve and actual climate impacts become clearer. This analysis synthesized current projections but uncertainties remain substantial regarding precipitation patterns, extreme event frequencies, and local impacts. Developing adaptive management frameworks that can adjust to new information as it emerges represents an important research priority. Scenario planning exercises engaging stakeholders in exploring alternative futures could build adaptive capacity while identifying robust strategies performing well across different plausible futures.

The transformation toward sustainable water management requires sustained commitment over decades rather than years. Political will, adequate financing, institutional capacity, and public engagement all prove essential for success. However, the costs of inaction far exceed the investments required for proactive adaptation. Water scarcity threatens economic development, food security, public health, and social stability across rapidly urbanizing regions. By implementing integrated management approaches combining the strategies outlined in this paper, cities can enhance water security while serving as models for other regions facing similar challenges. The window for action remains open but narrowing as climate change accelerates and urban populations grow. Decisive action now will determine whether future generations inherit resilient water systems or face deepening crises.

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Energy Budget Calculation Methods in Crop Production (A literature review on energy balance)

Serap AKDEMİR[1]

1- Prof.Dr. Tekirdag Namik Kemal University, Technical Sciences Vocational School Department of Machinery and Metal Technologies, Machinery Programme. sakdemir@gmail.com ORCID No: https://orcid.org/0000-0001-5057-174X

ABSTRACT

Objective of this study is to give information about energy balance calculations methods for crop production. Related literatures were summarized. In addition, formulas for the calculation of energy budget were given in the study. Total energy input and energy output can be calculated methods were explained. Energy ratio, specific energy and energy productivity were explained. In addition, possible future works were evaluated. Energy budget calculations mostly based on literature and interviews with the farmers. Most of the literature were also based on the interviews with the farmers. There is a few research to use measurement to determine energy balance in agriculture. Technology is changing but most of the publications on energy balance have been using old data because they don't carry our research to determine exact values of energy equivalents of the agricultural production inputs. In addition, it is not easy to collect reliable data from farmer because farmers have responsibility is to continuing crop production to get income for their life. Traceability systems can be used to determine amount of the agricultural inputs which are used for crop production to make good energy balance evaluations. Future works may be focused on determine real energy cost of agricultural production inputs for new technologies.

Keywords – Energy, Crop Production, Production Input, Efficiency, Methods.

INTRODUCTION

Energy conversion process is important for agriculture. Various parts of the world are at different stages of agricultural development; therefore, energy-use practices vary widely (Fluck, 1992). In agricultural production, fossil energy are used to increase yields of crop, livestock, and forestry and also to replace labour. The major inputs that increase crop yields include energy used in fertilizers, pesticides, and irrigation. The energy used to reduce human labour input in crop production has little or no effect on crop yield except to facilitate the timing of planting and harvesting. (Piementel, 1992).

Energy balance of crop and livestock production, net energy ratio (NER), and water use efficiency (WUE) of crops were investigated for a selected farm in Sri Lanka using the life cycle assessment (LCA). The data were obtained from farm records, personal contacts, and previously published literature. The energy related WUE of crop production was 31.35 MJ m^{-3}. Energy balance of crop production was 316.87 $GJha^{-1}Year^{-1}$ and livestock

production was 758.73 GJYear^{-1}. The total energy balance of the farm was 736.2 GJYear^{-1} (Dhanapal et al., 2023).

In a research article, evaluation of energy balance and energy indices under watered farming wheat in Iran (Guilan province) were investigated. Data were collected from 72 farms by using questionnaire method. Energy efficiency for seed and straw was calculated to be 2.47 and 2.48, respectively. Energy balance efficiency for seed and straw was calculated 1.50 and 1.29, respectively (Azarpour, 2012).

The aim of the work was to assess energy inputs and outputs of various crop in 2011–2012. Silage maize and winter wheat were grown on lowland, whilst two semi-natural grasslands and grasslands infested by tufted hair-grass were located in mountainous regions of Slovakia. In these crops and grasslands, the dry matter yield was measured and subsequently the supplementary energy, energy gain and unifying energy value tonne of oil equivalent (TOE) were calculated (Hrčková Et Al., 2016).

Greenhouse gas emissions (GHG) were calculated for winter wheat for ethanol production, winter rapeseed for production of biodiesel and biogas production. The calculations were made to comply with the requirements outlined in the EU Directive 2009/28/EC from the European Parliament (2009). Life Cycle Assessment methodology and interpretations of the EU Directive 2009/28/EC were generally used according to the report of Ahlgren et al. (2009). Sensitivity analyses of the cropping systems showed that the final emission results depended to a large extent on the emission factors assumed for N_2O emission from the soil (Elsgaard, 2010).

Energy requirements for different planting techniques and herbicide applications were evaluated, The drill sowing with 18 cm was found the most efficient method for energy calculations followed by three row bed planting and 20 cm row spacing. This may be attributed to total energy output (grain + straw). Tank mix application of pinoxaden (50 gha^{-1}) with RM of carfentrazone and metsulfuron-methyl was very efficient for energy and recorded higher value of different energy calculations (Devi et al., 2018).

Energy consumption for wheat with different crop geometry and irrigation practices was investigated. The total energy inputs used in various farm operations during wheat crop, the total energy inputs required respectively for conventional practice, for System of Wheat Intensification (SWI) practice and for SWI with drip irrigation was 87,937 MJ ha^{-1}, 69,817 MJ ha^{-1} and 46,679 MJ ha^{-1} (Rao and Gangwar, 2019).

Results indicated that total energy inputs were 47.08 GJ ha^{-1}. 31.19% of the total energy input was generated by chemical fertilizers, 26.05% from diesel oil and machinery. About 73.27% of the total energy inputs used in wheat production was indirect (seeds, fertilizers, manure, chemicals, machinery) and 26.73% was direct (human labour, diesel). The ratio of energy outputs to energy inputs was found to be 1.97. Benefit–cost ratio was calculated as 1.43 (Shahan et al., 2008).

The efficient use of energy inputs in agricultural production processes enhances farm efficiency, improves factor productivity, and ultimately reduces costs and the negative environmental impacts of inputs on natural resources. Given the limited availability of resources, studying the economic aspects of energy balances in the agricultural sector is crucial. This research aims to analyse the economic aspects of energy balance in rainfed wheat production in Saqqez County. Data were collected from 270 farmers in the region, and input and output (wheat) values were converted into energy equivalents. A translog production function was estimated to determine the marginal product and elasticity of production factors. The results revealed that labor, pesticides, and machinery energy significantly impact wheat output energy (Dashti et al. 2025).

A research on rice-wheat systems mainly focuses on in-situ controlled experiments at the point scale, with limited studies addressing carbon footprint (CF) and energy balance (EB) at the regional scale and long-time series. Evolution patterns of the CF and EB of the rice-wheat system in Jiangsu Province from 1980 to 2022 was investigated. The CF of rice and wheat increased by 4172.27 kg CO2 eq ha^{-1} and 2729.18 kg CO2 eq ha^{1}, respectively, with the greenhouse gas emissions intensity (GHGI) showing a fluctuating upward trend (Wu et al., 2025).

Energy balance and Greenhouse Gas Emissions (GHG) of cotton cultivation in Diyarbakır, Turkiye was determined. The energy balance and GHG of cotton cultivation were calculated by using survey results with 73 farms. The energy input and output in cotton cultivation were 54617.62 MJ ha^{-1} and 65984.42 MJ ha^{-1}, respectively. (Baran et al., 2021).

Agricultural production has increased, and new areas have been opened to agricultural production because of mechanization practices in agriculture. On the other hand, energy consumption has increased for modern technology applications in agriculture.

The use of agricultural tools/machinery and pesticides requires the consumption of fossil fuels, which are the most important energy sources. Additional energy use significantly reduces the energy efficiency of agricultural ecosystems compared to natural systems. Energy is consumed intensively especially in pesticide production. Since agricultural systems also include natural processes, energy use must be analysed in order to evaluate energy efficiency in the management of natural resources. Within the scope of the study; direct energy use as a result of consumption of energies such as electricity, fuel, oil, coal, petroleum products, natural gas, biomass, etc. in agricultural production and indirect energy use, which consists of the amount of energy consumed for human/animal labour, agricultural tools/machinery, fertilizer, agricultural pesticides, irrigation and seed production, were examined. In order to effectively prevent environmental problems arising from the direct or indirect use of fossil fuels, renewable energy sources should be used in the agricultural sector, as in all sectors. The use of solar energy,

wind energy, geothermal energy and biomass energy, which are the main renewable energy sources that can be used effectively in the agricultural sector, in agricultural production has been examined (Öztürk et al., 2010).

The use of energy in the vineyard of a semi-arid zone of Iran was investigated. Energy use efficiency, energy productivity, specific energy and net energy were calculated. Input energies were labour, machinery, chemicals, farmyard manure (FYM), diesel, electricity and water for irrigation. Results of sensitivity analysis showed that machinery had the greatest impact on grape yield followed by diesel fuel and labour (Khoshroo et al., 2018).

Total amount of inputs and energy equivalent of these inputs were determined for wheat and sunflower production. The data of this study was collected by survey method which was carried out with 169 wheat and sunflower producers in Thrace Region. The total energy inputs in wheat and sunflower production were determined to be 23,231MJ ha^{-1} and 10,139 MJ ha^{-1} and based on the energy output, it was noticed that energy outputs in wheat (including straw) and sunflower production were determined to be 81,720 MJ and 38,250 MJ, respectively. Energy use efficiency, energy productivity, specific energy and net energy in wheat production were calculated as 3.52, 0.19 kg MJ^{-1}, 5.16MJkg^{-1} and 58,489 MJ ha^{-1} respectively in wheat production and 3.77, 0.15 kgMJ^{-1}, 6.63 MJkg^{-1} and 28111MJ ha^{-1} respectively in sunflower production (Unakıtan and Aydın, 2018).

Cost of raisin production was calculated in a research study. Costs of inputs and prices of raisin were obtained from various sources. The total energy input necessity for raisin production was 39,066.91 MJha^{-1}. The research results indicated that the total energy input used for raisin was mainly dependent on non-renewable energy forms (%97). The high ratio of non-renewable energy in the total used energy inputs causes negative effects on the sustainability in agricultural production (Uysal and Saner, 2016).

An energy analysis was realised for sunflower crop production in Trakya Region, Turkey. Data for the common production procedures were collected from farmers with questionnaires. The results showed that sunflower presented positive energy balance for both cases. Net energy was 35,334 MJ ha^{-1} when only the seed was taken into account and 87,308 MJ ha^{-1} for both seed and stalks. Energy efficiency was 3.67 and 7.34 respectively (Akdemir et al., 2017).

Energy usage productivity in grape production for wine was determined. According to the results, the energy rate was calculated 9.72. Net energy was 105855.37 MJha^{-1}. Specific energy and energy productivity were 0.10 MJkg^{-1} and 0.82 kgMJ^{-1}, respectively. Direct energy and its share were calculated to be 3936.05 MJha^{-1} and 32.41%, respectively. Indirect energy and its share of the total energy budget were 8208.58 MJha^{-1} and 67.59%. Agricultural machinery was generally used for soil tillage and chemical fertilizer and pesticide application (Akdemir, 2022).

Energy cost, energy efficiency and net energy were determined for maize. Amount of the inputs and outputs were determined from statistics and surveys with farmers. Energy efficiency and net energy were calculated 20.2 and 745 034 $MJha^{-1}$ for silage consist of 25% grain, respectively. Energy efficiency and net energy were determined for different energy equivalent of silage maize. Energy efficiency was found as 19.4 and net energy 712317.4 $MJha^{-1}$ for 12.95 $MJkg^{-1}$, 425217.4 $MJha^{-1}$ for 8.0 $MJkg^{-1}$, and 280217.4 MJ ha^{-1} for 5.50 $MJkg^{-1}$. Specific energy and energy productivity were determined 0.7 $MJkg^{-1}$ and 1.5 $kgMJ^{-1}$ for silage maize (Akdemir, 2020).

Objective of this study is to give information about energy balance calculations methods for crop production. Related literatures were summarized. In addition, formulas for the calculation of energy budget were given in the study. In addition, possible future works were evaluated.

MATERIAL AND METHODS

Research area

Information about research region is important. The information about research area should be given briefly. Thrace Region is generally our research area and information about Thrace Research was given below as an example. Tekirdağ, Kırklareli and Edirne cities are located in Thrace Region of Türkiye. Total land of the Thrace Region was 1 022 498 ha., area of fruits, beverages and spices was 21 385.9 ha. (Figure 1).

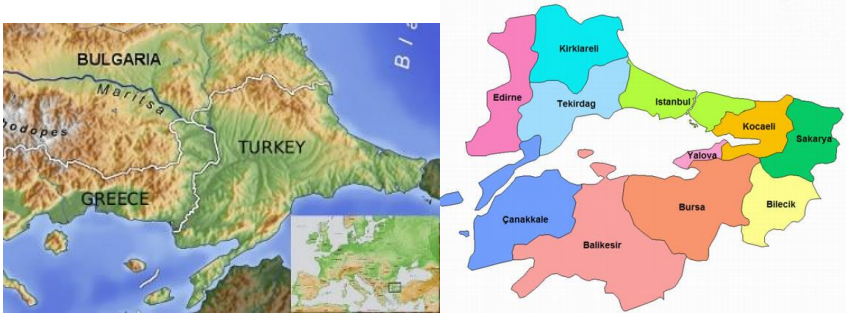


Figure 1: Thrace region (Anonymous, 2025-a; Anonymous, 2025-b)

Data collection for Cultivation practices

Data can be collected from farmers, non-governmental institutions such as farmer associations, governmental institutions such as Ministry of Agriculture and Forestry with surveys. If the survey method will be used in the research, sampling method, total number of the farmers etc. should be given in the article. Data can also be collected from web sites of Turkish Statistical Institute or Research studies.

Cultivation practices should be determined in detail. Each production process will be detailed for time, amount and type of the inputs and outputs, labour, tractor ad machinery, fuels etc. Production stages of the wheat, sunflower, and maize produced widely in Trakya Region were given below in Table 1, Table 2 and Table 3, respectively.

Table 1: Wheat mechanization

Field operations / Machine Type	Working Time	Machine Width (m)	Working Speed (km/h)	Efficiency (%)	Effective Field Capacity (ha/h)	Fuel consumption (l/ha)	Man labour (h/ha)
Plough	August-September	1.4	6	0.80	0.67	30.0	1.190
Disc harrow	September	3.0	10	0.85	2.55	12.0	0.333
Cultivator	September October	4.0	13	0.80	4.16	7.0	0.192
Centrifugal fertiliser spreader	October	16.0	14	0.70	15.68	3.5	0.045
Toothed roller	October	4.0	17	0.80	5.44	4.5	0.147
Sowing machine	October	4.0	12	0.70	2.24	12.0	0.208
Roller	October	5.0	13	0.85	5.53	4.5	0.308
Fertiliser spreader	January-February	16.0	14	0.70	15.68	3.5	0.045
Sprayer	February	16.0	14	0.65	14.56	3.5	0.045
Sprayer	March	16.0	14	0.65	14.56	3.5	0.089
Fertiliser spreader	March-April	16.0	14	0.70	15.68	3.5	0.089
Sprayer	April	16.0	14	0.65	14.56	3.5	0.089
Sprayer	May	16.0	14	0.65	14.56	3.5	0.089
Sprayer	May-June	16.0	14	0.65	14.56	3.5	0.089
Combine	June-July	5.2	4	0.70	1.46	20.0	0.962
TOTAL						118.0	3.920

Source: Akdemir, 2018

Table 2: Sunflower mechanization

Field operations / Machine Type	Working Time	Machine Width (m)	Working Speed (km/h)	Efficiency (%)	Effective Capacity (ha/h)	Fuel Consumption (l/ha)	Man labour requirement (h/ha)
Plough	September-November	1.40	6	0.8	0.67	30.00	1.190
Cultivator	March	3.40	9	0.85	2.60	10.00	0.327
Cultivator	April	3.50	10	0.8	2.80	8.00	0.286
Toothed harrow	April	4.00	15	0.8	4.80	4.00	0.167
Fertiliser spreader	April	16.00	14	0.7	15.68	3.50	0.089
Sprayer	April	16.00	14	0.65	14.56	3.50	0.089
Sowing machine	April-May	4.20	7	0.7	2.06	8.00	0.340
Roller	April-May	5.00	12	0.85	5.10	4.50	0.167
Fertiliser spreader	June	16.00	14	0.7	15.68	3.50	0.089
Hoeing	June	4.20	7	0.8	2.35	9.00	0.340
Sprayer	June	16.00	14	0.65	14.56	3.50	0.089
Combine	September	5.20	7	0.7	2.55	20.00	0.549
TOTAL						107.50	3.723

Source: Akdemir, B., 2018.

Table 3: Maize mechanization

Field operations Machine Type	Working Time (months)	Machine Width (m)	Working Speed (km/h)	Efficiency (%)	Effective Capacity (ha/h)	Fuel Consumption (l/ha)	Man labour requirement (h/ha)
Plough	September-October	1.4	6	0.80	0.672	30.0	1.190
Cultivator	March-April	3.5	10	0.85	2.975	10.0	0.286
Fertiliser Spreader	April-May	16.0	14	0.70	15.680	3.5	0.089
Sowing	April-May	4.2	7	0.70	2.058	8.0	0.340
Sprayer	May	16.0	14	0.65	14.560	3.5	0.089
Fertiliser Spreader	June	16.0	14	0.70	15.680	3.5	0.089
Hoeing	June	4.2	7	0.80	2.352	9.0	0.340
Sprayer	June	16.0	14	0.65	14.560	3.5	0.089
Lister	June-July	4.2	7	0.80	2.352	7.0	0.340
Combine	September-October	5.2	7	0.70	2.450	66.0	0.286
TOTAL						144.0	3.139

Source: Akdemir, B., 2018

Energy Budget Calculations

Depending on the duration of use of an agricultural tractor, fuel consumption can be calculated with the following equation (Öztürk et al., …).

$$V_f = q_s . T_i . P_m \quad (1)$$

Where;

V_f = Total fuel consumption depending on the duration of the tractor's use (g

q_s = Average specific fuel consumption (g/kWh),

T_i = Power of the tractor engine (kW).

The hourly oil consumption of agricultural tractors can be determined by the following equation depending on the PTO power.

$$Q_{oil} = 0.00059 . P_{max} + 0.02169 \quad (2)$$

Where:

Q_{oil} = Tractor oil consumption per hour (L/h)

P_{max} = Maximum tractor PTO power (kW)

Direct fuel energy use per unit area (ha) during agricultural production operations is calculated as follows.

$$YE = AIV . YT . YID . US \quad (3)$$

YE = Fuel energy (MJ ha^{-1})

AIV =Area work efficiency (h ha^{-1})

YT = Fuel consumption per hour (Lh^{-1})

YID = Lower calorific value of fuel (MJ L^{-1})

US = Number of applications

Based on these records the direct and indirect energy consumption was estimated (Pimentel, 1992). Direct energy is consumed ii farm such as fuel, lubricants and human labour. Indirect energy is consumed outside of farm boundaries to produce any input (machinery, chemicals) used in farm. Energy equivalent of agricultural production inputs was given in Table 4.

Table 4. Energy equivalent of agricultural production inputs

Input	Energy equivalent (MJ per unit)	Literature
Human Labour (h^{-1})	2.67	Özcan, 1985, Arın and Akdemir,1987
Tractor (h)	64.8	Singh, 2002
Agricultural machinery (kg)	121.30	Doering, 1980
Diesel + Oil (l)	56.31	Singh, 2002
Nitrogen (kg)	78.10	Helsel, 1992; Gemtos et al, 2013
Phosphorous (kg)	17.00	Helsel, 1992; Gemtos et al, 2013
Potassium (kg)	13.70	Helsel, 1992; Gemtos et al, 2013
Herbicide (kg)	461.00	Gemtos et al, 2013, Heichel, 1980

Energy inputs of the agricultural machineries used for soil tillage, fertilization, spraying, harvesting and transportation is calculated by given formulae (Yaldız et al. 1990).

$$ME = \frac{WxE}{TxEFC} \quad (4)$$

Where;

ME: Machine energy input (MJ ha^{-1})
W: Weight of the equipment (kg)
E: Manufacturing energy of the agricultural machine (MJ kg^{-1})
T: Economic life (h)
EFC: Effective Field Capacity (ha h^{-1}).

Total energy input and energy output can be calculated for crops growing. Energy ratio, specific energy and energy productivity can also be calculated by using following equations (Arin et al., 1988).

$$\text{Energy Rate} = \text{Energy Output} / \text{Energy Input} \quad (5)$$

$$\text{Specific Energy} = \text{Total Energy Input} / \text{Total crop harvested} \quad (6)$$

$$\text{Energy Productivity} = \text{Total harvested product} / \text{Total Energy Input} \quad (6)$$

$$\text{Net Energy Productivity} = \text{Energy output} - \text{Energy input} \quad (7)$$

Energy input is evaluated for renewable/non-renewable and direct/indirect energy types. Fuel is evaluated as direct energy, and others (fertilizers, pesticides and machine power) as indirect energy, human labour as renewable, and other (fuel, fertilizers, pesticides and machine power) as non-renewable energy (Şeflek et al. 2018).

RESULTS AND DISCUSSION

Objective of this study is to give information about energy balance calculations methods for crop production. Related literatures were summarized. In addition, formulas for the calculation of energy budget were given in the study. Total energy input and energy output can be calculated methods were explained. Energy ratio, specific energy and energy productivity were explained.

Energy budget calculations mostly based on literature and interviews with the farmers. Most of the literature were also based on the interviews with the farmers. There is a few research to use measurement to determine energy balance in agriculture. Technology is changing but most of the publications on energy balance have been using old data because they don't carry our research to determine exact values of energy equivalents of the agricultural production inputs. In addition, it is not easy to collect reliable data from farmer because farmers have responsibility is to continuing crop production to get income for their life. Traceability systems can be used to determine amount of the agricultural inputs which are used for crop production to make good energy balance evaluations. Future works may be focused on determine real energy cost of agricultural production inputs for new technologies.

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An Assessment of The Turkish Food Industry from a Sustainability Perspective

Şule TURHAN[1]

[1] Prof. Dr. Bursa Uludağ University, Faculty of Agriculture, Department of Agricultural Economics sbudak@uludag.edu.tr ORCID No:0000-0001-9155-8170

ABSTRACT

The Turkish food industry, with its strong agricultural infrastructure, extensive domestic market opportunities, and strategic export capacity, is one of the fundamental sectors of the country's economy. In recent years, in line with increasing environmental awareness and global sustainability goals, the principles of environmental, social, and economic sustainability in the sector's production and consumption processes have become increasingly important. Sustainability in the food industry encompasses multidimensional strategies such as the efficient use of natural resources, waste management, reducing the carbon footprint, supporting local producers, and increasing access to healthy food. In this context, the integration of innovative technologies, circular economy practices, the promotion of organic and local products, and sustainable packaging solutions are accelerating the sector's transformation. However, structural challenges such as regulatory compliance, financial access, consumer awareness, and supply chain coordination limit the widespread adoption of sustainability practices. Sustainability-focused production models, comprehensive policy tools, and strengthening collaboration among stakeholders are critical for the Turkish food industry to maintain its long-term competitiveness.

Keywords: Food, Turkey, Sustainability.

INTRODUCTION

The Turkish food industry accounts for approximately 15–20% of the manufacturing industry and is one of the most strategic sectors of the country's economy in terms of employment and added value (Anonymous 2023). This sector, which serves as a bridge between agricultural production and industry, supports rural development and accounts for a significant portion of export revenues. However, today, the success of the food industry is measured not only by production volume but also by sustainability criteria.

A sustainability perspective requires a holistic approach to the environmental, economic, and social dimensions of the food industry (Du Pisani 2006, Vallance et al. 2011). In line with the United Nations Sustainable Development Goals (SDGs), resource efficiency in food production, carbon footprint reduction, water and energy efficiency, waste management, and circular economy practices are prioritized. Turkey's 2021 Sustainable Food Systems Country Report emphasizes the priority of issues such as adaptation to climate change, preservation of biodiversity, and ensuring food security in the agriculture and food sector.

At the private sector level, TSRS-compliant sustainability reports published by large companies reveal the sector's risk management, adaptation to climate change, and sustainability practices across the value chain. These reports demonstrate that the food industry is undergoing a transformation not only in terms of production but also in terms of corporate governance, social responsibility, and environmental awareness.

The Ministry of Industry and Technology's 2022 Food and Beverage Sector Report highlights the sector's strengths (high production capacity, large domestic market, export potential) and weaknesses (energy-intensive production, limited water resources, and deficiencies in waste management), emphasizing the strategic importance of a sustainability perspective.

Therefore, assessing the Turkish food industry from a sustainability perspective aims not only to reduce environmental impacts but also to enhance economic competitiveness, support rural development, and enhance social welfare. In this context, the future of the sector will be shaped by sustainable production models, the use of innovative technologies, and compliance with international standards. This study evaluated the current state of the food industry in Turkey and its sustainability.

THE CURRENT STATUS AND IMPORTANCE OF THE TURKISH FOOD INDUSTRY

The Turkish Food and Beverage Industry holds a key position within the manufacturing industry. According to data from the Turkish Statistical Institute (TurkStat), the food production industry represents one of the largest sectors within manufacturing industries. For example, as of 2022, the food production industry constituted approximately 15-20% of all manufacturing industries, making it the second-largest manufacturing industry in Türkiye after the motor vehicles sector (Food and Beverage Sector Report 2023, Açıkgöz and Günay, 2018).

The sector boasts a massive production volume, with total turnover reaching 465.9 billion TL and contributing 68.1 billion TL in added value to the economy, according to 2021 data from the Federation of Turkish Food and Beverage Industry Associations (TGDF). The number of businesses exceeds 53,000 and creates employment for over 555,000 people, contributing significantly to social welfare (TGDF Activity Report, 2021). However, the types of enterprises in the sector are heterogeneous, with a large number of small and medium-sized enterprises (SMEs). Academic studies cite the

existence of informal production and the problems of operating at low capacity due to the weaknesses in the financial structures of enterprises as key structural challenges limiting productivity growth (Economic Research Foundation Analysis, 2011).
The importance of the Turkish food industry is reinforced by the preservation of its trend toward foreign trade surpluses in international trade. Despite economic fluctuations, the sector regularly generates foreign trade surpluses, contributing foreign currency inflows to the national economy (Fulfood, 2019).
Export Volume: According to 2021 data, the sector's total exports reached $14.3 billion, while imports remained around $6.7 billion, resulting in a foreign trade surplus of $7.6 billion (TGDF Activity Report, 2021).
Global Ranking: Thanks to its agricultural production strength, Turkey ranks among the top 10 countries in the world in food-oriented agricultural production (FAO data, Ministry of Industry and Technology, 2020). In food and beverage exports, Iraq ranks among the top 25 globally, accounting for a 1.22% share (Ministry of Industry and Technology, 2020).
Major Markets: Due to geographical proximity and historical ties, Iraq is one of the sector's main export markets.
The food industry has the advantage of being able to procure its basic raw materials largely from domestic sources, which reduces external dependency and supports economic stability. However, some subsectors, such as vegetable oils and grains, may be dependent on external sources for raw material supplies, albeit in small amounts (TOBB Turkey Food Sector Compilation Report, 2024).

FOOD SAFETY AND CONSUMER HEALTH

The primary objective of food safety policy is to ensure a high level of protection for human health in the food industry (Badrie et al. 2006). The European Union embraces the principles outlined in the White Paper on food safety and implements an integrated approach, from farm to table, encompassing all sectors of the food chain. To date, new EU food legislation has been largely shaped and harmonized with member states. Turkey has restructured its food policies during the EU harmonization process and has undergone rapid changes in food legislation (Açar 2021).
During the accession partnership with the European Union, efforts to harmonize agricultural and food policies and practices will be undertaken. The

European Food Authority, which will inspect food products using scientific risk analysis methods, will inspect not only the final product but also the production chain through which the product is formed. The White Paper, published with the latest regulations, stipulates that, during the future expansion of the Union, new countries will be obligated to comply with the fundamental principles of food health and safety and harmonize their laws and control systems. In recent years, the emergence of foodborne hazards threatening human health has further increased the need for serious measures in this area. Mad cow disease, BSE (Bovine Spongiform Encephalopathy) (1996), the dioxin and nitrophene crisis (1999-2000), the foot-and-mouth disease crisis (2001), and the avian flu crisis (2006-) have significantly impacted food supply security and the prevention of serious economic crises for the food sector. Recognizing this, food sector managers are establishing internationally recognized food safety and quality systems that cover all company employees and implementing voluntary practices. Türkiye's agricultural structure differs significantly from the EU in terms of its agricultural population, the small size and dispersed nature of enterprises, the organization of producers, agricultural support, productivity, technological use, institutional organization, plant and animal health requirements, and product quality and standards. How the regulations on safety and quality practices in food products, which are increasingly important for consumers, are addressed in the EU food legislation and the practices of the meat-dairy products industry, fruit juice-concentrate industry, pasta industry and olive oil industry enterprises, which are important food manufacturing industry subgroups in Türkiye, are taken into consideration.

The current situation of the Turkish food manufacturing industry requires a series of structural and organizational initiatives to improve its future prospects through EU food legislation harmonization efforts. Companies producing safe, high-quality, and environmentally friendly food have established and documented a number of quality and safety systems. Information on the current status of the meat and dairy products industry, processed fruit and vegetable industry, milling products industry, and olive oil industry, all of which hold significant roles in the Turkish food manufacturing industry, will be essential, along with legal requirements for harmonization with EU food legislation, technological investments, requirements for SMEs, and scale-up requirements for businesses.

Issues arising during assessment and management are disclosed to the public within a legal framework, as stipulated in the principle of transparency. A "Food Safety Information System" (GGBS), compatible with EU and developed countries, has been established to facilitate food import and export and regulate businesses engaged in these activities. Through this system, food businesses planning to import and export can submit product notifications to the Provincial Directorate of Agriculture and Forestry and complete all necessary procedures by the designated product inspection deadline. The

system contains and updates all information regarding product certificates, approved and registered businesses, and product origins. The National Food Reference Laboratory has been established, a significant step towards compliance with the food safety chapter in the EU accession negotiations of 94 countries. Established with EU financial assistance as a sustainable laboratory project within an effective food control system, the reference laboratory supports compliance with EU standards in food inspection. Communiqués stipulated in the priority food safety chapter within the revised regulatory framework of the EU acquis are continuously being developed and implemented. A new era has begun in Turkey with the publication of these communiqués, and positive developments are being experienced in the food sector as a result. Turkey, having accelerated its harmonization efforts with the opening of Chapter 12, continues to make progress in this area. However, implementation of legislation remains challenging and progress needs to be made in increasing institutional capacity. To comply with the acquis, institutional capacity must be developed, and capacity must also be improved in terms of personnel training, the number of inspection bodies and personnel, and technical facilities. Work at border control points, in particular, must be accelerated. Reforms provide consumers with a healthier food supply, making the agricultural and food industries more competitive. Counterfeiting and adulteration have increased in today's food industry due to scientific, technological, and economic advancements, as well as regulatory deficiencies. This situation constitutes one of the biggest obstacles to ensuring food safety in our country. Due to the lack of deterrent effect of the administrative sanctions stipulated in Law No. 5996, the Regulation on the Calculation of Actual and Administrative Fines for Counterfeiting and Adulteration in Food and Feed entered into force on April 16, 2021, aiming to prevent counterfeiting and adulteration. Small-scale businesses, which are widespread in Turkey, fail to meet EU standards. These businesses need financial support to comply with the legislation. In-service training for technical personnel working in the public and private sectors in the food sector should be increased, the technical equipment in laboratories and the diversity of accredited analyses should be increased, and collaboration with universities should be increased. Food safety is one of the most important legal issues of modern life. In order to ensure the production of safe products in the food sector, to defend consumer rights, and to prevent deficiencies in the applicability of the 95 laws in force in the food field, food law departments should be opened in law faculties and food law-related institutions should be established.

Rural Development (IPARD II) Sub-Sector Priorities within the Indicative Strategy Document for Turkey: Within the scope of the IPARD II priority for Turkey, the ESB aims to establish modern farms and agricultural and food enterprises in line with EU standards, increase investment in agricultural enterprises, increase investment in the processing and marketing of

agricultural and fish products, develop the rural economy and increase diversity, and enhance the capacity of the IPARD program. IPARD program activities should be strengthened to support the management and sale of agricultural land, agricultural and aquatic products, the expansion of agricultural activities, and investment in tangible assets for business development. Complementary activities include a rural development strategy program in line with the LEADER approach, which could include environmental measures for agriculture, organic farming, technical assistance, and consultancy services. There should be a good balance between activities aimed at balancing alignment with the acquis and the socioeconomic development of the sector. The IPARD II program will be sufficient to meet the country's rural development objectives. Among the above priorities, nine measure headings have been defined, and investment is targeted to be implemented under these headings. These nine headings cover the following investment areas.

1. Investing in agricultural enterprises,
2. Investing in the processing and marketing of agricultural products,
3. Investing in rural infrastructure,
4. Investing in the development and expansion of rural economic activities,
5. Ensuring the establishment of producer groups,
6. Investing in environmental-agricultural and animal breeding programs,
7. Ensuring local rural development/rural preparation for the EU mechanism,
8. Vocational training,
9. Technical assistance

Since its establishment, the European Union has provided extensive financial assistance to EU member states, candidate countries, and third countries within the scope of agreements. With this assistance, the European Union transfers significant amounts of finance to countries benefiting from this financial support, in the form of grants or loans. From the perspective of candidate countries, the financial cooperation it has developed with the European Union and the financing provided within this scope constitute an important part of the relationship between the EU and candidate countries. Essentially, the financial assistance provided prepares the candidate country for EU membership. The Ministry of Agriculture and Forestry has benefited from financial assistance in many areas such as veterinary medicine, plant health, aquaculture, food safety, organic farming, rural development, statistics, land parcel identification system and many other projects.

Food safety is the primary condition for securing consumers' most fundamental and universal rights: the right to a healthy diet and life. Food safety means providing food free from all physical, chemical, and biological harmful agents at all stages from production to consumption (Soysal, 2007). A hazard that may arise at any stage of the food chain can lead to foodborne illnesses (FBIs), which directly threaten consumer health, causing both individual suffering and loss of labor, as well as significant treatment and

social costs for the national economy (Ministry of Agriculture and Forestry Publication, 2025).

1. Main Risks Threatening Consumer Health

Foodborne hazards are categorized into three main categories that negatively impact consumer health:

Biological Hazards: This constitutes the most common and most risky group. These hazards arise from the presence of microorganisms such as bacteria (Salmonella, E. coli), viruses, parasites, and biotoxins in food. These hazards can cause a wide range of illnesses, from digestive tract infections to neurological damage.

Chemical Hazards: These arise from chemical substances that should not be present in foods or at levels exceeding legal limits. These include:

Pesticide and Veterinary Drug Residues (in Raw Materials),

Heavy Metals (Environmental Pollution or Contamination from Equipment),

Excessive Use of Food Additives, and

Contamination of Cleaning and Disinfectants from the Production Environment. Chemical hazards often lead to long-term chronic diseases and toxic effects.

Physical Hazards: These are unwanted foreign objects found in food (stones, soil, glass shards, metal fragments, hair, bone, etc.). These can cause direct injuries, choking, or negatively impact consumer preferences (ADÜ Academic Publication, 2024).

2. Systems that Safeguard Consumer Health

To protect consumer health, all businesses in the food chain must systematically manage the traceability and safety of raw materials from the farm to the table. The main management systems implemented in this context are:

HACCP (Hazard Analysis and Critical Control Point System): This is the most basic and systematic management method for ensuring food safety. It analyzes potential hazards at every stage of food production, identifies critical control points (CCPs), and prevents foodborne risks by controlling these points (Medipol University, 2024).

Good Manufacturing Practices (GMP) and Good Hygiene Practices (GHP): These define the basic hygiene and sanitation rules that businesses must adhere to in their facilities, personnel, equipment, and production processes. These practices increase product safety by minimizing biological and physical contamination.

Traceability: A recording system that enables the backward and forward tracking of food at all stages. It is vital for the rapid withdrawal of a product posing a health risk from the market and the identification of the source of the problem.

ISO 22000 Food Safety Management System: This is an integrated management standard, including HACCP principles, with international validity and encompassing all organizations in the food chain.

3. The Role of Legislation and Consumer Awareness

Food safety and the protection of consumer health in Türkiye are regulated by the Veterinary Services, Plant Health, Food and Feed Law No. 5996 and the relevant Turkish Food Codex regulations (Ankara University, 2017). This legislation defines foods that are harmless to health and pose an acceptable level of risk as "safe food."

Consumer awareness is the final and most important link in the food safety chain. Consumers; Paying attention to production and expiration dates on product labels,

checking ingredient information and storage conditions,

choosing packaged and reputable branded products,

and being knowledgeable about proper home food storage and preparation (preventing cross-contamination and cooking at the correct temperature) all play a significant role in preventing foodborne illnesses (TEPGE Report, 2012).

DEVELOPMENTS IN EUROPEAN UNION FOOD LEGISLATION AND TURKEY

Since ancient times, people have valued food quality and food safety. Moving from the individual agricultural society to today's information society, where trade and free competition have increased, countries, academic institutions, civil society associations, and consumer associations have developed a number of standards and legal regulations to ensure the trade of high-quality and safe food, ensure food sustainability, and protect consumers, reliable producers, and traders against unfair competition. Developments Before the General Food Law: The CAP (Common Agricultural Policy), which began in 1960 based on the Treaty of Rome, signed on March 25, 1957, by six countries seeking peace following the famine following World War II—France, West Germany, Italy, Belgium, the Netherlands, and Luxembourg—and entered into force on January 1, 1958, shaped EU food legislation around the establishment of the internal market. However, as conditions changed over

time, it became more difficult to meet societal needs. The agricultural sector was also affected by these changes due to globalization. Therefore, agricultural products trade is also affected by this situation. During this period of change, food and agricultural products trade has been faced with safety and quality issues, which, in parallel with growing consumer anxiety, has led to an increased emphasis on this area. This is because potential problems, whether direct or indirect, lead to certain problems in terms of consumer interests (health, economy, etc.). Therefore, the EU has adopted a new approach to food safety crises that arise within the Community, especially within the EU, and that have brought this issue to the forefront. BSE is an animal disease that causes fatal nerve degeneration and was first identified in 1986. The disease was diagnosed in cattle in 26 different countries, including the USA, in June 2005. The agent believed to be responsible for BSE is a defective protein found in certain tissues, particularly the brain and central nervous systems of BSE-infected animals. The spread of spongiform encephalopathy (BSE), commonly known as mad cow disease, from cattle to Europe; the dioxin crisis, which began in Belgium; avian plague in Asian countries; and other epidemics such as swine plague; The production of genetically modified food, drug, and pesticide residues has jeopardized consumer health and destabilized food markets worldwide. Following painful experiences, research on the control and elimination of animal diseases within the "food safety" field has begun in the EU and in third countries with trading relations with the EU and WTO countries. The EU has chosen an approach that integrates animal health, plant protection, animal welfare, and food safety within the framework of its "food safety from farm to table" discourse. The BSE crisis and other food concerns of the 1990s exposed many serious shortcomings in Europe. In this regard, several regulations, most notably the Green Paper, were introduced. The Green Paper is not primarily a source of food safety, but was developed as part of efforts to simplify the Common Agricultural Policy and, due to its relevance, has enhanced the overall framework of food legislation. However, it is one of the main texts on this topic, as it has initiated discussions on how to develop the best food legislation for the EU.

The Green Paper's objectives are:

1. To examine the extent to which legislation meets the needs and expectations of consumers, producers, and traders.
2. To consider measures to strengthen independence and impartiality, the equivalence and effectiveness of official control and inspection systems, the fundamental objectives of ensuring a safe and healthy food supply, and the protection of other consumer interests.
3. To initiate a public debate on our food legislation, thereby enabling the Commission to propose appropriate measures for the future.

4. To ensure that Community food law is amended when necessary. On 12 January 2000, the European Commission outlined its vision for the future development of Europe and published the White Paper on Food Safety. One of the main outcomes of this document was the establishment of the "European Food Authority." Therefore, it is clear that the primary focus of this Authority is the public interest.

Consequently, the principle is to gather information and provide scientific advice at all stages of the food chain, analyze risks, operate emergency alert systems, establish relationships with consumers and scientific organizations, and ensure their participation in food control. The principles included adopting a "farm-to-fork" approach to food safety, developing control systems for food additives and novel foods, ensuring traceability throughout the food chain, drafting effective legislation, and implementing more than 80 necessary actions. The five principles of the EU's new food safety approach were adopted:

- an integrated and comprehensive approach,
- consistency,
- accountability,
- retrospective monitoring,
- a dynamic and effective approach,
- risk analysis,
- transparency,
- precautionary measures.

The guiding principle in the White Paper is based on a comprehensive and integrated approach to food safety policy. This principle encompasses all stages of the monetary and policy cycle, from farm to table, across all food sectors; among Member States; within and outside the EU; and in international and EU decision-making processes. The fundamentals of food safety outlined in the White Paper (scientific advice, data collection and analysis, regulatory and control aspects, as well as consumer information) form a seamless whole to achieve the integrated approach. In addition to establishing an independent authority, the White Paper set out various measures for a legislative structure covering all aspects of food produced using a "farm-to-fork" approach (CoEC 2009). Recent developments have demonstrated the need for updated legislation, and the Commission has taken comprehensive measures to improve food safety standards.

Recent developments and changes in European Union (EU) food legislation primarily focus on further strengthening consumer health and food safety, supporting environmental sustainability, and increasing labeling transparency (Runhaar 2014). Amendments to EU regulations on food contact materials (especially plastics) are among the most important recent steps in this area. The EU has redefined or removed from the lists the migration limits (SMLs)

for certain substances in food contact plastics (e.g., some phthalates and primary aromatic amines (PAA)). The aim is to protect consumer health from the risk of potentially harmful chemicals migrating into food. Significant revisions to labeling rules are underway to enable consumers to make more informed choices. The issue of presenting mandatory nutritional information (energy, fat, sugar, salt, etc.) on the front of packaging in a simpler and more understandable way (e.g., traffic light-like systems) is being discussed. The requirement to include the country of origin of the main ingredient of food, in addition to meat and fish products, is part of efforts to increase traceability. Future changes include improving label readability and integrating digital labeling (online information) solutions into traditional labels. Regulations are also being implemented to reduce the impact of chemicals used in food production on human health and the environment. The EU is taking a more stringent approach to addressing the chemical burden in the food chain by continuously updating the Maximum Residue Limit (MRL) for pesticides in food. For example, new categories and MRLs have been established for certain product groups, such as small radish leaves, taking into account different pesticide residue profiles. In line with the EU's "farm-to-table" approach, risk assessment and control processes are constantly being improved. Risk analysis mechanisms, including risk assessment, risk management, and risk communication in the food chain, are of central importance (EU Regulation No. 178/2002). The European Food Safety Authority (EFSA) continues to underpin legislation with scientific advice and safety assessments. The Rapid Alert System for Food and Feed (RASFF) is being strengthened to ensure a rapid and integrated control process.

General Situation in Food Safety in Turkey: Various efforts are underway in Turkey to ensure integration with the EU regarding food legislation. Initially, the General Hygiene Law, which had been in effect since 1926, was abolished, and replaced by more effective regulations with Decree Law No. 560, published on June 28, 1995, and numbered 22327. This Decree stipulated that businesses producing food products must obtain a non-sanitary establishment license and operating permit from the Ministry of Health, as well as a food registry and production permit from the Ministry of Agriculture and Forestry, before commencing production. The National Programme for Turkey's adoption of the EU acquis has included extensive coverage of food safety, animal and plant health. In addition to revisions to existing legislation on plant and animal health and animal welfare, new legislative regulations are also envisaged. Regulation No. 178/2002/EC of the European Parliament and of the Council, which determines the general principles and conditions regarding Food and Feed Law, establishes the European Food Safety Authority, and determines procedures related to food and feed safety issues, was published and entered into force on January 28, 2002. It was committed to completing harmonization with the EU General Food and Feed Law by May 2, 2004, according to the National Program harmonization calendar. Alignment with

this EU legislation was achieved with the "Law on the Amendment and Adoption of the Legislative Decree on the Production, Consumption, and Inspection of Food." To ensure the safe supply and consumption of food products, Legislative Decree No. 560 was revised, and Law No. 5179, published in the Official Gazette No. 25483 dated June 5, 2004, aimed to bring it into line with the EU acquis. While the primary requirement for safe food production is the supply of safe raw materials, significant challenges remain. Physical, chemical, and biological adverse effects occurring in plant and animal raw materials or during subsequent processing stages also pose a risk to human health, while adverse effects originating from feedstuffs can threaten animal health and, consequently, human health. Furthermore, the Food Law No. 5179 was enacted to centralize food-related services and reduce bureaucracy. The law's purpose and scope are to ensure food safety, the technical and hygienic production, processing, preservation, storage, and marketing of all food products, and the establishment of minimum technical and hygienic requirements for food-producing businesses to ensure the proper nutrition of the public. Therefore, the primary objective in ensuring food safety is to implement effective food control practices nationwide within the framework of legislation prepared in accordance with the EU, and to establish a single, competent, and EU-compliant administrative infrastructure and control system. However, the authority assigned to such institutions remains unclear in Law No. 5179 and related regulations. Due to its conflict with the Municipalities Law, the Council of State partially transferred the implementation of Article 4 of Law No. 5179 from the Ministry of Agriculture and Forestry to municipalities. This practice created a new deadlock in the food safety and control system. The first regulation enacted after the law came into effect was the Regulation on Work Permits, Food Registry and Production Permits, and the Employment of Responsible Managers for Businesses Producing Food and Food-Contact Materials and Substances. The new regulation, added as an annex to this regulation, classified the business lines producing food and food-contact materials and substances and specified the professional personnel to be employed as responsible managers in food businesses based on the nature of production. This regulation was followed by the Regulation on Market Surveillance, Control, and Inspection of Food and Food-Contact Materials and Substances and Workplace Responsibilities. According to this regulation, the implementation of the HACCP system became mandatory in food production and sales facilities. It was stated that businesses producing meat, dairy, and seafood, ready-made food factories, and low-acid canned foods must develop hygiene codes and implement the HACCP system within the first one or two years, depending on their size; and other businesses must also implement the HACCP system within two or three years, depending on their size. This situation has led to jurisdictional confusion regarding food control and prevented effective food control practices. Because the Customs Union Agreement signed with the EU in 1995

stipulated the harmonization of food legislation with that of the EU, the authority confusion was largely eliminated with the enactment of Decree Law No. 560 on the Production, Consumption, and Control of Food in 1995. This regulation was transformed into Law No. 5179 with some amendments in 2004. Law No. 5996 was subsequently published in the Official Gazette on June 13, 2010, under number 27601. Law No. 5996 on Veterinary Services, Plant Health, Food, and Feed covers all stages of the production, processing, and distribution of food, food-contact substances and materials, and feed; controls for residues of plant protection products and veterinary medicinal products, as well as other residues and contaminants; combating epidemic or contagious animal diseases and harmful organisms in plants and plant products; the welfare of farm and experimental animals and domestic and ornamental animals; zootechnical matters; veterinary health and plant protection products; veterinary and plant health services; entry and exit procedures for live animals and products into the country; and official controls and sanctions related to these matters. It consolidates supervisory powers within the Ministry of Agriculture and Forestry. The purpose of Law No. 5996 on Veterinary Services, Plant Health, Food, and Feed is to ensure food safety (Kılıçaslan and Seda 2015). The procedures required to achieve this objective are:

• To ensure the technical and hygienic production, processing, preservation, storage, and marketing of all foodstuffs and food-contact materials and materials, and to ensure the proper nutrition of the public.
• To determine the safety characteristics of all raw, semi-finished, and finished foodstuffs, food processing aids, and food-contact materials and materials used in food production in order to protect the interests of producers and consumers and public health.

• To determine the minimum technical and hygienic requirements for businesses producing and selling foodstuffs, and to determine the procedures and principles for food-related services and inspections. Furthermore, the objectives of this law are to protect and ensure food and feed safety, public health, plant and animal health, animal breeding and welfare, while also taking into account consumer interests and the protection of the environment.
Within the framework of harmonization with EU food legislation, Turkey is transposing the EU acquis into national legislation, particularly within the scope of the Food Safety, Veterinary and Phytosanitary Chapter. As with recent regulatory changes regarding food contact plastics, current EU regulations and amendments are being closely monitored and incorporated into national legislation. This process requires food producers and exporters in Türkiye to comply with new standards and technical regulations.

CONCLUSION

While Turkey possesses rich agricultural resources and a large domestic market, it faces significant challenges in maintaining its international competitiveness in this sector and leaving sufficient resources for future generations. The Turkish food industry is heavily populated by SMEs. This can make it difficult to capitalize on economies of scale. The sector should focus on producing high-value-added products by investing more in R&D and innovation, thereby increasing its competitiveness in international markets. High input costs in agricultural production, yield fluctuations due to climate conditions, and logistical challenges threaten cost stability. Traceability, transparency, and preventing unfair trade practices in the supply chain are critical. It is especially necessary for small businesses to facilitate access to financing for compliance with environmental regulations, modernization, and energy efficiency investments.

Turkey is in a region experiencing water stress. Because the food industry and agriculture are major water users, the expansion of water footprint-reducing technologies (closed-circuit systems, wastewater recycling) is essential. Drought and irregular rainfall caused by climate change directly impact raw material supply. One of the food industry's biggest challenges is organic waste generated during production. Circular economy practices, such as converting this waste into energy in biogas plants or using it as animal feed/fertilizer, reduce environmental impact and create new economic value. Reducing food loss during the production, processing, and storage stages, as well as during consumption, is one of the biggest sustainability goals, both environmentally and economically. Switching to renewable energy sources (solar, biogas) in facilities and modernizing to increase energy efficiency are vital steps to reducing the sector's carbon footprint. Providing consumers with safe, healthy, and high-quality food is the sector's most important social responsibility. Full compliance with the stringent standards introduced during the EU harmonization process establishes this trust. An integrated approach is needed for the Turkish food industry to succeed on its sustainability journey. Smart agricultural technologies, digital traceability systems, and automation will both increase efficiency and optimize resource utilization.

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Bee Products and Their Use in Apitherapy

Nuray ŞAHİNLER[1]
Esra KOCABAŞ[2]

1-Prof.Dr.;Uşak Üniversitesi Ziraat Fakültesi Zootekni Bölümü.
nuray.sahinler@usak.edu.tr ORCID No:0000-0003-4999-773X
2-Uşak Üniversitesi Lisansüstü Eğitim Enstitüsü Zootekni Anabilim Dalı Uşak
esrakocabas95@gmail.com ORCID No:0000-0003-4227-2103

ABSTRACT

In recent years, treatment methods known as “Apitherapy,” which utilize bee products, have shown rapid development worldwide. Products obtained from beekeeping activitiessuch as honey, pollen, propolis, royal jelly, and bee venomare widely used among the public for the treatment of various illnesses. Honey, propolis, and royal jelly possess strong antibacterial properties, while bee venom exhibits anti-rheumatic effects. Additionally, pollen is considered a supportive product in the treatment of immunological diseases.

Keywords: Honey, Pollen, Royal Jelly, Propolis, Beevenom, Treatment Methods.

INTRODUCTION

Apitherapy is a word derived from the Latin word apis, meaning bee. Apitherapy is defined as the use of bee products such as honey, pollen, royal jelly, beeswax, bee venom, and propolis to maintain health and prevent and treat disease. The practice of apitherapy dates back hundreds of years. There are documents showing that physicians in ancient Egypt and China used certain bee products 4,000 years ago. These products are generally known to have significant effects, such as antibacterial, antioxidant, anti-inflammatory, vasodilatory , and antitumor effects. In addition to their positive effects, studies have also shown that the use of some apitherapy products can cause allergic reactions (Özdemir, Ersöz, Dilek, 2021:168).

DEVELOPMENT OF APITHERAPY IN THE WORLD

Although the term apitherapy is modern, its content dates back hundreds of years. Apitherapy was used by Indians 6,000 years ago, and by the Sumerians 5,000 years ago. According to some archaeological findings, some ancient civilizations in Anatolia used certain bee products. There are documents indicating that ancient Egyptian and Chinese physicians prescribed certain bee products 4,000 years ago (Atayoğlu , 2019:62). Bees exist in relatively unchanged form, numbering around 50 million. 6,000 years ago, Native Americans used honey as a food and propolis as a wound healer. The first book on apitherapy appeared 5,000 years ago . On the other hand, bee products, especially honey, beeswax, and propolis, were used in traditional Egyptian medicine 4,000 years ago. Similar prescriptions appeared 1,000 years later in Ancient Greece and 1,500 years later in the

Middle Ages. It originates in England . Today, Apimondia has begun to support and publish many of the research studies, especially after 1965 (Çelik, Aşgun, 2020:6).

DEVELOPMENT OF APITHERAPY IN TÜRKIYE

Apitherapy was defined as "the use of bees and bee products as a preventive measure and supportive treatment for certain diseases" in the Traditional and Complementary Medicine Practices Regulation issued by the Ministry of Health in Turkey on October 27, 2014 (Atayoğlu , 2019:62). Studies in this field have been initiated in Turkey in recent years, and apitherapy courses and centers have begun to be established following the traditional and complementary medicine practices regulation published in 2014 (Sorucu, 2019:1).

HONEY

Natural honey is defined as a sweet, delicious liquid with high nutritional value and therapeutic benefits (Özdemir et al. , 2021:168). It is obtained from the flowers of plants or nectar secreted from other living parts and byproducts secreted by some insects living on the plant, taking advantage of the living parts of the plants, honey bees(Apismellifera) combines with its own unique substances after being collected, changes its water content, and then matures by storing it in the honeycomb (Atayoğlu , 2019:63). Honey is a natural food composed primarily of sugars and enzymes, amino acids, organic acids, carotenoids, vitamins, minerals, and aromatic substances. It is also rich in flavonoids and phenolic acids. The composition, color, aroma, and taste of honey depend primarily on the flowers, geographic regions, climate, and honeybee species involved in its production. The content is also affected by weather conditions, processing, packaging, and storage time. However, it generally consists of sugars, water, enzymes, organic acids, vitamins (especially vitamin B6, thiamine, niacin , riboflavin, and pantothenic acid), minerals (calcium, copper, iron, magnesium, manganese, phosphorus, potassium, sodium, and zinc), phenolic compounds, and a wide variety of volatile compounds (Arslan and Kızıltan, 2024:178). The glycemic index values of the monosaccharides found in honey, especially

glucose and fructose, are importantamong There are differences . Fructose has a glycemic index of 23. The glycemic index of a sugar is estimated based on the molar ratio of glucose to other monosaccharides in the sugar molecule (Silici, 2019:1250). The medical importance of honey has been documented in the world's oldest medical literature, and it has been known since ancient times that it has antimicrobial properties in addition to its wound healing effect, thus facilitating wound healing (Arslan and Kızıltan, 2024:179). Today, there is an increasing interest in the therapeutic use of honey . For therapeutic purposes, honey is used in the treatment of ulcers, wounds , and burns . It is used in the treatment of skin infections and bed sores. There are studies reporting the inhibitory properties of honey not only against bacteria but also against viruses, fungi, and parasites (Silici, 2019:1250). It's important to ensure that honey used in apitherapy hasn't been heated in a way that would destroy or significantly inactivate its natural enzymes. It's important to remember that some parameters, such as hydroxymethyl furfural (HMF) and enzyme activity, will change with heating and storage. Fresh honey has very low HMF levels, while natural enzyme levels are high. For apitherapy, there are recommendations that honey should contain a maximum of 25 mg/kg HMF, or even 15 mg/kg, and have an invertase activity of at least 10 Hadorn units (Atayoğlu , 2019:63).

Table-1: Honey content by source.

Characteristics/ Features	Nectar source honey (%)	Honeydew honey
Moisture	17,20	16,30
Fructose	38,19	31,80
Glucose	31,28	26,08
Sucrose	1,31	0,80
Maltose	7,31	8,80
High Molecular Weight Sugar	1,50	4,70
Vitamin, Mineral	3,10	10,1
Ph	3,90	4,45
Total Acidity (meq/kg.)	29,12	54,88
Ash	0,169	0,73
Nitrogen	0,041	0,100
Diastase Number	20,80	31,90

Parlakpınar ve Polat, 2021:40.

POLLEN

Pollen is a bioactive structure formed by flowering plants for reproduction purposes and is used for feeding bees, classifying honey, and for treatment purposes in the field of health (Onbaşlı , Yuvalı Çelik, Kahraman, Kanbur ,

2019:50-51).Pollen is the main source of protein, lipids and vitamins for honey bees (Arslan and Kızıltan, 2024:180). While collected from plants, it is usually made sticky with some saliva. pelletform It is carried to the hive in a pollen basket . Bee pollen is used to support the tissues, muscles, glands and other organs of honeybees during their post- larval and juvenile periods. sufficientlydeveloped Protein, lipid, sterol, vitamin necessary for andminarets It is the most important nutrient that provides nutrients (Silici, 2019:1255). It is an important nutritional source for humans. The collected pollen is immediately cleaned, frozen to -17 ° C ± 2 ° C in airtight packages and stored in deep freezers. Freshly frozen pollen does not show any decrease in its nutritional value (Atayoğlu , 2019:64). Depending on the source, pollen has been shown to exhibit beneficial effedcts such as being antibacterial, antifungal, anti-inflammatory and providing relief for prostate and kidney-related issues. It is also known for its memory-enhancing, probiotic, regenerative, performance-boosting and aphrodisiac effects (Sorucu, 2019:8). Bee pollen has been found effective in reducing the negative effects of cancer treatment. It has been reported to have a positive effect on radiation side effects such as loss of appetite, nausea, hair loss, inflammation, low white blood cell count (leukopenia), and insomnia. Pollen has been shown to be beneficial for digestive system disorders such as chronic colitis, stomach ulcers, bleeding, diarrhea, and constipation, as well as for treating anemia and controlling cholesterol, lipids, and triglycerides (Onbaşlı et al., 2019:51).

Table-2: The average composition of dried pollen.

Component	Bee-collected		Hand-collected
	%	%	%
Water (air-dried-pollen)	7	11	10
Crude protein	20	21	20
Ash	3	3	4
Etherextracts (crudefat)	5	5	5
Carbohydrate			
Reducingsugars	36	26	3
Non-reducingsugars	1	3	8
Starch	-	3	8
Undetermined	28	29	43

Krell, 1996:92.

ROYAL JELLY

Royal jelly, 5 - 15 days old workerbees It is a bee product secreted from the pharyngeal glands. It has a creamy white color with a fluid gel-like consistency . It tastes sour. and its smell It has a sharp phenolic structure. Its density is 1.1 g / cm^3 . It is partially soluble in water (Silici, 2019:1251). Royal jelly was first introduced by a scientist named Huber in 1972. Royal jelly, known as " royale ," is secreted from the glandular tissues (hypopharyngeal) found in the heads of young worker bees (Onbaşlı et al., 2019:51). Royal jelly is a specialized nutrient synthesized to nourish the queen bee. Royal jelly primarily consists of 50-60% water, approximately 18% protein, 15% carbohydrates, 3-6% lipids, and 1.5% minerals and vitamins. Royalactin is the most important protein found in royal jelly. Royal jelly also contains various bioactive compound, including 10-hydroxy-2-decenoic acid (HAD), which has some immunomodulatory properties. Some of these include adenosine monophosphate (AMP), nitric oxide, adenosine, acetylcholine, polyphenols, and hormones such as testosterone,

progesterone, prolactin, and estradiol. The robuts compounds in royal jelly enable it to display numerous beneficial effects. These reported activities include anti-lipidemia, antioxidant, anti-proliferative, anti-inflammatory, immunomodulatory, anti-aging and estrogenic properties (Arslan and Kızıltan, 2024:182, Silici, 2019:1252). It is also reported to be beneficial for liver disorders, hair and skin disorders, and tuberculosis, as well as inhibiting the development of some types of tumors. Royal jelly is also used for neurological disorders, reproductive health problems, and to regulate sexual function (Şahinler and Toy, 2021:132).

Table-3: Composition of royal jelly.

Component	Minumum	Maxımum
Water	57%	70%
Proteins (N x 6.25)	17% of dryweight	45% of dryweight
Sugars	18% of dryweight	52% of dryweight
Lipids	3.5% of dryweight	19% of dryweight
Minerals	2% of dryweight	3% of dryweight

Lercker, Vecchi, Sabatini and Nanetti, 1984.

PROPOLIS

Propolis is a mixture of molecules secreted by bees and plant extracts. Bees are known to produce propolis as a defense and protective mechanism, and propolis is a resinous substance (Arslan and Kızıltan, 2024:183). The word " propolis " comes from the Greek word " protection of the city ." Propolis protects honeybee colonies from diseases and microbial infections, protecting the hive walls. and larvae It is used for multiple purposes, such as providing a hygienic living environment by covering the honeycomb cells placed in the hive , covering dead creatures in the hive to prevent them from stinking and spreading infection, and shrinking the hive entrance hole. Propolis varies in color from yellowish green to reddish dark brown and has different aromatic odors. Propolis has a waxy consistency at 15-20°C and a sticky and gum-like consistency at 30-40°C. It generally melts at 60-70°C and becomes hard and brittle when frozen. In general, propolis consists of 45-50% resin, 30% wax, 10% essential and aromatic oils, 5% pollen, and 5% other organic substances (Sorucu, 2019:6).Propolis medicine useas Itdates back to ancient times. While the Egyptians mummified their dead, Greek and Roman doctors used propolis as an antiseptic and wound healer (Silici, 2019:1252, Sorucu, 2019:6). Studies have investigated propolis's antibacterial, antifungal, antiviral, antitumoral, antioxidant, immunomodulatory, anti-inflammatory, hepatoprotective, cardioprotective,

neuroprotective, radioprotective, antidiabetic, regenerative, gastroprotective, renalprotective, antiulcer, chelator, antimutagenic, anesthetic, antiallergic, analgesic, otorhinolaryngogenic biological effects, as well as its effects on inflammations such as peridontitis, gingivitis, osteoarthritis, mastitis, rhinitis, asthma, and tooth decay, as well as many other gynecological and ophthalmic effects (Sorucu, 2019:7). For apitherapy, high-quality propolis means propolis with a high balsam content, high bioactivity, and pure, organic propolis. Careful attention should be paid to contamination with heavy metals and lipophilic synthetic acaricides used for varroa control (Atayoğlu , 2019:63).

Table-4: The number and identified chemical composition of propolis.

Identified Compounds	Number
Flavonoids	38
Hydroxyflavones	27
Hydroxyflavanones	11
Chalcones	2
Benzoic acid and derivates	12
Acidsd	8
Esters	4
Benzaldehyde derivaties	2
Cinnamyl and Cinnamic acid derivatives	14
Alcohols, Ketones, Phenols	8
Heteroaromatic Compounds	12
Terpene and Sesquiterpene derivatives	7
Aliphatic Hydrocarbons	6
Sesquiterpene and Triterpene Hydrocarbons	6
Hydrocarbons	11
Sterols ve Steroid Hydrocarbons	6
Minerals	22
Sugar	7
Amino acid	24

Coşkun ve İnci, 2020:1059.

APILARNIL

Apilarnil is obtained by collecting and homogenizing drone larvae over a 3-7 day period. It has a homogeneous milky consistency and contains numerous amino acids, minerals, sugars, fatty acids, and androgenic hormones (Sorucu, 2019:11). Apilarnil contains approximately 25-35% dry matter. The protein content is 9-12%, the carbohydrate content is 6-10%, and the lipid content is 5-8%. The nutritional content of apilarnil is influenced by the pollen sources honeybees feed on. However, it provides a generally mix vitamins (A, B1, B6, and choline) and key minerals (calcium, phosphorus,

sodium, zinc, manganese, iron, copper, and potassium) (Arslan and Kızıltan, 2024, Silici:184, 2019:1257). Characterized by its antiviral, immune-boosting and anabolic stimulant biological activities, Apilarnil is also known to promote heihtened appetite, increased physical energy, enhanced vitality and improved regenerative capacity. It is also very rich in androgenic hormones, so it stimulates spermatogenesis in men (Arslan and Kızıltan, 2024:185).

Table-5: Chemical composition of apilarnil.

Water	% 65-75
Dry matter	% 25-35
Protein ve Aminoacid	% 12,9
Glucose	% 6-10
Fructose	% 3,16
Saccharose	% 0,03
Fats	% 5-8
Fat soluble vitamins	A,D,E and K
Water soluble Vitamins	B grup and C
Mineral, Hormone,Ksantofil,Kolin	-
Ash	% 2-3

İnci, İlkaya ve İzol, 2021:3.

PERGA (BEE BREAD)

Honeybees the pollen they collect into the hive when they carry, honeycomb bees in your eyes It is stored in the form of bread . While bee bread is produced in the hive, pollen, honey and other beesecretions being confused with andis subjected to lactic acid fermentation. The mixture turns into bee bread in about two weeks, and the fermented bee bread can thus be stored in the hive for a long time. Bee bread is a source of protein, fat, and vitamins for bees ' nutrition, and milkproduction It also forms the raw material (Silici, 2019:1255). Bee bread contains the same minerals, vitamins, and other phenolic compounds as regular pollen, but it is considered more valuable than raw pollen for human consumption. Due to its contribution to reproductive hormones, it is used to increase sexual potency and muscle strength and volume. Due to its acetylcholine content, it is used in the treatment of blood pressure and chronic constipation (Sorucu, 2019:9).

BEE VENOM

Bee venom is produced by two glands connected to the stings of worker bees. Bee venom production reaches its peak when worker bees begin to engage in hive defense and foraging (Onbaşlı et al., 2019:52). Bee venom is a pungent, bitter- tasting , yellowish , transparent substance that dries and crystallizes quickly upon contact with air and has acidic properties (pH 4.5–5.5). Dry, liquid, or diluted honey bee venom should be stored in refrigerators (-20°C) or frozen in dark glass bottles with tightly closed lids. Honey bee venom packaging should be protected from direct sunlight in transportation and sales areas (Atayoğlu , 2019:65).

Melittin , It is a major peptide. It has strong anti -inflammatory , radioprotective , antibacterial , antifungal , and antitumoral effects (Sorucu, 2019:10). Specifically, bee venom is considered a treatment option for neurological diseases affecting the musculoskeletal system such as Parkinson's and MS (Multiple Sclerosis); rheumatic disorders like ankylosing spondoylitis and rheumatoid arthritis; Lyme disease and pain syndromes such as myalgia, fibromyalgia, arthralgia anf neuralgia. However, bee venom is also the product that requires the most caution due to the risk of allergic reactions (Atayoğlu , 2019:65).

Table-6: Chemical composition of bee venom.

Molecule types	Components	Ratio %
Enzymes	Phospholipase A Hyaluronidase Acid phosphomonoesterase Glycosidase Lysophospholipase	10-12 1-3 1 0 0,6 1
Proteins and peptides	Melittin Apamin Mast cell degranulating peptide Secapin Procamine Adolapin Protease inhibitor Tertiapin Other small peptides (<5 amino acids)	40-50 1-3 1-2 0,5-2 1-2 1.0 0.8 0.1 13-15
Physiological active amines	Histamine Dopamine Norepinephrine	0,5-2,0 0,2-1 0,1-0,7
Amino acid	Alpha amino acid Aminobutyric acid	1 0,5
Sugars	Glucose and fructose	2
Phospholipids		5
Volatile compounds		4-8

Sorucu,2019:11.

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Effects of Structural and Operational Features of a Flail-Type Forage Harvester on Chopping Length and Energy Consumption

Hüseyin SAUK [1]
Mehmet Arif BEYHAN[2]

[1] Dr. Öğr. Üyesi; Ondokuz Mayıs University, Faculty of Agriculture, Department of Agricultural Machinery and Technologies Engineering, Samsun. hsauk@omu.edu.tr, orcid id: 0000-0001-5622-6170
[2] Prof. Dr.; Ondokuz Mayıs University, Faculty of Agriculture, Department of Agricultural Machinery and Technologies Engineering, Samsun. mabeyhan@omu.edu.tr, orcid id: 0000-0002-4536-0865

ABSTRACT

For flail-type forage harvesters, the appropriate selection of design parameters such as knife geometry (thickness, knife rake angle, and knife bevel angle), diameter of the chopping unit, knife peripheral speed, and counter-knife position is essential to achieve the desired chop length and optimum energy consumption. In addition, the type of crop, stem thickness, moisture content, plant inclination angle, maturity stage, and plant height also affect both chopping length and energy consumption. In this study, the effects of ***kps*** and ***nkp*** on chopping length and energy consumption were investigated in silage maize harvesting using an experimental model of a flail-type forage harvester. According to the results obtained, the average chop length decreased significantly with increasing ***kps*** and ***nkp***. An increase in ***kps*** and ***nkp*** led to higher ***scec*** and ***stec***, particularly at ***kps*** of 40 and 45 m/s. The lowest average chop length (92.7 mm) was achieved at a ***kps*** of 40 m/s with two circumferential knives on ***nkp***. Under these conditions, ***scec*** was 3.79 kWh/t, and ***stec*** was 7.57 kWh/t.

Keywords: Flail-Type, Forage Harvester, Length Chopping, Cutting Energy.

INTRODUCTION

Silage is an important source of roughage for animal production. In recent years, silage has become increasingly significant for the livestock sector in Türkiye, and accordingly, the use of silage machines has been expanding. According to the 2024 statistics, there were a total of 45031 silage machines in Türkiye, consisting of 36760 maize silage harvesters and 8271 forage silage harvesters (TOB, 2025).

Silage harvesters are classified into three groups based on their chopping mechanisms: flail-type, disc-type, and drum-type choppers. Flail-type forage harvesters are machines equipped with horizontally rotating knives that chop the plant material through impact without any feeding mechanism. In principle, the crop is cut, fragmented, and then the chopped material is conveyed to the carrier through the discharge channel. These types of machines have two major disadvantages. The first is the non-uniformity of the obtained chop length, where only about 25–35% of the chopped material falls within the desired length range. The second disadvantage is the high power requirement. The energy required in flail-type forage harvesters is used for fragmenting the crop, moving the chopped material within the chopping unit, and transporting the product to the carrier through ventilation effects (Kanafojski and Karwowski, 1976).

For flail-type forage harvesters, the appropriate selection of design parameters such as knife geometry (thickness, knife rake angle, and knife bevel angle), diameter of the chopping unit, knife peripheral speed, and counter-knife position is essential to achieve the desired chop length and optimum energy consumption. In addition, the type of crop, stem thickness,

moisture content, plant inclination angle, maturity stage, and plant height also affect both chop length and energy consumption (Kepner et al. 1987; Persson 1987). Chattopadhyay and Pandey (1999) studied the cutting energy of sorghum stalks at the seeding and harvesting stages and found that the cutting energy consumption of stalks at the seeding stage was 5–12% higher than that at the harvesting stage. They also reported that increasing the knife peripheral speed from 20 m/s to 60 m/s increased the specific cutting energy consumption by 3–4 times, whereas increasing the knife rake angle from 20° to 60° (at constant cutting speed) reduced the specific cutting energy consumption by 25–30%. In a subsequent study, Chattopadhyay and Pandey (2001) examined the effects of knife shape and knife peripheral speed on the conveying of chopped forage through the discharge channel. They found that the knife bevel angle had no significant effect on the throwing distance of the chopped material. The air speed at the outlet of the discharge channel increased logarithmically with knife peripheral speed, but decreased linearly with an increase in knife rake angle. When the knife rake angle increased from 20° to 60°, the throwing distance decreased by 20–40%, whereas increasing the knife peripheral speed from 20 m/s to 60 m/s increased the throwing distance by 65–95%. They determined that the optimum knife peripheral speed, knife rake angle, and knife bevel angle were 40 m/s, 39°, and 30°, respectively. Godeša (2004) developed a mathematical model to determine the minimum cutting speed of knives during the harvesting of leaves using a flail-type forage harvester. The model was based on parameters such as stem height, cutting height, physical properties of the material to be cut, and the bending moment.

In this study, the objective was to determine the combination of the number of circular knives on the same plane ***(nkp)*** and knife peripheral speed ***(kps)*** that would increase the proportion of suitable chop lengths for silage while reducing energy consumption during maize chopping with a flail-type forage harvesters silage unit. For this purpose, under a constant feeding speed, the effects of the ***nkp*** and the ***kps*** on chop length, specific cutting energy consumption ***(scec),*** and specific total energy consumption ***(stec)*** were investigated.

MATERIALS AND METHODS

Materials

The experiments were conducted using a flail-type forage harvester and a feeding unit specifically manufactured for experimental purposes (Figure 1a). The chopping unit was equipped with two drums, divided into 45° and 60° segments (Figure 1b). The chopping knives, which were mounted on the drums, were made of high-carbon steel (St 60) with a width of 80 mm and a thickness of 8 mm. Knives with a rake angle of 40° and a bevel angle of 30° were used in the experiments.

In the study, hybrid maize (RX 9292 dent maize variety) was used as the plant material. The torque values of the chopping unit were measured using a UMV 2000 model torque sensor and analyzer with an input voltage of 115–230 V and a frequency of 50–60 Hz. To obtain different ***kps*** in the chopping unit, the drum rotational speed was adjusted using a frequency converter operating at an input voltage of 380–480 V (±10%) and a frequency of 50–60 Hz (±5%).

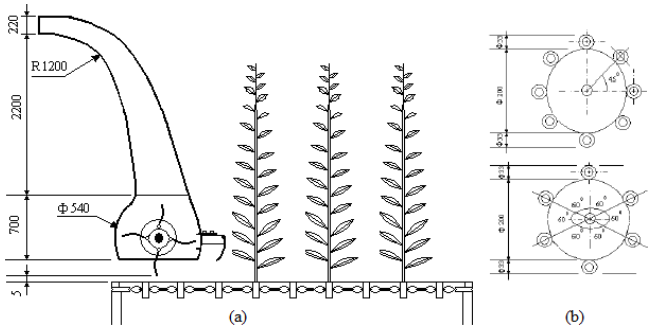


Figure 1. (a) Flail-type forage harvesters and feeding unit, (b) Drums.

Methods

The experiments were conducted using four different ***nkp*** (1, 2, 3, and 4) and six different ***kps*** (20, 25, 30, 35, 40, and 45 m/s). For silage harvester operations, an optimum forward speed of approximately 3 km/h is recommended (Akıncı and Çanakçı, 2000). Based on this recommendation, maize stalks were conveyed to the chopping unit at a feeding speed of 3.3 km/h. The moisture content of the maize stalks was determined by drying the collected samples in an oven until a constant weight was achieved and calculated on a wet basis. The chopping knives were arranged on the drums in a helical pattern, with each knife overlapping the next by 20 mm in their horizontal projections. The circular arrangement of ***nkp*** is shown in Figure 2.

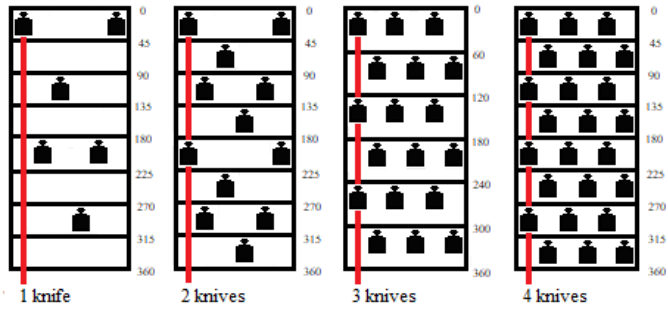


Figure 2. Arrangement of knives on the drum in the chopping unit.

To determine the energy consumption of the chopping unit, a torque sensor was connected to the power unit. For each treatment, the machine's power consumption was calculated using the torque values obtained and the following equation (Saral and Avcıoğlu, 2002).

$$N = M_d.n/9550 \quad (1)$$

Where, N: power (kW), M_d: torque (Nm), n: rotation speed (min^{-1}).

During chopping, the power values measured in the chopping unit were divided by the amount of dry matter chopped per unit time to determine ***stec***. The ***stec*** was calculated using the following equation (Persson, 1987).

$$P = N_T/Q \quad (2)$$

*Where, P: **stec** (kWh/t), N_T: total power requirement (kW), Q: capacity (t/h).*

To determine ***scec***, the power required for idle operation was subtracted from the total power requirement of the chopping unit, and the resulting values were divided by the amount of material chopped per unit time. The ***scec*** consumption was calculated using the following equation (Persson, 1987).

$$p = N_S/Q \quad (3)$$

*Where, p: **scec** (kWh/t), N: power required (kW), Q: Capacity (t/h).*

The chopped material ejected from the discharge channel of the chopping unit was subjected to particle size analysis. For this purpose, a measurement scale was established, and manual size analysis was conducted (Persson, 1987). The geometric mean chop length values, characterizing the length distribution of the samples and based on a log-normal distribution, were calculated using the following equations (Baker and Herrman, 2002).

$$d_{gw} = log^{-1}\left[\sum_{i=1}^{n} W_i \, log\bar{d}_\iota \Big/ \sum_{i=1}^{n} W_i\right] \quad (4)$$

Where, d_{gw}: geometric mean (mm), W_i : weight of chopped material on the i-th sieve (g), d_i : geometric mean length of the material retained on the i-th sieve (mm).

$$d_i = \sqrt{(d_u/d_0)} \quad (5)$$

Where, d_u: aperture of the i-th sieve that passes the chopped material (mm), d_0: aperture of the i-th sieve that does not pass the chopped material (mm).

The data obtained in the study were analyzed using the SPSS statistical software package, based on a randomized complete block design, and compared using the Duncan multiple range test. Furthermore, regression analyses were performed to determine the effects of ***kps*** and the ***nkp*** on ***scec*** and ***stec***.

RESULTS

Chop Length

The changes in chop length values obtained from the experiments, depending on ***kps*** and ***nkp***, are presented in Table 1. The results of the analysis of variance indicated that these factors had a highly significant effect (P<0.01) on the chop length of maize.

Accordingly, for all ***nkp***, increasing ***kps*** decreased the maize chop length. Similarly, increasing the ***nkp*** caused a reduction in chop length at all knife peripheral speeds.

Table 1. Variation of chopping length depending on *kps* and *nkp*

kps (m/s)	***nkp***				Average
	1	2	3	4	
20	188.4	149.8	158.2	174.2	167.7 A
25	148.1	136.3	121.1	118.3	131.0 B
30	140.3	133.9	134.0	108.1	129.1 B
35	122.6	83.0	100.8	76.9	95.8 C
40	89.0	92.7	85.6	67.4	83.7 CD
45	83.5	79.9	73.8	65.1	75.6 D
Average	128.7 A	112.6 B	112.2 B	101.7 B	

"There is no significant difference among the data indicated by the same capital letter at P<0.01."

However, as shown in Table 1, increasing ***kps*** from 20 m/s to 25 m/s (5 m/s increment) resulted in a highly significant decrease (P<0.01) in average chop length, from 167.7 mm to 131.0 mm, respectively. At ***kps*** above 25 m/s, the decrease in average chop length was highly significant (P<0.01) when the speed was increased to 35 m/s (131.0 mm for 25 m/s, 95.8 mm for 35 m/s).

The effect of the number of circular knives on the average chop length was highly significant (P<0.01) when the number of knives increased from 1 to 2 (128.7 mm for 1 knife, 112.6 mm for 2 knives). However, increasing the number of knives beyond 2 did not result in a statistically significant reduction in average chop length.

Specific Cutting Energy Consumption

The changes in ***scec*** values obtained from the experiments, depending on ***kps*** and ***nkp***, are presented in Figure 3. Results of the regression analysis indicated that variations in ***scec*** were dependent on the interactive effects of ***kps*** and ***nkp***.

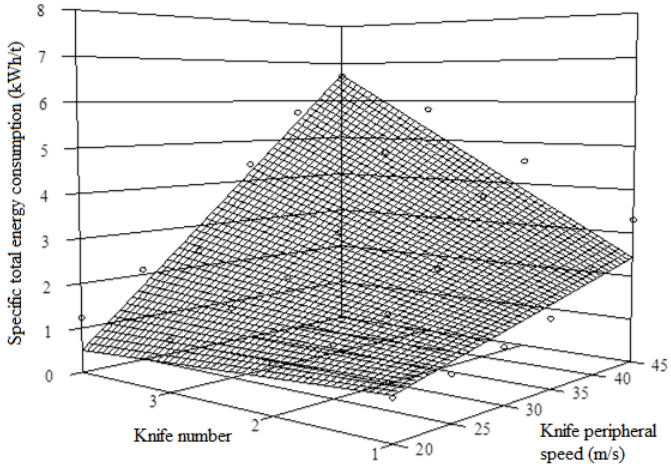


Figure 3. Changes in *scec* depending on *kps* and *nkp*. *The regression equation was developed for scec (kWh/t) as a function of nkp and kps (m/s) is;* $scec = 0.062\ (kps)(nkp) - 1.368\ (nkp) + 1.009$ $R^2 = 0.93;\ n = 24; SE: 0.004^{*},\ 0.15^{**}, 0.22^{**}\ (^{**}P < 0.01;\ ^{*}P < 0.05)$.

As seen in Figure 3, ***scec*** increased with increasing knife peripheral speed. However, the rate of increase in ***scec*** was significantly influenced by ***nkp***. In particular, at knife peripheral speeds of 40 and 45 m/s, ***scec*** increased sharply with an increase in the number of circular knives.

Specific Total Energy Consumption

The changes in ***stec*** values, depending on ***kps*** and ***nkp***, are shown in Figure 4. Regression analysis indicated that variations in ***stec*** were also dependent on the interactive effects of ***kps*** and the number of circular knives.

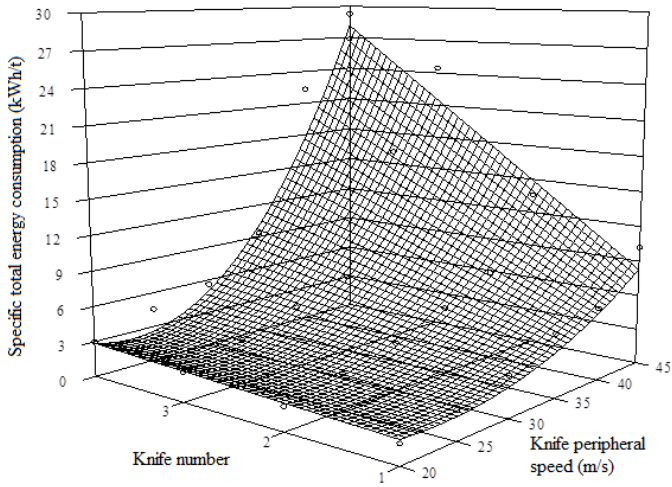


Figure 4. Changes in *stec* depending on *kps* and *nkp*. *The regression equation was developed for stec (kWh/t) as a function of nkp and kps (m/s) is;*

$$stec = 0.013\,(kps^2)(nkp) - 0.613\,(kps)(nkp) + 7.25\,(nkp) + 1.63$$

$R^2 = 0.96, n = 24;\ SE: 0.006^{*}, 0.43^{**}, 6.78^{**}, 2.77^{*}\ (^{**}P < 0.01;\ ^{*}P < 0.05)$.

As shown in Figure 4, ***stec*** increased with increasing knife peripheral speed. Moreover, the rate of increase in ***stec*** was significantly affected by ***nkp***. As observed, up to a ***kps*** of 35 m/s, the increase in ***stec*** due to the number of circular knives was relatively moderate. However, at 40 and 45 m/s, especially when the number of circular knives was 3 or 4, the increase became considerably pronounced.

DISCUSSION AND CONCLUSION

In the harvesting of silage maize using a flail-type forage harvester, an increase in ***kps*** and the ***nkp*** led to a reduction in the average chop length. For all ***nkp***, increasing the ***kps*** above 40 m/s did not result in a statistically significant further decrease in average chop length. Similarly, increasing the number of circular knives from 2 to 3 did not significantly reduce the average chop length. Accordingly, the average chop length of 92.7 mm was achieved at a ***kps*** of 40 m/s with a 2-knife arrangement. Ayık (1997) reported that the ***kps*** of flail-type forage harvesters range between 35–40 m/s. Özemir and Kurtay (1977) suggested that, for facilitating anaerobic storage of silage materials and easier handling in silos, a theoretical chop length of 12.7–19.05

mm is sufficient. Considering that the average chop length obtained at a ***kps*** of 40 $m \cdot s^{-1}$ with a single knife on ***nkp*** was 89.0 mm, the 2-knife arrangement produced a value quite close to this.

Both ***scec*** and ***stec*** increased with increasing knife peripheral speed. However, the rate of increase in these energy values was significantly influenced by ***nkp***. Accordingly, the minimum average chop length (statistically significant) was achieved at a ***kps*** of 40 m/s and a 2-knife arrangement, with a ***scec*** of 3.79 kWh/t. Under the same knife speed, a single-knife arrangement resulted in a ***scec*** of 2.35 kWh/t, indicating an approximate 61% increase in ***scec*** when using the 2-knife arrangement.

Considering the idle power requirements of the flail-type forage harvesters, the ***stec*** at 40 m/s and a 2-knife arrangement was 7.57 kWh/t, which is approximately 24% higher than that of the single-knife arrangement at the same knife speed (6.08 kWh/t). This increase is a result of enhanced ventilation effects caused by the greater number of knives. However, when using a single knife, increasing the ***kps*** to 45 m/s reduced the average chop length to 83.5 mm without a statistically significant difference, while the ***stec*** reached 10.19 kWh/t. From a silage technique perspective, where minimizing average chop length is crucial, this increase in energy consumption can be considered negligible.

In conclusion, the optimal average chop length (92.7 mm) was obtained at a ***kps*** of 40 m/s with 2 ***nkp***. In this configuration, the ***scec*** was 3.79 kWh/t, and the ***stec*** was 7.57 kWh/t.

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Use of Digital Farming in Plant Production

Cenk PAŞA[1]

1- Dr., Balıkesir Üniversitesi, Altınoluk Meslek Yüksekokulu, Bitkisel ve Hayvansal Üretim Bölümü, cpasa@balikesir.edu.tr, ORCID No: 0000-0002-6125-9767.

ABSTRACT

Digital agriculture is a system that enhances productivity in agriculture, soil, and crop management while minimizing environmental damage and enabling more economical use of resources. Recent global challenges have brought the importance of agriculture back to the forefront. These challenges include pandemics, rural-to-urban migration, climate change, a growing world population, shrinking agricultural land, structural soil degradation, the non-agricultural use of land, an aging rural population, and increasing food demand and food security concerns. The rising labour costs in agriculture, the physical challenges of farming, and the repetitive nature of agricultural tasks have driven an increase in mechatronic and robotic applications in the sector. These applications not only enhance efficiency in agricultural production but also provide social and environmental benefits. For instance, robotic weeding applications and precision spraying systems reduce the use of pesticides and herbicides, directly contributing to a positive environmental impact. Artificial intelligence has recently become widely utilized in agriculture. The agricultural sector is increasingly turning to AI technologies to cultivate healthier crops, manage pests, monitor soil and growing conditions, analyse data for farmers, and optimize various management activities within the food supply chain. In this study, the necessity and application areas of digital agriculture in plant production have been examined.

Keywords – Digital Agriculture, Plant Production, Technology, Artificial Intelligence.

INTRODUCTION

The continuous growth of the world population also leads to an increasing demand for food. As the global population continues to rise in the coming years, the demand for food will escalate even further. Meeting this growing demand requires the adoption of more efficient and sustainable methods in the agricultural sector (Özdemir and Ürüşan, 2023). The way to feeding a rapidly expanding population lies in increasing plant production. However, efficiency in plant production is influenced by various social, environmental and economic factors. Sustainability increases in production can only be achieved by maintaining a balance among these factors (Tuğay 2012). Similarly, identifying the factors that limit production is essential for developing accurate solutions and achieving the desired improvements in yield. To ensure the sustainability of the agriculture sector and food security, a serious of measures should be implemented. These measures should include promoting efficient agriculture practices, optimizing resource use, improving water management, protecting soil health, adopting climate-

resilient farming techniques, and integrating innovative agricultural technologies (Gupta et al., 2020).

The first revolution in the agricultural sector, known as Agriculture 1.0, was characterized by high labor intensity and low efficiency. In the mid-20th century, the Green Revolution, referred to as Agriculture 2.0, began. During this period, machines that reduced production costs were developed, and the use of fertilizers and pesticides increased. By the late 20th century, the transition to Agriculture 3.0—also known as precision agriculture—took place. This era saw advancements in GPS technology and the implementation of Variable Rate Application (VRA) systems in harvesters, allowing for improved monitoring and management of the fertilization process (Çilesiz and Karaköy, 2022). After 2011, an industrial transformation was announced, first referred to as Industry 4.0 in Germany. This revolution marked the integration of information technologies with the industrial sector, enabling maximum production efficiency through computer-integrated systems and the emergence of artificial intelligence as a key component. A parallel transformation began in agriculture, mirroring the advancements seen in Industry 4.0. As a result, the era of smart farming—known as Agriculture 4.0—emerged (Hammam and Mohamed, 2020; Said et al., 2020).

Smart agricultural applications provide solutions aimed at increasing productivity, optimizing resource use, and enhancing agricultural processes through technology. Traditionally, agriculture has been characterized by manual operations such as fieldwork, irrigation, fertilization, and harvesting. However, with the advent of the digital age, the sector is rapidly moving toward digitalization. Smart agricultural applications offer farmers new opportunities to make agricultural processes more efficient, precise, and sustainable (Rajasekaran and Anandamurugan, 2019).

Producers are compelled to seek new solutions due to labor shortages, strict regulations, a growing global population, and a declining number of farmers. Today, technologies such as the Internet of Things (IoT), Big Data and Analytics, Artificial Intelligence (AI), and Machine Learning (ML) are being integrated into nearly every sector. Research and development efforts are ongoing to leverage AI in agricultural production to enhance both the quality and quantity of agricultural products (Jha et al., 2019; Smith, 2018). Farmers can also utilize ML as part of precision agriculture management, applying pesticides based on timing, location, and affected crops. Accurately detecting and classifying crop quality traits is essential for increasing market value and reducing waste. Machines can analyze data to identify and highlight new traits that significantly contribute to crop quality. Water management plays a crucial role in maintaining agricultural, climatic, and hydrological balance. ML-based applications facilitate more efficient irrigation system management on a daily, weekly, or monthly basis (Waleed et al., 2020; Eli-Chukwu, 2009).

Today, AI is rapidly evolving. With advancements in computing power and the increasing adoption of cloud technologies, more sectors of the global economy are beginning to leverage AI. Agriculture is among the industries benefiting from these advancements. Whether in weed control, determining the optimal time for harvesting, monitoring soil and crop health, or predicting yields, AI and machine learning have been tested as development tools across various industries over the past decade. However, it has only recently become evident that AI can significantly enhance agricultural decision-making (Vyas et al., 2022; Bhardwaj et al., 2021).

Artificial Intelligence

Artificial intelligence is an interdisciplinary field of study focused on replicating human intelligence in robots that mimic human behaviors, including cognition, learning, and problem-solving (Javaid et al., 2023).

The foundation of artificial intelligence lies in the assumption that human intelligence can be defined in a way that enables computers to replicate it and perform tasks of various complexities. Learning, reasoning, and perception are the primary goals of artificial intelligence. AI has a significant impact across all fields, with every industry striving to use intelligent machines to automate specific tasks. This is achieved by defining human intelligence in a manner that allows machines to comprehend and replicate it. Furthermore, AI technology in agriculture has the potential to revolutionize the sector. It can perform tasks ranging from simple to complex. The purpose of AI systems is to learn, reason, and perceive, aiding in the automation of tasks across various industries. The use of intelligent machines simplifies a wide range of tasks (Jung et al., 2021; Javaid et al., 2022).

AI technology can assist producers in increasing yields by helping them select appropriate plant varieties, adopt improved soil and nutrient management practices, manage pests and diseases, predict crop production, and forecast crop prices. AI leverages deep learning, robotics, the Internet of Things, image processing, artificial neural networks, wireless sensor networks (WSNs), machine learning, and other advanced methods to tackle agricultural challenges. These AI technologies now enable producers to monitor real-time data, such as meteorological and soil conditions (Liu, 2020; Ayed and Hanana, 2021). Thanks to AI, agriculture can benefit in various ways, including higher productivity, improved quality, more efficient resource use, better control of diseases and pests, enhanced human health and food safety, environmental sustainability, data-driven insights, adaptation to climate change, remote monitoring and control, and sectoral development (Javaid et al., 2023).

Digital Agriculture Applications

It is well-established that the use of satellite technologies, agricultural robots, automated steering systems, drones, sensors, and other technologies reflecting Industry 4.0 in agriculture leads to input savings. Farmers can save time and money by remotely monitoring certain tasks without physically going to the field (Şahin, 2022). Furthermore, previous studies have indicated that farmers can take early precautions based on the results obtained from data analysis.

Thanks to the Internet of Things, robots, drones, sensors, and satellite technologies, the temperature and humidity of both the air and soil can be measured, and the water requirements of plants can be determined. Farmers save time, water, and money by performing tasks remotely, without having to visit their fields. Additionally, they can take preventative measures by accessing weather forecasts (Üstün, 2021).

There are various ways in which digital technology can be applied in agriculture to ensure proper implementation:

Sensors: With sensors used in agriculture, information such as soil moisture, soil temperature, soil pH, and EC value, fertilizer adequacy are measured, and the data is examined with data analytics software and finalized with artificial intelligence and presented to producers (Yılmazer and Tunalıoğlu, 2024).

Drone and Satellite Data: Detailed mapping of agricultural areas enables the analysis of field topography, plant density, moisture levels, and other critical parameters. Information such as plant density, productivity, and water availability in the field is collected and organized using drones and satellites. Additionally, advanced sensors and targeted spraying systems in drones can apply precise amounts of pesticides to specific areas, effectively combating diseases and pests. Equipped with high-resolution cameras, drones are used to monitor crops and assess their health status. Early detection of factors such as plant growth conditions, disease symptoms, or pest infestations can enhance efficiency in agricultural production and optimize intervention processes (Özdemir and Ürüşan, 2023; Çakmakçı and Çakmakçı, 2023).

Data Analytics: Agricultural data is analysed using data analytics software. These software solutions enable operations such as soil analysis, plant analysis, monitoring plant phenological development stages, managing water and fertilizer usage, and detecting diseases and pests.

Machine Learning: Machine learning enhances the efficiency of agricultural applications and simplifies data interpretation. Agricultural algorithms make it possible to determine plant water requirements, manage fertilizer use, identify diseases and pests, and conduct soil analysis.

Additionally, the benefits of digital agriculture in plant production technology include:

- Enhancing the quality and health of agricultural products,
- Predicting plant diseases and pest infestations,
- Improving productivity for producers,
- Utilizing driverless tractors and autonomous agricultural vehicles,
- Monitoring plant and soil conditions,
- Reducing waste,
- Identifying soil deficiencies,
- Determining optimal planting locations for specific crops,
- Managing water resources efficiently.

Strengths and Weaknesses of Using Artificial Intelligence in Agriculture

Strengths

One of the key strengths of artificial intelligence in agriculture is its ability to increase productivity and efficiency. AI-powered systems can automate labor-intensive tasks such as planting, maintenance, sorting, and harvesting, enabling these activities to be carried out more precisely and on time. By leveraging machine learning algorithms and computer vision techniques, AI-powered technologies can accurately monitor crop development, detect pests and diseases, and make data-driven decisions to optimize resource allocation. This automation and data-driven approach has the potential to significantly increase yields, reduce waste, and contribute to increased agricultural productivity. Another significant strength of artificial intelligence in agriculture is its role in precision farming and resource management. AI-based systems can leverage a wide range of sensor data, including soil moisture, temperature, and weather conditions, to optimize irrigation and fertilization strategies. AI precisely monitors key variables in crop cultivation, making data-driven adjustments. This enables applications aimed at increasing the yield and quality of agricultural products while reducing the consumption of water and nutrients essential for plant growth. This precision-focused approach not only improves the efficiency of agricultural practices but also contributes to sustainability in agriculture (Anbarasan, 2022; Eli-Chukwu, 2019).

AI-powered autonomous systems and robotics technologies are improving the process by automating many agricultural activities such as planting, spraying, and harvesting (Lakshmi and Corbett, 2020; Ikrang et al. 2022). This automation provides increased yield and production with minimal input use (Mahmoud, 2022), while also offering significant contributions such as improving the quality of agricultural products, ensuring food security, conserving natural resources, and supporting sustainable agriculture (Sharma et al., 2023; Cosmin, 2011).

AI-powered systems enable real-time monitoring and early detection of pests and diseases, allowing for location-based agricultural control (Fountas et al. 2020; Mahibha and Balasubramanian, 2023). This minimizes

the use of agricultural pesticides and ensures optimal pesticide application only on target surfaces (Ryan et al., 2023; Kumar et al. 2017). These systems provide effective, targeted, and timely interventions, protecting the health of agricultural products. It also minimizes negative impacts on human health by reducing the use of agricultural pesticides.

The strengths of artificial intelligence in agriculture, by increasing productivity, optimizing resource management, and improving the quality of agricultural outputs, mean that AI-driven solutions are poised to play a significant role in addressing the pressing challenges facing the agricultural sector, such as food security and environmental sustainability. As the integration of AI into agriculture continues to evolve, these strengths are likely to become even more pronounced, paving the way for a more efficient, sustainable, and technologically advanced agricultural environment.

Weaknesses

The significant initial investment costs and technological infrastructure needs are the main drawbacks of artificial intelligence (Anbarasan, 2022; Eli Chukwu, 2019). Drones, sensor networks, and autonomous tractors are examples of AI-powered systems that may need a large initial financial outlay to implement (Mahmoud, 2022). For small farmers, these expenses provide a significant challenge (Lakshmi and Corbett, 2020).

Technology dependency and the potential for job loss are other significant weaknesses (Sharma et al., 2023; Ikrang et al., 2022). As AI-powered automation and robotics replace manual, labor-intensive tasks, job loss risks will arise, particularly for agricultural workers engaged in activities such as planting, harvesting, and spraying, significantly increasing potential unemployment dependent on the agricultural sector (Fountas et al., 2020; Mahiba and Balasubramanian, 2023). Increased technological dependency may cause anxiety and resistance among farmers and agricultural communities, who are concerned about the long-term impacts on employment and the future of traditional farming practices (Ryan et al., 2023; Kumar et al., 2017).

Concerns about data security and privacy that arise when artificial intelligence is used can be emphasized (Jerhammre et al., 2022; Issa et al., 2022; Mesias-Ruiz et al., 2023). Concerns about data ownership, privacy, and the possibility of misuse or unauthorized access arise when AI-powered systems gather and process vast amounts of agricultural data resulting from soil composition, weather variations, yield variations, area variations, and plant characteristics (Liakos et al., 2018).

Strong data management systems and security measures are required to allay these worries and enable farmers to employ AI technologies (Balaska et al., 2023; Marco-Detchart et al., 2024).

The weaknesses associated with artificial intelligence in agriculture have highlighted the need for a comprehensive and strategic approach to integrating this transformative technology. Addressing financial barriers, job loss concerns, and data privacy issues will be crucial in facilitating the widespread adoption of AI in the agricultural sector (Mark, 2019; Sumangala, 2022).

CONCLUSION

Agriculture is a vital and strategic sector that plays a key role in strengthening national economies, reducing poverty, meeting food demand, enhancing societal development, contributing to national income and employment, and improving social well-being. Scientific and technological advancements are more crucial than ever to address current and future challenges in agriculture and to enhance productivity. By developing both existing and emerging technologies, agricultural processes can be made more efficient, contributing to high-quality and sustainable food production. These advancements can improve yield and quality, reduce costs, mitigate soil salinity, enhance precision irrigation and plant nutrient use efficiency, and minimize environmental pollution caused by chemical fertilizers and pesticides. The advancement of agricultural technologies will encourage producers to make new investments, embrace innovation, and strengthen their resilience. In today's world, global climate change and population growth pose significant challenges to accessing healthy and sufficient food. The implementation of digital agricultural practices is expected to improve yield, quality, and sustainability, addressing these pressing concerns.

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Weed-Induced Losses in Pakistan: Economic Liability, Herbicide Reliance and Sustainable Solutions

Haroon KHAN[1*]
Ömer Süha USLU[2]
Shah Alam KHAN[3]
Osman GEDİK[4]

[1]The University of Agriculture, Faculty of Crop Protection, Department of Weed Science & Botany, Peshawar, Pakistan
haroonkhan@aup.edu.pk ORCID ID: https://orcid.org/0000-0001-6089-9407
[2]Kahramanmaraş Sütçü İmam University, Agriculture Faculty, Field Crops Department, Kahramanmaraş, Türkiye.
suhauslu@ksu.edu.tr ORCID ID: https://orcid.org/0000-0003-0858-0305
[3]The University of Agriculture, Faculty of Crop Protection, Department of Plant Protection, Peshawar, Pakistan.
profkhansa69@aup.edu.pk https://orcid.org/0000-0003-2510-0326
[4]Kahramanmaraş Sütçü İmam University, Agriculture Faculty, Field Crops Department, Kahramanmaraş, Türkiye.
ogedik@ksu.edu.tr ORCID ID: https://orcid.org/0000-0002-4816-3154
*Corresponding author email: haroonkhan@aup.edu.pk

ABSTRACT

Weeds have posed a significant biotic limitation to our agriculture, causing significant damage in terms of loss of yield, reduced profitability and aggravating our growing dependency on herbicides. The resultant excessive usage of herbicides is provoking herbicide resistance, environmental pollution, as well as severe human health hazards. There are three main problems that this review will discuss: (1) the economic cost of the loss caused by weeds in Pakistan; (2) our reliance on herbicides and their associated risk and related problems; and (3) adaptation of sustainable weed management strategies instead of herbicides, which should be applied in the agro-ecological situation in Pakistan. The amount of national level yield lost through infestation of weeds and the financial effects of the same on the major crops and the trend of the herbicides imports and the resistance development, it becomes clear that the major portion of the yield is lost by the infestation of the weeds and on the other hand the import of herbicides is another portion of the hard cash that is a huge burden on credit based and fragile economy of the country. It is examined through the prism of sustainable agriculture that integrated weed management (IWM) approaches, such as cultural, mechanical, biological, and precision technologies, are the new cry of the day as opposed to herbicides. The case studies and international best practices are introduced to provide information for the national policy. A combination of weed control approaches with a basis on farmer education, research and development, policy redesigning, and climate-sensitive solutions is urgently needed in Pakistan regarding food security and environmental well-being.

Keywords: Weeds, Herbicide Resistance, Integrated Weed Management, Sustainable Agriculture, Food Security.

INTRODUCTION

Importance of Agriculture in Pakistan's Economy

The sector of agriculture plays a significant role in the Pakistani economy because it makes up about 23% of the domestic Gross Domestic Product (GDP) and employs nearly 37.4% of the total population, which is the highest among all sectors (PBS, 2023). It is a major source of food security, generation of livelihood, and industrial growth, especially as it supplies raw materials to most sectors of industrialized countries, like textiles, sugar, and leather.

Such major crops as wheat, rice, sugarcane, cotton, and maize are not only required to serve the domestic market but also for export. During 2022-23, agricultural exports comprised approximately 19% of total export

earnings, with rice and cotton being the highest contributors to total exports (SBP, 2023). The livestock sub-sector, comprising more than 60% of agricultural value addition, sustains millions of small-scale farmers and contributes a lot to the assurance of the rural livelihoods (MNFSR, 2023).

Since more than 65% of the Pakistani population resides in rural regions, it is a key economic activity, as well as a key poverty alleviation and rural development instrument (FAO, 2022). Nevertheless, the industry is facing more pressure, including climatic changes, water shortages, attacks of pests and diseases, and losses in yields caused by weeds. These demands require the transformation to climate-smart and sustainable agricultural technologies to increase production and resilience.

One of the worst biotic limitations in crop production in Pakistan, as well as other parts of the world, includes weeds. Such undesired plants directly compete with crops in terms of light, water, nutrients, and space, causing a drastic yield and quality decrease of the produce. In most cropping systems, the loss of yields to weeds is between 25-40% and in some situations, it is over 80-90% should they be left unchecked (Oerke, 2006; Chauhan, 2020), as in the case of onion or any less competitive crop.

Weeds are unlike insect pests or diseases; they do not occur only during the growing season, and their effect is felt immediately the seed germinates. The other weed species have allele-chemicals that suppress the growth of crops, and some contain pests and pathogens that serve as alternative hosts. This complicates and increases the levels of weed management in comparison with the other biotic stresses.

In Pakistan, weed control is a significant problem because of the toxicity of major crops such as wheat, rice, maize, and cotton to dominant weed species like *Phalaris minor, Convolvulus arvensis, Chenopodium album, Cyperus rotundus, Cirsium arvense, Silybum marianum, Echichloa crus-galli, Trianthma partulacastrum, Poa annua, Sorghum halepense* and the invasive *Parthenium hysterophorus* (Javaid and Tanveer, 2021).

These weeds lower the efficiency of photosynthesis, interfere with the uptake of nutrients and raise production costs due to the necessity to hire extra labor, herbicides, and machinery. In addition, aquatic invasive species such as *Eichornia crassipes, Typha Latifolia and Alternanthera philoxeroides* intrudes water locations, blocks waterways, and degrade the quality and the biodiversity of aquatic systems. There are also some parasitic weeds such as *Orobanhe* spp, which are common in Tobacco, mustard, and clovers and lead to massive losses in crops.

On the other hand, weeds have a greater financial impact than just reducing yield. It includes decreased harvest productivity, produce contamination, degraded soil, and higher greenhouse gas emissions from mechanical tillage or repeated herbicide applications. The harm posed by weeds is increasing as herbicide resistance spreads, making traditional weed control methods less effective (Heap, 2024). Maintaining agricultural profitability, guaranteeing food security, and attaining sustainable crop productivity depend on efficient weed control.

Yield Losses Attributed to Weeds in Pakistan: Statistics and Case Studies

Weeds are among the most economically destructive biotic stressors in agriculture, causing large quantitative and qualitative production losses. Weed-induced losses pose a persistent threat to national food security and farm profitability in Pakistan, where cropping systems are highly diverse and resource inputs are frequently limited. Crop-wise yield losses due to weeds in Pakistan are presented in (Table-1). Total Estimated Loss (All Major Crops): PKR 250–340 billion/year.

Table 1: Crop-Wise Yield Losses Due to Weeds in Pakistan

Crop	Estimated Yield Loss (%)	Estimated Economic Loss (PKR)	Major Weed Species	Key Studies (Reference)
Wheat	20–40%	80–100 billion/year	*Phalaris minor*, *Avena fatua*	Punjab & KP (Tanveer *et al*., 2022)
Rice	30–50%	60–90 billion/year	*Echinochloa crus-galli*, *Cyperus spp.*	Sindh & Southern Punjab (Ali *et al*., 2021)
Maize	25–45%	25–40 billion/year	*Amaranthus spp.*, *Trianthema spp.*	KP & Central Punjab (Nazir *et al*., 2020)
Sugarcane	20–35%	30–50 billion/year	*Cyperus rotundus*, *Parthenium hysterophorus*	Multan, Mardan, Thatta (Shabbir *et al*., 2021)
Cotton	30–45%	40–60 billion/year	*Trianthema portulacastrum*, *Cynodon dactylon*	Bahawalpur, Multan (Khan *et al*., 2019)

General Impact

If no weed management techniques are implemented, the average agricultural yield losses worldwide as a result of weeds are 23% for wheat, 35% for maize, 34% for rice, and 42% for cotton (Oerke, 2006; Chauhan, 2020), While in case of *Cirsium arvense* or *Carthamus oxycantha* the whole crop is abandoned or sold to sheep herders for grazing. Similarly, in case of less competitive crop with small canopy (onion), early slow growth (sugarcane) crops the % losses may be up to 80 % or complete failure of crop. Because of the high frequency of aggressive weed species and restricted availability of efficient integrated weed management (IWM) techniques, the situation in Pakistan is even more worrisome.

National Economic Impact

Weeds compete with crops for nutrients, water, sunlight, and space. Weeds are predicted to cause yearly losses of around PKR 400 billion (~USD 2 billion) worldwide (FAO, 2022). According to a nationwide evaluation by the Pakistan Agricultural Research Council (PARC), weeds cause more than PKR 300 billion (~USD 1 billion) in economic losses each year. This involves not just decreased output, but also additional labor, herbicide expenditures, and lower harvest quality. In some cropping systems, weed control costs 20-25% of total production costs.

Indirect Costs

- Increased Production Expenses
- Labor costs for manual weeding: USD 200–300 million/year (Khan *et al*., 2021).
- Herbicide costs: USD 400 million/year (SBP, 2023).
- Labor: Manual weeding costs $50–100/ha.
- Trade: EU rejections of rice due to pesticide residues.

Besides reducing yields, weeds have indirect costs entailing increased costs in terms of labor when weeding manually as well as spending more money on herbicides and reduced grain quality due to polluted grain. Weed imbalances in provinces are associated with the intensity of cropping, irrigation, and climates. To illustrate, Phalaris minor is the pest that is plaguing wheat in Punjab; Cyperus rotundus is invading rice in Sindh; Parthenium hysterophorus is infesting the territory of Khyber Pakhtunkhwa (FAO, 2022; PARC, 2022).

Regional Disparities

- Punjab: Highest losses due to mono-cropping.
- Sindh: Waterlogging exacerbates weed growth in rice.
- Khyber Pakhtunkhwa: Invasive weeds like Parthenium threaten maize.

National Estimates of Monetary Losses Due to Weeds in Pakistan

Weeds cause great economic losses to our agriculture not only the direct one of decreasing the crop yields but also indirect one of raising the costs of production, decreasing the market quality, and lowering efficiency of the other production means. Though they are important, there is very little nationwide information on the economic damages caused by the use of weed that is either fragmented or old. Nevertheless, different sectoral evaluation, field testing, and institutional reports have reliable estimates of the financial cost of the weeds.

Estimated Annual Economic Losses

Pakistan Agricultural Research Council (PARC) estimates that weeds cause losses of over PKR 300 billion (approximately USD 1 billion) per year in the important crop systems in wheat, rice, maize, cotton and sugarcane (PARC, 2022). These losses stem from:

- Yield reduction (30–50%) due to competition for light, nutrients, and water
- Increased input costs (labor, herbicides, fuel)
- Harvest contamination and post-harvest losses
- Reduced land productivity due to invasive or perennial weed species

Prevalent Weed Species in Major Cropping Systems in Pakistan

In Pakistan, weeds continue to pose a danger to all of the main cropping systems, decreasing potential yields, producing lower-quality products, and raising production costs. Every crop has a unique weed flora that is associated with our cropping patterns, irrigation techniques, soil types, and climate. Developing efficient and crop-specific weed control techniques requires an understanding of the main weed species in important crops.

1. **Wheat:** Wheat is the staple food crop of Pakistan and is highly vulnerable to weed infestation, particularly during early growth stages. Major weeds infesting wheat crop include:
   a. *Phalaris minor* (Canary grass)
   b. *Avena fatua* (Wild oat)
   c. *Chenopodium album* (Bathu)
   d. *Convolvulus arvensis* (Field bindweed)
   e. *Lolium temolentum*
   f. *Cirsium arvense*
   g. *Carthamus oxycantha*

2. **Rice:** Weeds present a major problem in rice production systems, whether transplanted (TPR) or direct seeded (DSR), due to high levels of moisture in the soil. The five most common types of weeds in rice fields are:
   a. *Echinochloa crus-galli*

b. *Cyperus difformis*
c. *Fimbristylis miliacea*
d. *Marsilea quadrifolia*
e. *Monochoria vaginalis*

In DSR systems, grassy weeds, particularly *Echinochloa* spp., tend to dominate weed populations and require the application of integrated weed management techniques to control their growth (Ali et al., 2021).

3. **Maize:** Maize fields are usually infested by both broadleaf and grassy weeds, especially during the early vegetative stage. Prevalent species include:
   a. *Trianthema portulacastrum*
   b. *Echinochloa crus-galli*
   c. *Sorghum halepense*
   d. *Amaranthus viridis*
   e. *Digitaria sanguinalis*
   f. *Cyperus rotundus*

Weed infestation in maize can reduce yield by 20–50%, especially in rainfed zones where weed competition for moisture is severe (Nazir *et al*., 2020).

4. **Sugarcane:** Sugarcane is a long-duration crop, and its wide spacing and slow canopy closure make it susceptible to prolonged weed infestation. Common weeds include:
   a. *Cyperus rotundus*
   b. *Sorghum halepense*
   c. *Parthenium hysterophorus*
   d. *Digitaria sanguinalis*
   e. *Sorghum halepense*
   f. *Convolvulus arvensis*
   g. *Cynodon dactylon*

Some of these species, especially Parthenium hysterophorus, are invasive and allelopathic, significantly hampering cane growth and quality (Shabbir *et al*., 2021).

5. **Cotton:** In cotton, weeds compete throughout the season and interfere with pest control and irrigation. Major weed species are:
   a. *Boerhavia diffusa*
   b. *Euphorbia hirta*
   c. *Cynodon dactylon*
   d. *Trianthema portulacastrum*
   e. *Dactyloctenium aegyptium*

Uncontrolled weed growth can lead to up to 40% yield reduction and complicates the management of cotton-specific insect pests (Khan *et al*., 2019).

Selected Case Studies from Pakistan

1. Wheat in Punjab and Khyber Pakhtunkhwa

According to a 4-year field research carried out in Faisalabad and Peshawar, significant infestations of *Phalaris minor* and *Chenopodium album* were the main cause of the up to 38% reduction in wheat output caused by unmanaged weeds. The effects were exacerbated by insufficient or delayed herbicide treatment (Tanveer *et al*., 2022).

2. Rice (Direct-Seeded) in Sindh

Echinochloa crus-galli and *Cyperus difformis* weed competition caused yield losses of more than 50% in a Sindh research on direct-seeded rice (DSR) systems when early-season weed treatment was not used. Additionally, reports of herbicide resistance in *Echinochloa* were also reported (Ali et al., 2021).

3. Maize in Swat Valley

According to on-farm experiments conducted in the Swat region, *Amaranthus viridis* and *Trianthema portulacastrum* infestations in maize fields resulted in a yield reduction of up to 44%. This was primarily caused by aggressive weed emergence in the early stages of the crop before inadequate canopy closure (Nazir *et al*., 2020).

4. Sugarcane in Multan and Thatta

In a survey undertaken in Multan and Thatta districts, explorers came up with the fact that the yield of sugarcane faced a decrease of 22-35% as a result of prolonged competition with Cyperus rotundus and Parthenium hysterophorus. Many farmers were very much depending on the pre-emergent herbicides as they could not afford the costs of manual weeding and faced penalties in the form of (Shabbir et al., 2021).

5. Cotton in Bahawalpur

The data obtained through surveys conducted in the Bahawalpur division revealed that cotton fields heavily infested with Trianthema portulacastrum suffered yield losses of 42% and faced challenges of delayed maturity and poor boll development (Khan et al., 2019). These losses were aggravated by the fact that improper tillage practices were applied, and irrigation water was insufficient.

Herbicide Market and Indirect Economic Costs

Pakistan spends PKR 12–18 billion annually on herbicide imports (PES, 2023). However, inefficient application, non-target effects, and herbicide resistance often reduce returns on this investment. Indirect economic impacts include:

- ✓ Increased labor costs in manual/mechanical weeding (~PKR 8,000-16,000 ha^{-1})
- ✓ Delayed sowing or replanting due to heavy weed infestations
- ✓ Environmental externalities and soil health degradation

Long-Term Consequences

- Invasive weeds like *Parthenium hysterophorus* and *Sorghum halepense* are expanding rapidly, with long-term implications for land degradation, grazing suppression, and biodiversity loss (Shabbir et al., 2021).
- Weed-induced herbicide resistance is increasing in *Phalaris minor*, *Echinochloa spp.*, and *Cyperus rotundus*, further inflating control costs and complicating future management strategies (Heap, 2024).
- Land and groundwater pollution that affect aquatic ecosystems and drinking water and human and animal health
- Shift in the weeds flora from broadleaf to grassy and from minor weeds to major troublesome weeds depending upon the herbicides applied.

Herbicide Dependency: Trends and Challenges

In excess of 70% of farmers in the country are using chemical herbicides (PIDE, 2021). Imports of herbicides in Pakistan are rising from USD 280 million in 2018 to over USD 520 million in 2023 (SBP, 2023), with glyphosate, paraquat, 2,4-D, and atrazine herbicides in high demand. During the period 2022–2023, herbicides imported from China contributed over 60% of imports in terms of value and approximately 80% in terms of volume (Table 2). Over 70% of farmers in both wheat and rice are exclusively using herbicides. This over-reliance can be attributed to a lack of farm labor and aggressive marketers using non-technical sales incentives based on marketers. Nonetheless, repeated occurrence of herbicides on similar active ingredients has led to herbicide resistance in some target species like Phalaris minor in wheat and Echinochloa crus-galli in rice. In addition, herbicidal residues are evident in Pakistan's soils, ground waters, as well as traded grain.

Problems Arising from Herbicide Dependence

- **Herbicide Resistance:** Continuous use of the same herbicides has led to resistance in *Phalaris minor*, *Conyza spp.*, and *Chenopodium album*.
- **Environmental Pollution:** Residues contaminate soil and water, affecting non-target organisms, including soil microbes and aquatic life.
- **Health Hazards:** Improper handling leads to acute poisoning, skin burns, and chronic diseases in farm workers.
- **Ecological Disruption:** Herbicide overuse disturbs weed-crop ecology, making farming systems more vulnerable to invasive weeds.

Factors Driving Herbicide Imports

- **Currency Depreciation:** PKR devaluation increased costs by 30% (2020–2023).
- **Lack of Local Production:** Only 20% of herbicides are formulated locally.
- **Farmer Preferences:** Quick-fix solutions over labor-intensive weeding.

Socio-Economic Impact of Herbicide Dependency

- **Smallholder Debt:** Farmers spend 15–20% of their income on herbicides (PIDE, 2021).
- **Health Costs:** Pesticide-related illnesses cost USD 50 million/year (WHO, 2022).

Environmental and Health Risks

The ecological and health effects of herbicide misuse are adverse. For instance, a recent research showed that 40% of the groundwater in Punjab was affected by glyphosate (PCRWR, 2022). The side effects included the disappearance of beneficial soil microbes, the decrease in biodiversity, and the contamination of surface water. Annually, pesticide-associated poisoning cases are 20,000 (MOH, 2023), and chronic exposure is related to problems such as cancer, kidney dysfunction, and neurological disorders. The issue is further aggravated by poor enforcement of safety regulations, the presence of illiterate applicators, and the sale of unregistered or iffy products.

Table 2: Herbicide Import Bill of Pakistan (2018–2023)

Year	Import Value (USD Million)	% of Agrochemical Imports	Top Supplier Countries
2018	280	65%	China, USA, Germany
2-019	320	68%	China, USA, Germany
2020	350	70%	China, USA, Germany
2021	420	72%	China, USA, Germany
2022	480	75%	China, USA, Germany, Malaysia
2023	520	78%	China, USA, Germany, Vietnam

Source: State Bank of Pakistan 2023

Knowledge Gaps and Policy Constraints

Pakistan does not have a national weed tracking program, despite the seriousness of the issue. Farmers know very little about safe and efficient weed control, especially when it pertains to handling herbicides, eliminating resistance, and using non-chemical alternatives. Only 30% of farmers receive any training on integrated weed management, and extension assistance is underfunded and dispersed (PARC, 2022). Widespread abuse of restricted or out-of-date herbicides is made possible by regulatory gaps. Indigenous initiatives are hampered by the meager funding for biological control and weed ecology research.

Sustainable Weed Management Solutions

Integrated Weed Management (IWM)

IWM provides a comprehensive, site-specific, eco-friendly, and sustainable plan for weed control. IWM involves various weed control strategies to reduce herbicide dependence and enhance long-term sustainability.

Cultural Practices

- **Crop Rotation:** Breaks weed life cycles and reduces weed seedbanks.
- **Cover Crops and Mulching:** Suppress weeds by shading and allelopathy.
- **Stale Seedbed Technique:** Germinates and eliminates weeds before planting.
- **Row cropping instead of broadcasting**
- **Intercropping to fill the gaps and deprive the weeds from space for growth**

Mechanical and Manual Control

Mechanical approaches such as zero tillage, rotary weeders, and inter-row cultivation can suppress weeds without chemicals. Traditional hand weeding remains effective in smallholder systems. Mechanical weed control can reduce labor needs.

Biological Control

Biological solutions like allelopathy (e.g., sorghum, sunflower residues) and bioherbicides (e.g., *Trichoderma* spp., Mycoherbicides for *Cyperus*) reduce weed pressure sustainably. Use of natural enemies, pathogens, and bio-herbicides like *Alternaria alternata* against *Parthenium*.

Precision Agriculture and ICTs

Precision agriculture tools including drone-assisted spraying, remote sensing, and AI-based weed detection enable targeted interventions and herbicide savings of 30-50%. Drone-based weed detection, GIS mapping, and selective spraying technologies offer site-specific solutions for commercial farms.

Case Studies and Global Best Practices

In Punjab, zero tillage wheat after rice has reduced weed biomass by over 50% while improving soil health. In India, farmer participatory IWM trials have reduced herbicide use by 40% while enhancing yields. China's precision weed control systems integrate drone mapping with variable rate application. Australia's harvest weed seed control systems have delayed resistance development by 8-10 years.

Recommendations for Policy and Practice

- ✓ Develop a comprehensive National Weed Management Strategy: Exploit the synergy of all weed management options by developing a coordinated government policy framework that incorporates the various elements of weed management, including research, extension and regulation.
- ✓ Establish and improve Extension Services that provide farmers training on Integrated Weed Management (IWM) practices and the safe use of herbicides by utilizing public-private partnerships.
- ✓ Expand the funding support to the Universities and Research Institutions for the development of new and innovative Biological Methods & Non-Chemical methods for the reduction of Weeds.
- ✓ Regulate the use of Herbicides - to ensure herbicides are used in accordance with the manufacturer's recommendations and that they do not contain any harmful active ingredients.
- ✓ The Farmer Field Schools (FFS) will provide farmers with the knowledge and skills necessary to manage weeds sustainably, utilizing interactive learning techniques.
- ✓ Develop a National Weeds Surveillance & Management Agency.
- ✓ Increase Import Regulations on Herbicides and Enhance the Packaging of Herbicides.
- ✓ Conduct Research & Development of Bio-Herbicides in-country.
- ✓ Encourage the use of Zero Tillage and Mechanized Weeding Methods

CONCLUSION

In Pakistan, economic and biological threats come from weeds. Weeds alone will cost more than $2 billion a year in terms of direct/indirect economic losses. It costs around $500 million a year to import herbicides into Pakistan. By relying solely on herbicides, many farmers have created herbicide-resistant weed biotypes as well as disrupted ecosystems and created potential environmental hazards for the health of the rural farming population of Pakistan. Ultimately, the use of herbicides to ward off weeds can be eliminated by adopting the holistic principle of Integrated Weed Management (IWM).

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Nanoparticles for Plant Production

Cenk PAŞA[1]

Alper YARDAN [2]

1- Dr., Balıkesir Üniversitesi, Altınoluk Vocational School, Plant and Animal Production Department, cpasa@balikesir.edu.tr, Orcid: 0000-0002-6125-9767.

2- Dr., Balıkesir University, Altınoluk Vocational School, Department of Chemistry and Chemical Processing Technologies, Orcid: 0000-0001-6916-831X .

ABSTRACT

The agricultural sector faces the dual challenge of meeting the escalating food demand of a growing global population while mitigating the environmental footprint of traditional farming practices. Nanotechnology has emerged as a transformative solution to these issues, giving rise to specialized fields such as agro-nanotechnology and phyto-nanotechnology. This chapter provides a comprehensive overview of nanomaterial applications in plant production, ranging from nutrition and protection to monitoring and resource management. Key areas discussed include the development of nano-fertilizers for controlled nutrient release and enhanced efficiency, and the formulation of nano-pesticides and nano-herbicides that offer target-specific delivery with reduced environmental toxicity. Furthermore, the chapter explores the integration of nano-biosensors for real-time crop monitoring (precision agriculture) and the utilization of nanotechnological filtration systems for irrigation water treatment. While highlighting the immense potential for a "minimum input - maximum efficiency" approach, the text also addresses critical considerations regarding material synthesis—including green synthesis routes using endemic flora—and the potential ecotoxicological risks of nanomaterials. Ultimately, this work posits that the strategic and conscious adoption of nanotechnology is essential for achieving sustainable, high-yield agricultural systems.

Keywords: *Agronanotechnology, Nano-fertilizers, Precision Agriculture, Phytonanotechnology, Controlled Release Systems, Green Synthesis, Sustainable Plant Production.*

INTRODUCTION

A vital part of the developing economy is agriculture, and agricultural products—most notably food—can be utilized in a variety of industries to improve the lives of living things. Agricultural regions face a variety of difficulties in the twenty-first century, such as unpredictable climate change, soil contamination from various dangerous environmental pollutants like pesticides and fertilizers, and particularly the growing demand for food brought on by the world's expanding population (Pouratashi and Iravani, 2012). It is estimated that 50% of the world's population will require more food production to meet their needs. On the other hand, growing industrialization, improper contamination or depletion of current water resources, and a decline in forested areas and biological biodiversity are all contributing to the rapid depletion of natural resources (Kang et al., 2009). New methods must be created in order to address these anticipated and predictable issues. Integrating products based on nanomaterials into the system is one of these solutions.

Nanotechnology refers to technologies where at least 50% of natural or manufactured particles have a size between 1-100 nm (one billionth of a meter). Nanotechnology owes its properties to the unique characteristics of nanoparticles (such as high surface-to-volume ratio and high resolution). Therefore, nanoparticles possess high reactivity and efficiency. It has been demonstrated that agricultural goods can be produced, processed, transported, packaged, and handled using nanomaterials (Scott and Chen, 2003; Wiesner et al., 2006; Cinisli et al., 2019). The fact that nanoparticles are used in smaller amounts than other fertilizers is one of the main benefits of employing them in agriculture (Selivanov and Zorin, 2001; Reynolds, 2002; Raikova et al., 2006; Batsmanova et al., 2013; Subramanian et al., 2015).

Because of their unique physicochemical characteristics and enormous surface area-to-volume ratios, nanomaterials have high reactivity and may be readily modified to satisfy growing demand. Numerous industries, including biomedical, biotechnology, engineering, medicine, and healthcare, use nanoscale particles (Leso et al., 2019; Gökdemir et al., 2023). Research on reducing bacterial growth, managing inflammation, and stimulating tissue growth are examples of medical applications (Taylor and Webster, 2011; Seil and Webster, 2012). Many additives, such as gold nanocapsules used in cancer treatment, have been developed recently (Heiligtag and Niederberger, 2013). Nanoparticles, at the forefront of nanotechnology, are being incorporated into various consumer products due to their enormous potential compared to their counterparts (Jeevanandam et al., 2018). Thus, there is no doubt that the food and agriculture industries are interested in these new generation materials due to their distinctive and developing qualities. Numerous studies on seed germination, biotic and abiotic stress conditions in plants, plant development, and growth are using nanoparticles in agriculture (Wang et al., 2016). Phytonanotechnology is the joint field of plant science and nanotechnology, while agronanotechnology is the joint field of agricultural sciences and nanotechnology (Gökdemir et al., 2023). Through target-specific programming and multifunctional capabilities in plants, nanoparticles reduce the use of environmentally hazardous chemicals like pesticides and fertilizers (Nair et al., 2010). Recent research in this domain has expanded beyond traditional nanoparticles to explore the thermodynamic boundaries of particle formation. For instance, studies on endemic Turkish flora, such as *Origanum sipyleum* L. and *Sideritis trojana* Bornm., have demonstrated that plant extracts can drive the synthesis of silver microparticles (AgMPs) through mechanisms like Ostwald ripening and phytochemical bridging (Yardan, 2025a; Yardan, 2025b).

Other nanomaterials, such nanoclay, nanotubes, and nanowires, have special surface chemistry, electrical, and optical characteristics (Yaqoob et al., 2020) that provide them better sensitivity, higher detection limits, and quicker reaction times (Kumbhakar et al., 2014). Fertilization provides

plants with the nutrients they need to grow and develop healthily. According to Solanki et al. (2015), excessive or improper fertilizer application upsets the soil's nitrogen balance and lowers soil fertility, even if fertilizers used in agriculture boost production and quality. By minimizing production expenses to optimize output, eliminating nutrient losses, and using fewer plant protection chemicals, the use of nanomaterials in agriculture seeks to boost yield (Usman et al., 2020). Utilizing nanomaterials in agriculture will help solve current issues. Before using nanomaterial-based products in agriculture, it is essential to look into their levels of toxicity (Chen and Yada, 2011; de Oliveira et al., 2015; Amenta et al., 2015). Despite their many superior properties, nano-fertilizers also have some negative effects. Nano-sized particles pose certain risks to health and the environment. Initial studies on nanomaterials have shown that they cause toxic effects on humans (Cinisli et al., 2019). Nanoparticles can enter the human body, reach all vital organs, and cause damage to tissues. It has been reported that nano-fertilizers also have toxic effects, are a factor in the creation of significant problems for the ecosystem, and that the environmental problems they create are quite difficult to repair (Dağhan, 2017).

Despite these potential risks, the necessity to increase yield dictates that we explore these advanced technologies carefully. By balancing the risks with the immense benefits in efficiency and sustainability, nanotechnology offers a viable path forward. The following sections detail the specific applications of nanoparticles in agriculture, starting with the most fundamental requirement for plant growth: nutrition.

Nanoparticle Infiltration into Plants

There are two ways that nanoparticles can enter a plant: apoplastic and symplastic (Gökdemir et al., 2023). Apoplastic transport takes place in the cell wall, extracellular regions, and beyond the plasma membrane. Along with water and solutes in the cell cytoplasm, symplastic transfer occurs between the pores of the phloem parenchyma and plasmodesmata (Etxeberria et al., 2016; Lv et al., 2019).

The first area that is exposed to nanoparticles is the cell wall of a plant. The cell wall of root tissues is penetrated by nanoparticles or metal ions dissolved from nanoparticles, which combine with pectin-COOH groups to create a complex (Yang et al., 2008).

Stomata, hydathodes, stigmas, and bark are examples of micro-scale exterior surfaces on leaves that can directly absorb nanoparticles put to their surface. Nonetheless, a cuticle layer made of biopolymers covers the surfaces of shoots (Gökdemir et al., 2023). This layer keeps nanoparticles from penetrating the plant by acting as a lipophilic barrier. Nevertheless, it has been demonstrated that nano-TiO2 causes cuticle holes (Larue et al., 2014; Schwab et al., 2016).

The rhizodermis layer's lateral root connections, particularly those close to the root tip, are where nanoparticles are absorbed at the root level, whereas suberin in the upper portions of the root prevents nanoparticles from passing through (Chichiriccò and Poma, 2015).

The Use of Nanoparticles in Agriculture

1. The Effect of Nanoparticles on Abiotic Stress Conditions

In addition to encouraging healthy growth and development, nanoparticles shield plants from abiotic stressors. Salinity, dryness, pH, temperature, and toxicity from minerals and metals are examples of abiotic stressors. In the form of nano-enzymes that can alleviate oxidative stress, nanoparticles have the capacity to replicate the activity of antioxidant enzymes (Sharifi et al., 2020). According to a review of the literature, SiO2 nanoparticles give plants a defensive mechanism against salt stress. Additionally, they have been shown to increase plants' transpiration rate, water consumption efficiency, total chlorophyll, and carbonic anhydrase activity (Siddiqui et al., 2014). It has been discovered that TiO2 inhibits linolenic acid in the electron transport chain and modifies photoreduction activity in plants (Mingyu et al., 2008).

2. Nanopesticides

Chemical mixes used in agriculture to fight pests and diseases that harm plants are known as pesticides. Plant productivity and quality are severely impacted by pests and diseases (Çicek and Nadaroğlu, 2015). A defense mechanism against pests is formed by secondary metabolites released by the plant itself (Sharon, 2010). Despite the advantages of using chemical pesticides to combat illnesses and pests, their toxicity can pose serious risks to human, animal, and environmental health.

Nanotechnological formulations can enhance physicochemical stability, lessen undesirable harmful effects on non-target organisms, and stop microorganisms from degrading the active ingredient (Gogos et al., 2012, Durán and Marcato 2013, Perlatti et al., 2013).

Nanotechnology provides a novel and enhanced approach to the challenging and costly synthesis of safe and effective insecticides (Sasson et al., 2007). In addition to protecting plants from pests, nanotechnology is being used to reduce waste, track plant growth, enhance food quality, and ensure the expansion of food production worldwide (Jampílek and Kělová, 2017). Nano-herbicides, nano-insecticides, nano-nematodes, and nano-fungicides are the most often tested nano-pesticides.

Alumina with a nanostructure is a nanoinsecticide. Nanostructured alumina powder or particles have an insecticidal effect because they adhere to the insect's cuticle layer, upsetting the water balance and raising the ambient humidity. Because of their small size, intrinsic electrical charge,

sorptive richness, and wide surface area, nanoinsecticides have excellent insecticidal efficacy (Stadler et al., 2018).

Because of their long-lasting biological action, nano-pesticides lower the amount of pesticide required, improve contact with the target organism because of their large surface area, and exhibit a deadly effect quickly, all of which help producers financially. Furthermore, using nano-pesticides lessens the harm that pesticide waste does to the environment (Çiçek and Nadaroğlu, 2015; Peshin et al., 2009, Jo et al., 2009, Goswami et al., 2010, Teodoro et al., 2010).

Pests are not the only threat to agricultural yield; invasive plant species also compete for resources. The principles of nano-delivery systems described above are also being adapted to combat weeds more effectively and selectively.

3. Nanoherbicides

In agriculture, weeds significantly reduce both productivity and quality. Herbicides are chemical pesticides used in agriculture to get rid of weeds. Additionally, mechanical and physical weed management techniques are employed. Overuse of herbicides can contaminate agricultural areas and leave residues in the plants that thrive there. There are detrimental consequences on both human and animal health as a result of pesticide residues in the plants cultivated in this area.

For efficient weed management that doesn't leave any harmful residue in the soil, nanoherbicides might be a better, greener option (Pérez-de-Luque, 2017). Weeds may acquire resistance if the same herbicide is used consistently over an extended period of time. When compared to a commercial atrazine formulation, atrazine nanocapsules have demonstrated greater post-emergence herbicide activity in mustard plants (Oliveira et al., 2015). Nanoparticles have been found to lessen the toxicity of herbicides (Grilloa et al., 2014, Kashyap et al., 2015).

While improving chemical inputs (fertilizers, pesticides, and herbicides) is essential, modern precision agriculture requires more than just better materials; it requires accurate information. This brings us to the role of nanotechnology in monitoring agricultural conditions.

4. Nanobiosensors

By conveying nano-sized chemical, biological, and electrical changes to the macro level, nanoparticles which are classified as sensing materials allow for efficient evaluation (Chaudhry et al., 2018). The use of nanobiosensors in agricultural settings is growing daily. They are especially good in monitoring and sensing. Plants have been used to test a variety of nanosensor types, such as plasmonic nanosensors, carbon-based electrochemical nanosensors, nanowire nanosensors, fluorescence resonance energy transfer (FRET) based nanosensors, and antibody nanosensors

(Gökdemir et al., 2023). Abiotic and biotic variables are identified using nanobiosensors. Furthermore, climate change and irrigation system control can be accomplished by integrating GPS technology into the system (Humbal and Pathak, 2023).

Effective monitoring often reveals that water quality is as critical as water quantity. As water resources become scarcer, nanotechnology offers advanced solutions not just for monitoring but for the filtration and treatment of irrigation water.

5. Nano-fertilizers

Plants require macro and micronutrients to grow and develop healthily. Plants obtain these necessary nutrients from existing nutrients in the soil or through chemical fertilization. However, when soil nutrient levels are insufficient or unavailable to the plant, fertilization is often the primary method used to meet these needs. In some cases, excessive and indiscriminate fertilization leads to negative environmental impacts. Furthermore, over fertilization negatively affects the physical, chemical, and biological activity of the soil.

The usage of nanofertilizers is necessary because of these unfavorable environmental circumstances. The study found that humic acid and organic fertilizers were compared with nano-calcium carbonate in peanuts. According to the study, nano-calcium carbonate increased the number, area, dry weight, soluble sugar, and protein content of peanuts at low concentrations (Liu et al., 2009). Tomato plant germination was reported to be positively impacted by SiO_2 nanoparticles (Manzer and Mohamed, 2014; Ramalingam et al., 2015). According to research on the impact of TiO_2 (titanium dioxide) nanoparticles on maize development, these nanoparticles significantly affect growth by increasing light absorption and photo-energy transfer (Lu et al., 2002).

While providing nutrients is the first step in production, protecting the crop from biotic stressors is equally critical. Just as nanotechnology revolutionizes plant feeding, it also offers innovative solutions for plant protection against pests.

CONCLUSION

Nanoparticles are being used more and more in plant growth. Their use in plants must be increased in the future to ensure the sustainability of ecosystems and agriculture. The use of nanoparticles greatly aids in addressing the various issues brought on by growing populations, plant and animal diseases, and climate change. It also increases crop productivity by lowering the need for conventional fertilizers and pesticides while also safeguarding the environment.

In order to combat plant diseases and pests, research has shown that nanoparticles help plants develop more effectively under biotic and abiotic stress situations. When compared to conventional sources, agricultural productivity and efficiency have significantly increased with the advent of nanoparticles. The global economy will also be revitalized by encouraging and routinely implementing nanoparticle uses in the agriculture system.

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Agricultural Residue-Based Bio-Pellet Production: Resource Potential, Pelletization Technologies, Fuel Properties and Sustainability Perspectives

Doç.Dr.Emrah KUŞ[1]

[1] Doç. Dr.; Iğdır University, Faculty of Agriculture, Department of Biosystems Engineering, emrahkus@gmail.com ORCID ID: 0000-0001-6880-5591

ABSTRACT

The acceleration of global energy demand alongside stringent decarbonization targets has heightened interest in renewable, dispatchable fuels that can be integrated into existing energy infrastructures with limited system disruption. Agricultural residues constitute a vast but underutilized biomass resource, and their conversion into bio-pellets offers a promising pathway to simultaneously enhance energy security, valorize agricultural wastes, and reduce environmental externalities associated with residue burning and disposal. This study critically synthesizes current knowledge on agricultural residue–based bio-pellet systems, encompassing global and national resource potential, pelletization technologies, feedstock properties, fuel performance, and sustainability considerations. Particular attention is given to Türkiye as a representative case of a residue-rich, energy-import-dependent economy. The analysis demonstrates that, while residue-based pellets can deliver substantial fossil-fuel substitution—especially in heating and decentralized power applications—their broader deployment is constrained by intrinsic feedstock characteristics. Compared with woody biomass, agricultural residues typically exhibit higher ash contents and elevated alkali and chlorine concentrations, which exacerbate slagging, fouling, corrosion, and emission-related challenges during combustion. The study identifies integrated mitigation strategies—including feedstock blending, leaching and washing pretreatments, torrefaction, and the use of mineral additives—together with the optimization of pelletization parameters such as moisture content, particle size, die design, and compaction pressure, as critical enablers of technical viability. Beyond conversion efficiency, the synthesis reveals that supply-chain organization—seasonality, storage, logistics, and quality standardization—often dominates economic performance and market acceptance. Overall, agricultural residue–based bio-pellets emerge as a robust component of low-carbon energy systems when supported by coherent policy frameworks, quality standards, and integrated life-cycle and techno-economic assessments tailored to regional conditions.

Keywords – Biomass, Solid biofuels, Biomass pelletization, Bio-pellets, Supply chain optimization

INTRODUCTION

In recent decades, global energy demand has been increasing rapidly as a consequence of technological advancement, industrialization, and population growth. According to data from the International Energy Agency, global primary energy consumption in 2023 increased by approximately 2% compared to the previous year, with nearly two-thirds of total energy demand still being met by fossil fuels (IEA, 2024). Although the share of fossil fuels in global electricity generation has shown a declining trend, their continued dominance in the overall energy supply poses substantial risks in terms of climate change, air pollution, and energy supply security. This dependence has profound implications not only for energy security but also for environmental sustainability.

The combustion of fossil fuels such as coal, oil, and natural gas results in the release of carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O), and fluorinated gases into the atmosphere; the accumulation of these greenhouse gases accelerates global warming and, consequently, climate change. Within the framework of the Paris Agreement, limiting the increase in global average temperature to 1.5–2 °C above pre-industrial levels necessitates the gradual reduction of fossil fuel consumption, an expansion of the share of renewable energy sources, and significant improvements in energy efficiency. Nevertheless, historical data indicate that fossil fuels continue to play a dominant role in contemporary energy systems (Holechek et al., 2022). This situation renders the transition toward alternative energy sources capable of ensuring energy security while reducing carbon emissions increasingly inevitable.

In this context, the importance of alternative energy sources capable of lowering carbon intensity in energy production processes has become progressively more pronounced. The environmental impacts, vulnerability to economic volatility, and sustainability risks associated with fossil fuel–based energy production have directed research efforts toward cleaner, more reliable, and renewable energy options. Accordingly, alternative energy sources such as hydropower, geothermal energy, hydrogen, wave and tidal energy, wind, solar, and biomass have gained growing attention (Kuş et al., 2016). Among these, biomass occupies a distinctive position due to its sustainable nature and the wide diversity of available feedstocks. As a renewable energy source, biomass stands out for its environmental compatibility, sustainability, and broad geographical availability. Biomass is defined as an energy resource composed of materials of biological origin that can be utilized for energy generation owing to their organic carbon content (Ergüneş, 2009).

Within this framework, biomass is regarded as a strategic option capable of substituting fossil fuels in energy conversion processes. Owing to its renewable character and circular carbon cycle, biomass energy represents

a viable pathway for the partial replacement of fossil fuels. Biomass encompasses the entirety of organic materials derived from living or recently living plant and animal organisms, including agricultural residues, forestry by-products, animal wastes, and organic municipal wastes (McKendry, 2002a; Demirbaş, 2005). The carbon cycle of biomass is based on a closed-loop principle, whereby CO_2 absorbed from the atmosphere through photosynthesis is released back during combustion (Qiu et al., 2012).

However, the direct utilization of raw biomass for energy purposes entails several technical and economic challenges, such as low volumetric energy density, high moisture content, irregular shape and size, and heterogeneous chemical composition. Consequently, densification and pelletization processes applied to convert biomass into solid biofuels have gained increasing importance. Through pelletization, biomass can be transformed into small cylindrical units with high density, standardized dimensions, and enhanced transportability and storability (Stelte et al., 2012; Solórzano et al., 2017).

These processes are particularly relevant for the energy valorization of agricultural residues generated in large quantities. The utilization of agricultural wastes for bio-pellet production offers a dual strategic benefit. First, these residues constitute a local, sustainable, and renewable energy resource. Second, converting such wastes into solid biofuels contributes to mitigating environmental problems arising from common practices such as open-field burning, uncontrolled disposal, or natural decomposition, while simultaneously integrating them into the economy as value-added energy carriers (Pradhan et al., 2018; Svensson et al., 2024).

Recent literature demonstrates that biomass-based energy approaches are no longer confined to technical and economic considerations but are increasingly examined from the perspectives of governance, sustainability, and market dynamics (Scarlat et al., 2018; IEA, 2023; IRENA, 2024). Accordingly, the primary objective of this study is to provide a comprehensive assessment of bio-pellet production from agricultural residues by considering global and national potential, technological parameters of pelletization processes, fuel quality and emission behavior, as well as environmental and economic sustainability dimensions. In addition, the study addresses the chemical, physical, and thermal properties that determine the suitability of agricultural residues for pellet production, while also examining trends in the global bio-pellet market, policy frameworks, and sustainable growth strategies from a holistic perspective. Through this comprehensive approach, the potential role of agricultural biomass in energy systems is elucidated in a multidimensional manner encompassing technical, environmental, and economic aspects.

BIOMASS AND BIOENERGY: CONCEPTUAL FRAMEWORK

Definition and Classification of Biomass

Biomass is generally defined as all materials of plant, animal, or organic origin that have not undergone fossilization, are generated through biological processes, and contain organic carbon within their structure (McKendry, 2002a). This definition positions biomass as a strategic resource within both renewable energy systems and circular economy approaches. Depending on their origin and formation pathways, biomass resources may be found in terrestrial and aquatic environments and can be utilized through various technological routes for energy production, biofuel synthesis, and biochemical conversion applications.

With specific reference to solid biofuel applications for energy purposes, a detailed origin-based classification of biomass has been established under the ISO 17225-1 standard published by the International Organization for Standardization. Within this standard, biomass is hierarchically classified into woody, herbaceous, fruit-based, aquatic, and blended categories, providing a reference framework particularly for the evaluation of fuel properties of pellets and other solid biofuels (ISO, 2014).

In parallel with this standardized classification, the literature commonly categorizes biomass according to feedstock origin into the following main groups:

Animal biomass primarily encompasses wastes and by-products generated from livestock production systems. This category includes primary wastes such as animal manure, bedding materials, and milking parlor wash waters, as well as slaughterhouse and processing by-products including hides, wool, feathers, internal organs, fats, bones, blood, and rumen contents. In addition, processed by-products from the poultry industry—such as feather meal, bone meal, and blood meal—as well as residues arising from apiculture activities, including beeswax and propolis production wastes, are also considered within this group (McKendry, 2002a; Gerardi, 2003; Angelidaki & Ahring, 2003; Ward et al., 2008; Holm-Nielsen et al., 2009; Malik et al., 2015).

Plant-based biomass constitutes the largest biomass category, originating from agricultural production processes and plant-derived feedstocks. This group includes post-harvest field residues such as cereal straw, corn cobs, cotton stalks, and rice straw; oilseed meals and husks (sunflower, soybean, rapeseed, cotton, safflower); fiber crops such as flax, hemp, sorghum, and kenaf; carbohydrate-rich crops including potato, maize, sugar beet, wheat, and artichoke; as well as dedicated energy crops such as miscanthus, sorghum, and amaranth. Plant biomass exhibits high potential for both direct combustion and biofuel and biochemical conversion pathways

(McKendry, 2002a; Parikka, 2004; Demirbaş, 2005; Malik et al., 2015; Sindhu et al., 2016; Lisý et al., 2020; Uzunoğlu & Kuş, 2022).

Forestry biomass comprises woody materials derived from natural and plantation forests, along with residues and by-products generated through forestry operations. This group includes energy forests, roundwood, bark, branches, roots, leaves, wood chips, and wastes from the wood processing industry. Due to its relatively low ash content and high energy density, forestry biomass is widely preferred for solid biofuel and pellet production (Demirbaş, 2001; McKendry, 2002a; Demirbaş, 2011; Goh et al., 2013; Malik et al., 2015; Hanssen et al., 2020).

Industrial organic wastes encompass biomass types generated from agricultural product processing and biologically based industrial activities. This category includes tomato, apple, and citrus pomace; food industry residues such as pits, shells, and stalks; oilseed meals from sunflower, soybean, and canola; olive pomace; wastes from the wood processing industry; and organic residues arising from biochemical and biotechnological processes (Mata-Alvarez et al., 2000; Karaosmanoğlu, 2003; FAO, 2016).

Urban organic wastes include organic municipal solid waste, sewage sludge, household and commercial food waste, used cooking oils, and organic kitchen wastes originating from restaurants and cafés. These biomass types offer substantial potential, particularly for anaerobic digestion and waste-to-energy applications (Holm-Nielsen et al., 2009; IRENA, 2023).

This classification framework provides a fundamental basis for selecting appropriate conversion technologies, designing logistics systems, and conducting sustainability assessments for the integration of biomass into energy systems.

Role of Biomass in Energy Systems

International scenarios project that biomass will remain a key component of the transition toward low-carbon energy systems through the 2050s. Indeed, Scarlat et al. (2018) emphasize the critical role of biomass in achieving long-term supply security and carbon mitigation targets within European Union energy transition scenarios. In this context, the *World Energy Transitions Outlook 2023* published by IRENA estimates that bioenergy could account for approximately 22% of global primary energy supply by 2050, with this growth primarily driven by modern bioenergy applications based on sustainable feedstocks (IRENA, 2023). A substantial share of this contribution is expected to originate from the use of solid biofuels derived from agricultural and forestry residues—particularly densified forms such as pellets and

briquettes—for electricity generation and heating purposes (Pradhan et al., 2018).

This perspective positions biomass not merely as an "alternative fuel," but rather as a multifunctional energy carrier, especially in applications where electrification remains limited, in heat supply, and in certain transport sub-sectors. Correspondingly, the IEA's assessments of bioenergy underline its strategic importance within the renewable energy portfolio, highlighting its contribution not only to electricity generation but also—through heat provision and biofuels—to system flexibility and energy security.

This multifunctional role is manifested through the complementary functions biomass performs across the electricity, heat, and transport sectors. Within modern energy systems, biomass represents not only a fuel type but also a versatile energy carrier. In electricity generation, biomass power plants contribute to grid balancing due to their controllable and dispatchable generation characteristics, in contrast to intermittent renewable sources such as wind and solar. In the heat sector, particularly across European countries, biomass constitutes the largest share of renewable heat supply, serving residential heating, district heating networks, and small-scale industrial applications. In the transport sector, advanced biomass-based biofuels—including bioethanol, biodiesel, biomethane, and sustainable aviation fuels—form a critical complementary fuel portfolio in 2050 carbon-neutral scenarios (IEA, 2023).

One of the determining factors in integrating biomass resources into energy systems is the availability of locally based supply chains and their impacts along the energy security–rural development nexus. Domestic production reduces dependence on imported fossil fuels, supports regional development, and generates additional employment opportunities across agricultural and forestry supply chains. Moreover, biomass supply chains are inherently integrated with organic waste management systems. Agricultural residues, food industry by-products, forestry wastes, and municipal organic wastes constitute valuable feedstocks for energy production, thereby reducing waste management burdens while making tangible contributions to circular economy strategies.

The advantages of biomass can be summarized as local availability, employment creation potential, integration with waste management, low net greenhouse gas emissions under specific conditions, and flexible end-use options for heat, electricity, and biofuels (McKendry, 2002b; Sims et al., 2006). Nevertheless, biomass also entails sustainability-related risks that must be carefully managed. Issues such as land-use change, water consumption, impacts on soil organic carbon, biodiversity loss, and food–feed–fuel competition represent some of the most debated challenges associated with large-scale biomass deployment. Furthermore, the assumption of carbon neutrality for biomass is contingent upon scientific parameters such as short-term carbon debt and payback periods (Azizpanah & Taki, 2025).

Consequently, the sustainable development of the biomass sector requires a holistic approach encompassing feedstock management, land-use planning, environmental impact assessment, and optimization of technological efficiency.

Overall, biomass occupies a fundamental role in energy transition processes among existing renewable energy sources due to its capacity for continuous energy generation and its diverse product portfolio. Future scenarios consistently indicate that biomass will continue to be an indispensable component of energy systems in terms of both energy security and carbon mitigation.

GLOBAL AGRICULTURAL RESIDUE POTENTIAL AND BIO-PELLETS

Global Potential

Residues generated during agricultural production processes—such as stalks, straw, husks, leaves, roots, and pomace—constitute a substantial yet largely underutilized bioenergy resource at the global scale. Global primary energy supply reached approximately 620 EJ in 2022, of which around 55–60 EJ was provided by modern and traditional biomass utilization (WBA, 2024). The relatively low share of modern bioenergy highlights the magnitude of the untapped potential that could be realized through the large-scale integration of agricultural and forestry residues into energy systems.

Modeling studies assessing global biomass potential—while explicitly accounting for land-use constraints, food security considerations, and ecological limitations—generally report a sustainable bioenergy potential in the range of 160–270 EJ yr^{-1} (Hoogwijk et al., 2005; Haberl et al., 2010). Within this total, the contribution attributable to agricultural and forestry residues is estimated to fall between 30 and 70 EJ yr^{-1} (Searle & Malins, 2015). This volume corresponds to approximately 1.5–2 times the amount of modern biomass currently utilized in global energy systems and is expected to gain strategic importance, particularly during the 2030–2050 period as the pace of energy transition accelerates.

From a global energy transition perspective, IRENA's 1.5 °C scenario projects that bioenergy will contribute approximately 130 EJ yr^{-1} to global primary energy supply by 2050, with this growth predominantly met by sustainable biomass resources derived from agricultural and forestry residues (IRENA, 2024). Similarly, in the IEA's Net Zero by 2050 scenario, bioenergy supply is projected to reach around 100 EJ yr^{-1} by 2050, with more than 60% of this supply originating from residue- and waste-based biomass sources (IEA, 2023).

These global projections are consistent with detailed regional-scale assessments. For instance, Azizpanah and Taki (2025) reported that

approximately 13.9 million tonnes of agricultural residues generated annually in Iran's Khuzestan Province correspond to a technical energy potential of 58–92 million GJ, indicating that their utilization for combined heat and power generation could provide substantial substitution for fossil fuels. Similarly, Demirel (2019) conducted a comprehensive assessment of agricultural residue availability in Sudan for the 2016 production season, estimating a total of 11.2 million tonnes with an associated energy content of 154 PJ, and emphasized the critical role of biomass-based energy in reducing dependence on fossil fuels. Such regional studies demonstrate that the potentials projected in the global literature are supported by robust empirical foundations.

Nevertheless, the energy-oriented utilization of agricultural residues requires careful consideration of sustainability-related factors, including impacts on soil organic matter, biodiversity, water use, land management practices, and food–feed–fuel competition. In this regard, comparative scenario analyses conducted by Hanssen et al. (2020) clearly indicate that the environmental and climatic benefits of bioenergy systems can be maximized when energy production is prioritized within scenarios based primarily on agricultural and forestry residues, as well as other organic wastes.

Bio-Pellets and the Global Market

Pellet production and consumption are closely linked to renewable energy targets, carbon pricing mechanisms, and strategies aimed at reducing energy imports (Solórzano et al., 2017). Over the past two decades, the bio-pellet sector has experienced rapid growth—particularly in the European Union, North America, and Asia—positioning densified biomass fuels as strategic components of the energy transition. Goh et al. (2013) reported that global wood pellet production amounted to 14.3 million tonnes in 2010, with an installed production capacity of 28 million tonnes. According to WBA (2024), global pellet production increased to approximately 48 million tonnes by 2022, with Europe accounting for 52% of total output, North and South America for 32%, and the remainder produced in Asia and Oceania.

A similar growth trend is evident in pellet trade. Data from the UNECE–FAO *Forest Products Review* indicate that global wood pellet exports reached 12.5 million tonnes in 2022, with the majority of trade flows directed from North America to European and East Asian markets. Japan's pellet imports in 2022 totaled 4.4 million tonnes, of which 54% originated from Vietnam and 31% from Canada, underscoring the rapidly expanding role of Asian markets as major consumers (USDA FAS, 2023).

Alongside the rapid increase in pellet demand, these developments have intensified sustainability debates. In particular, the extensive use of forest-derived pellets in power generation facilities across the European Union and Japan has been criticized in the context of forest carbon stocks, indirect land-use change (ILUC), and the concept of carbon debt (Searchinger et al., 2018;

Sterman et al., 2022). One of the central concerns is the diversion of wood obtained from living trees toward pellet production, which is often cited as a factor undermining assumptions of carbon neutrality. These debates increasingly point to bio-pellets produced from agricultural residues as a relatively more sustainable alternative compared to forest-based biomass (Svensson et al., 2024; Polipalli et al., 2025).

In this context, bio-pellets derived from agricultural residues are becoming increasingly attractive alternatives in terms of both carbon footprint and land-use impacts. Studies by Hanssen et al. (2020) and Errera et al. (2023) demonstrate that residue-based bioenergy supply chains exhibit markedly superior sustainability performance, particularly by achieving significantly shorter carbon payback periods compared to dedicated energy crops or whole-tree harvesting systems. Moreover, the pelletization of agricultural residues contributes to improved air quality by reducing practices such as open-field burning (Azizpanah & Taki, 2025). Consequently, global projections increasingly anticipate that bio-pellets based on agricultural and forestry residues will assume a growing role in future energy supply diversification, sustainability, and environmental performance.

BIOMASS AND AGRICULTURAL RESIDUE POTENTIAL IN TÜRKİYE

Türkiye, located at the intersection of multiple climatic zones and characterized by a highly diversified agricultural production structure, possesses a substantial biomass potential. Given the cultivation of a wide range of crop groups—most notably cereals, industrial crops, legumes, oilseeds, and forage crops—large quantities of agricultural biomass are generated in parallel with production. Avcıoğlu and Aydoğdu (2019) reported that the technical energy potential obtainable from agricultural biomass residues across Türkiye varies between 551,000 and 998,000 TJ yr^{-1}, depending on alternative utilization scenarios. These magnitudes suggest that even if only a limited fraction of agricultural residues were valorized for energy purposes, a nationally significant contribution to the energy supply could still be achieved.

Detailed studies on the spatial distribution of agricultural biomass potential in Türkiye demonstrate that this potential is not homogeneous nationwide, but instead exhibits pronounced regional and provincial differences. Since early investigations, it has been emphasized that the spatial distribution of biomass resources varies substantially as a function of agricultural production patterns and climatic conditions (Öztürk & Başçetincelik, 2006). Within this context, Bahadıroğlu et al. (2022) mapped province-level quantities of primary (post-harvest field residues) and secondary (post-processing) agricultural residues, showing that the Central

Anatolia, Southeastern Anatolia, and Aegean regions stand out in terms of residue-based energy production potential.

Regional-scale assessments further underscore the importance of spatial analysis and planning approaches for the effective valorization of agricultural biomass resources. In this regard, Tümen Özdil and Çalışkan (2022) evaluated crop-based biomass potential at the scale of Türkiye's geographical regions and reported higher electricity generation potential in regions where cereal and industrial crop production is concentrated. In more recent, higher-resolution analyses, the temporal dimension of spatial heterogeneity has also been incorporated. Using multi-year data for the 2010–2021 period, Pence et al. (2024) assessed province-level agricultural biomass-based energy potential in Türkiye and demonstrated substantial inter-provincial variability, closely linked to climatic, environmental, and production-pattern determinants. Taken together, these studies clearly indicate that regional and local planning approaches constitute a fundamental prerequisite for the efficient utilization of Türkiye's agricultural biomass potential.

From an energy supply security perspective, the importance of Türkiye's agricultural biomass potential becomes even more pronounced. The International Energy Agency (IEA) has reported that Türkiye's total primary energy demand is largely met by imported fossil fuels and that the dependence on energy imports has remained around 70–75% (IEA, 2021). This high external dependence represents a significant risk in terms of energy supply security, the current account deficit, and vulnerability to fluctuations in energy prices. In this context, integrating domestically available and renewable agricultural biomass resources into the energy system is increasingly regarded as a strategic option to strengthen supply security and reduce the foreign trade deficit.

Recent studies published in the international literature indicate that Türkiye's agricultural biomass-based energy potential is not merely a theoretical magnitude, but could deliver substantial contributions in practice under appropriate technological and policy frameworks. In scenario analyses developed for Türkiye, Pence et al. (2024) showed that if agricultural residues are valorized through modern biomass technologies (biogas, biomass combustion, and pelletization), meaningful domestic energy contributions could be achieved, particularly in electricity generation and the heating sector. Moreover, Demirbaş et al. (2009) emphasized that the energy use of agricultural residues could contribute to greenhouse gas emission mitigation and support an energy transition pathway consistent with Türkiye's climate targets.

Nevertheless, the incorporation of sustainability criteria is crucial for the energy-oriented utilization of agricultural biomass. In the Turkish context, issues such as maintaining soil organic matter, sustaining agricultural productivity, reducing open-field burning practices, and ensuring balance

across the food–feed–energy nexus emerge as key determinants in biomass policy design. Accordingly, recent studies recommend that not all residues, but only environmentally and economically sustainable shares should be diverted to energy systems, and that this process should be supported by regional planning approaches (Bahadıroğlu et al., 2022; Pence et al., 2024).

Overall, Türkiye's agricultural biomass and residue potential provides a significant domestic resource base for both energy supply security and low-carbon energy transition objectives. Therefore, the effective realization of this potential depends on the coordinated and integrated implementation of appropriate policy instruments, incentive mechanisms, and advanced conversion technologies.

PROPERTIES OF AGRICULTURAL RESIDUES AS BIO-PELLET FEEDSTOCKS

The suitability of agricultural residues as feedstocks for solid biofuels and bio-pellets is largely governed by their chemical, physical, and thermal characteristics (Obernberger & Thek, 2010). Key parameters determining both pellet mechanical durability and combustion-related emission profiles and ash behavior include ash content, volatile matter fraction, fixed carbon content, moisture content, moisture–pressure relationships, mechanical strength, fiber structure, lignin content, and, in particular, the concentrations of alkali and alkaline earth metals (K, Na, Ca, Mg) (Jenkins et al., 1998; Kaliyan & Morey, 2009; Hupa, 2012; Lisý et al., 2020; Mlonka-Mędrala et al., 2020). These properties are also critical for the lower heating value of pellets, storage stability, and compatibility with different combustion systems.

Contemporary literature consistently demonstrates that, relative to woody biomass, agricultural residues typically exhibit higher ash contents and elevated alkali metal concentrations, which in turn lead to lower ash melting temperatures and an increased propensity for slagging and ash sintering during combustion (Obernberger & Thek, 2010). In particular, agricultural residues rich in potassium and silicon have been reported to promote the formation of reactive alkali–silicate phases at high temperatures, thereby increasing corrosion risks on boiler surfaces (Vassilev et al., 2010).

The mechanism underlying such ash-related problems is closely associated with the tendency of potassium- and chlorine-rich agricultural residues to form low-melting alkali silicate and alkali chloride phases during combustion. Comparative studies evaluating multiple indices developed to quantify slagging and fouling tendencies indicate that agricultural residues frequently fall within high-risk categories with respect to these indices (Lachman et al., 2021). These findings suggest that the direct, unconditioned use of agricultural residue–based pellets in pure form—without pretreatment or fuel conditioning—may constitute a technical limitation in many industrial combustion applications.

High alkali and chlorine contents in agricultural residue–based fuels can trigger operational problems such as ash deposition and fouling. The literature provides extensive analyses of the mechanisms of these phenomena and the underlying causes of associated operational issues. In particular, general studies addressing ash deposition behavior and high-temperature performance of biomass fuels emphasize that the accumulation tendencies of alkali metals and chlorine within the fuel matrix may contribute to aggravated fouling and slagging conditions (Shao et al., 2012). In this respect, ash deposition propensities and their economic implications constitute critical considerations for energy conversion systems.

In recent years, a range of technical approaches have been developed to enhance the usability of agricultural residues as solid biofuels, including blending, leaching/washing, torrefaction, and the use of mineral additives. Among these, blending strategies involve mixing agricultural residues with woody biomass or other low-ash biomass types at specified ratios. Stolarski et al. (2025) demonstrated that pellets produced from such blends exhibit higher ash melting temperatures, reduced slagging tendencies, and improved combustion stability. Studies on low-emission biomass combustion systems have further reported that optimizing fuel composition and combustion conditions can substantially reduce NO_x and particulate matter emissions (Brunner et al., 2009).

Another effective approach to improving the usability of agricultural residue–based fuels involves leaching (pre-washing) and chemical pretreatment. Washing agricultural residues with water or dilute acid solutions can remove a significant fraction of volatile and reactive elements such as potassium, chlorine, and sodium. Yu et al. (2014) showed that leaching pretreatments applied across different biomass types significantly alter ash composition, resulting in improved ash melting behavior and reduced risks of deposition and corrosion under high-temperature conditions. In a comprehensive assessment of ash-related issues and preventive strategies, Niu et al. (2016) noted that washing and similar pretreatments are among the effective countermeasures for mitigating alkali-metal-driven slagging, deposition, and corrosion tendencies. Likewise, in their extensive review focusing on washing pretreatments, Javanmard et al. (2023) emphasized that pre-washing is particularly effective in reducing ash-related operational problems in agriculturally derived biomass. These approaches are especially relevant for high-alkali agricultural residues such as straw, corn stover, and rice husk.

Thermochemical pretreatments—most notably torrefaction—have attracted increasing attention in recent years for improving the solid biofuel properties of agricultural residues. Torrefaction, typically conducted in an inert atmosphere within the 200–300 °C range, reduces moisture content, imparts hydrophobicity, and increases energy density. Comparative studies of torrefied agricultural and woody residues indicate that this treatment improves

pelletization and combustion performance by enhancing energy density, hydrophobicity, and pelletability (Tumuluru et al., 2011; Cahyanti et al., 2021). Ivanovski et al. (2022) further reported that pellets produced from torrefied agricultural residues exhibit higher heating values, improved grindability, and more stable combustion behavior.

Another approach that has gained prominence is the use of additives. The incorporation of kaolin, bentonite, or calcium-based minerals during pellet production can bind alkali metals, thereby increasing ash melting temperatures and reducing slagging tendencies. Studies such as Boström et al. (2008), Nor Aznizam Nik Norizam et al. (2024), and Dula et al. (2025) have reported that mineral-additive-containing agricultural residue pellets improve ash behavior and combustion performance, positively influence emission profiles, and mitigate alkali-related operational issues.

In parallel, the literature on alternative biomass types has expanded rapidly. Agricultural residues such as quinoa, amaranth, walnut shells, and pistachio shells can exhibit competitive characteristics for solid biofuel and bio-pellet production when appropriate pretreatment and blending strategies are applied. Lisý et al. (2020) compared the fuel properties of such alternative biomasses with conventional feedstocks and demonstrated their technical feasibility under suitable blending ratios. Thermogravimetric analyses conducted by Uzunoğlu and Kuş (2022) similarly support the integration of quinoa and amaranth harvest residues into modern biomass energy systems following pretreatment or blending.

Overall, the key constraints limiting the use of agricultural residues as feedstocks for solid biofuels and bio-pellets—namely high ash contents, excessive alkali metal levels, and combustion-related operational challenges—can be substantially alleviated through a range of technical approaches proposed in the literature. The application of methods such as blending, leaching, torrefaction, and the use of additives, either individually or in appropriate combinations, can enhance both the technical performance and environmental compatibility of agricultural residue–based pellets, thereby strengthening the role of these resources in sustainable bioenergy systems.

PELLETIZATION PROCESS AND PROCESS PARAMETERS

Pelletization is the process by which milled biomass is forced through a die under controlled moisture, temperature, and pressure conditions to produce a cylindrical solid biofuel with enhanced density and mechanical integrity. Beyond increasing the volumetric energy density of biomass, pelletization markedly improves storability, transportability, automated feeding, and compatibility with standardized combustion systems. Industrial pellet production typically comprises feedstock preconditioning (cleaning and size reduction), moisture adjustment, mechanical compaction, cooling–screening, and storage.

The bonding mechanisms governing pellet formation are closely linked to both the structural constituents of biomass and the prevailing process conditions. In lignocellulosic biomass in particular, approaching or exceeding the glass transition temperature of lignin facilitates inter-fiber bonding and enhances pellet mechanical strength. Stelte et al. (2012) elucidated that bonding during pelletization emerges from the concurrent effects of lignin softening, inter-particle mechanical interlocking, frictional forces, and surface energy interactions. The relative dominance of these mechanisms may vary depending on feedstock type and process parameters.

Moisture content is among the most critical determinants of pellet quality. Insufficient moisture can hinder adequate bonding, whereas excessive moisture may induce pellet cracking, reduced mechanical durability, and increased specific energy consumption. The literature commonly reports an optimal pelletization moisture range of approximately 8–15% for most agricultural and woody biomasses (Kaliyan & Morey, 2009). Deviations from this range adversely affect both pellet durability and overall process efficiency.

Particle size distribution also plays a decisive role in pelletization performance. While finer particles tend to improve bonding, overly fine grinding increases energy demand and accelerates die wear. Conversely, excessively coarse particles can promote void formation within pellets and reduce density. Accordingly, pre-pelletization milling should be optimized to achieve a target particle size distribution aligned with the intended pellet quality and process performance (Kaliyan & Morey, 2009).

Pressing pressure, die geometry, and process temperature exert direct influences on pellet density and mechanical integrity. In ring-die and flat-die systems, the die length-to-diameter (L/D) ratio governs the shear and compressive stresses experienced by biomass within the die channel, thereby affecting pellet durability and specific energy consumption. Tumuluru et al. (2011) demonstrated statistically significant relationships between pressing pressure and die design, pellet density, and electrical energy consumption during production.

The use of binders represents a particularly important strategy for pelletizing agricultural residues with low lignin content. Natural binders such as starch, lignosulfonate, and vegetable oil derivatives can enhance pellet durability; however, their cost implications and impacts on combustion behavior must be carefully assessed. Whittaker and Shield (2017) emphasized that binder application may improve pellet mechanical properties, yet the binder type and dosage should be selected to ensure compliance with fuel quality standards (ENplus, ISO 17225).

Recent studies indicate that the pelletization process should be optimized not only from a technical standpoint but also with respect to energy efficiency and cost-effectiveness. Pradhan et al. (2018) systematically examined the effects of process parameters on specific energy consumption

and pellet durability, showing that production costs can be substantially reduced when moisture content, particle size, and pressing conditions are jointly optimized. These findings underscore the necessity of approaching pelletization through an integrated process design perspective rather than focusing on individual parameters in isolation.

FUEL PROPERTIES, COMBUSTION, AND EMISSION BEHAVIOR OF BIO-PELLETS

The fuel performance of bio-pellets is governed by interrelated physicochemical properties, including lower heating value (LHV), bulk and true density, mechanical durability, moisture content, ash fraction, and elemental composition. These parameters directly shape both combustion efficiency and emission formation mechanisms. Compared with woody biomass pellets, agricultural residue–derived pellets generally exhibit higher ash contents and elevated concentrations of alkali metals (particularly K and Na) and chlorine, which can create additional challenges related to ash deposition, fouling, and emission control in small- and medium-scale combustion systems (Obernberger & Thek, 2010; Vassilev et al., 2010).

Experimental investigations of bio-pellet combustion and emission behavior have primarily focused on particulate matter (PM), nitrogen oxides (NO_x), sulfur dioxide (SO_2), carbon monoxide (CO), volatile organic compounds (VOCs), and polycyclic aromatic hydrocarbons. The formation of these emissions is influenced not only by pellet chemical composition but also by moisture content, pellet density, ash characteristics, and combustion conditions. Lachman et al. (2021) highlighted that ash composition and alkali content are among the critical factors governing both emission profiles and ash behavior during combustion.

Recent studies evaluating the quality and emission compliance of commercially available pellets suggest that conformity with standards is not consistently achieved. Drobniak et al. (2024) assessed a wide range of commercially marketed pellets in Poland in terms of quality classes (DINplus/ENplus) and emission parameters, reporting that some samples failed to meet standard limits with respect to ash content and mechanical durability. These findings demonstrate that variability in pellet quality can be directly determinative of combustion efficiency and emission performance.

The environmental and economic performance of agricultural residue pellets has increasingly been examined using holistic assessment frameworks. In 3E (energy, environmental, and economic) analyses of corn stover pellets for heating applications, Deng et al. (2025) reported pronounced reductions in CO_2, SO_2, NO_x, and $PM_{2.5}$ emissions relative to fossil fuels such as coal and fuel oil, alongside the potential for lower fuel costs. These results indicate that agricultural residue–derived pellets can make meaningful contributions to

low-carbon energy systems when deployed with appropriate combustion technologies.

From a combustion technology perspective, numerous studies have reported that pelletized biomass exhibits more stable and homogeneous combustion behavior than raw biomass. Arromdee et al. (2023) compared pelletized and raw biomass fuels in fluidized-bed combustion systems and showed that pellets enabled more uniform fluidization, improved fuel–air contact, and more consistent temperature profiles. These characteristics were reported to increase combustion intensity and reduce fluctuations in emissions.

Similarly, studies examining the combustion performance of commercial pellets indicate strong relationships between pellet quality and combustion efficiency and flue gas temperature. Pellets exhibiting higher density and mechanical durability have been reported to be characterized by more stable combustion and lower CO emissions (Pinho & Borges, 2025). These findings underscore that quality control in pellet production is critical not only for logistics and storage but also for emission performance.

Overall, the fuel properties, combustion behavior, and emission profiles of bio-pellets constitute a multidimensional domain that requires the joint consideration of feedstock type, pelletization conditions, and the combustion technology employed. In particular, for the broader deployment of agricultural residue–derived pellets, the management of ash- and alkali-driven challenges through appropriate pretreatments, blending strategies, and advanced combustion systems emerges as a fundamental requirement for environmental and technical sustainability.

SUSTAINABILITY, POLICY, AND MARKET DYNAMICS

Bio-pellet production from agricultural residues is increasingly recognized as a multidimensional transformation pathway that extends beyond technical feasibility and cost parameters, intersecting with waste management, rural development, air quality, and climate policy objectives. Within this holistic framework, sustainability performance should not be reduced to a single indicator; rather, environmental burdens, economic feasibility, and supply chain organization must be jointly evaluated. Indeed, Deng et al. (2025) assessed pellet production from agricultural residues (corn stover) using a scenario-based 3E (energy–environment–economic) framework and reported that pellet utilization can reduce heating costs while achieving quantifiable reductions in SO_2, NO_x, CO, $PM_{2.5}$, and CO_2 emissions.

Nevertheless, the primary bottleneck in the large-scale deployment of agricultural residue–based pellets is often not the availability of feedstock itself, but the lack of standardization across supply chain stages, including collection, separation, drying, storage, and transportation. Even as the contribution of pellets to “sustainable energy” is debated at the global level,

logistics costs and supply continuity—particularly the seasonal nature of agricultural residues—are widely acknowledged as critical constraints. Consequently, recent studies increasingly evaluate pellet production not only in terms of densification parameters, but also by integrating environmental impacts (life cycle assessment), economic performance, and logistics/supply chain dimensions, thereby explicitly linking market dynamics with policy frameworks (Scarlat et al., 2018; Visser et al., 2020; IRENA, 2023).

From a policy perspective, support and incentive mechanisms should be designed to address not only fuel substitution targets, but also quality assurance and compliance with established standards. Market acceptance of pellets depends not solely on their energy content, but also on quality attributes such as ash and moisture content, transportability and storability, and the predictability of emission performance. Using ISO 17225:2021 as a reference, Deng et al. (2025) demonstrated that standardization plays a decisive role in enabling market scaling and fostering consumer confidence.

Finally, from the standpoint of market dynamics, the competitiveness of agricultural residue pellets is highly sensitive to local coal and fossil fuel prices, transportation-related unit costs, and spatial conditions such as the proximity of surplus biomass resources. Accordingly, sustainable upscaling requires the simultaneous organization of several institutional components: (i) identification of regional supply basins, (ii) strengthening of storage and logistics infrastructure, and (iii) the organization of local market actors (e.g., cooperatives and producer associations) under effective quality standard oversight. This integrated approach enables agricultural residues to become a long-term, environmentally compatible, and economically viable component of sustainable bioenergy systems.

CONCLUSIONS

This study provides a comprehensive assessment of the utilization of agricultural residues as biomass pellets, synthesizing literature evidence on feedstock potential, pelletization processes, fuel properties, combustion and emission behavior, and sustainability dimensions. The reviewed studies collectively indicate that converting agricultural production residues into energy through pelletization offers a significant opportunity to reduce waste management challenges while expanding the supply of renewable energy. Global and national potential assessments further demonstrate that integrating agricultural residues into energy systems can deliver meaningful contributions in terms of fossil fuel substitution and energy supply security.

A consistent finding across the literature is that the fuel properties of agricultural residue–based pellets vary substantially with feedstock type, with ash content and alkali constituents playing a decisive role in combustion performance and emission formation. Compared with woody biomass, agricultural residues typically exhibit higher ash and alkali metal contents,

which may impose technical constraints related to slagging, fouling, and emission control. However, when pretreatment strategies—such as blending, leaching, torrefaction, and the use of mineral additives—are applied in appropriate combinations, these challenges can be significantly mitigated, enabling the technical integration of agricultural residue pellets into a wide range of combustion systems. These findings clearly demonstrate that the suitability of agricultural residues as solid biofuels depends not only on inherent feedstock characteristics, but also on process design and fuel conditioning strategies.

One of the key conclusions of this study is that the principal limitations to the widespread deployment of agricultural residue–based bio-pellets are often structural issues within the feedstock supply chain rather than the absolute availability of resources. The seasonality of agricultural residues, low bulk density, and the lack of standardization across collection, drying, storage, and transportation stages increase logistics costs and constrain market competitiveness. Therefore, pellet production should be evaluated not solely through pressing parameters and fuel properties, but in conjunction with life cycle assessment, techno-economic analysis, and regional supply chain organization.

In conclusion, bio-pellets produced from agricultural residues represent an environmentally compatible and economically viable option for low-carbon energy systems when appropriate technological and governance conditions are in place. However, the effective realization of this potential depends on the widespread implementation of quality standards, the strengthening of logistics infrastructure, and the development of policy and incentive mechanisms that are responsive to regional conditions. Future research should integrate field-based logistics scenarios with life cycle and techno-economic assessments to identify and design agricultural residue–based bio-pellet systems that are optimally suited to local contexts, thereby further enhancing both scientific understanding and practical deployment in this domain.

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The Role of Plant Flora in the Sustainable Management of Clean Water Resources

Koray KAÇAN[1]

1- Assoc. Prof. Dr.; Muğla Sıtkı Koçman Üniversitesity, Ortaca Vocational School, Plant and Animal Production. koraykacan@mu.edu.tr ORCID No: 0000-0003-3316-9286

ABSTRACT

Clean water resources are vital to both the environment and the economy worldwide. Plants play a crucial role in maintaining these resources by regulating water quality and quantity, reducing pollution, and shaping hydrological processes. This review examines the impact of vegetation on water resources, focusing on how it improves water quality, manages water levels, and filters out pollutants. It highlights the key functions of filtration, absorption, and phytoremediation that make water cleaner. Vegetation also supports the water cycle by allowing more water to soak into the soil, regulating evapotranspiration, and preventing floods. Restoration of riverbanks, ecological engineering, and constructed wetlands offer effective and sustainable solutions to improve access to clean water and protect aquatic ecosystems. This review of 87 articles from top scientific databases between 1997 and 2025 emphasizes the potential of integrating plant life into water resource management, tackles current challenges, and outlines future research directions, arguing for a balanced approach to sustainable water management. By focusing on plant life, we can effectively manage clean water resources at the watershed level. This study aims to be a valuable resource for scientists and water management experts.

Keywords – water quality, phytoremediation, ecosystem, flora, water resources

INTRODUCTION

Access to clean water is essential for human well-being, ecological health, and sustainable development (Okafor et al., 2024; Bolatova et al., 2025; Ejiohuo et al., 2025). However, the increasing global demand for water, combined with the degradation of water resources due to land-use changes, pollution, and climate change, poses a complex and urgent challenge for current and future generations (Okafor et al., 2024; Shrivastava et al., 2025). Traditional approaches to water management often fail to address these multifaceted issues, making it necessary to explore innovative, nature-based solutions.

Among these solutions, plant flora plays a vital and often underappreciated role in the sustainable management of clean water resources (Sustainable Development Goal, 2025). Plants are more than just aesthetic elements; they provide a range of essential ecosystem services that are crucial for maintaining the water cycle, improving water quality, and supporting overall ecosystem health (Guru et al., 2025; Olivadese et al., 2024; Stroud et al., 2022; Xia et al., 2025).

This review examines the significant impact of vegetation in various hydrological contexts, including riparian zones, wetlands, forests, and aquatic

macrophytes, which are all integral to complex processes affecting the physical, chemical, and biological properties of water. Plant flora makes a substantial contribution to improving water quality through natural mechanisms such as physical filtration, nutrient removal, and advanced phytoremediation techniques, offering effective and cost-efficient strategies for reducing pollution loads in aquatic ecosystems (Guru et al., 2025; Xia et al., 2025).

Plants play a vital role in nutrient cycling—particularly nitrogen, which is essential for understanding ecosystem productivity and aquatic eutrophication—through various processes, including dilution, uptake, chemical transformations, and biological activities involving microorganisms (Ghaly and Ramakrishnan, 2015; Lønborg et al., 2021; Wu et al., 2025).

Wetland plants, for example, effectively absorb and store pollutants in their root and shoot systems, functioning as natural biological filters (Russo, 2008; Frenzel et al., 2024; Rathinam Krishnaswamy and Ribeiro Da Silva, 2025). Additionally, phytoremediation, which employs specific aquatic plant species to treat contaminated water, is an advancing field, with ongoing research aimed at enhancing its effectiveness through innovative technologies like nanotechnology and genetic engineering. Within the rhizosphere, plants, often in partnership with microorganisms, can metabolize and transform organic pollutants into less harmful compounds (Zhilkina et al., 2024; Frenzel et al., 2024; Khadidja et al., 2025).

In addition to pollutant removal, plant life is crucial for regulating water quantity and the broader hydrological cycle. Plant canopies intercept a significant amount of rainfall, reducing the volume of water that directly reaches the ground and consequently decreasing surface runoff (Berland et al., 2017; Liu and Zhao, 2020; Shadmehri Toosi et al., 2025; Vilhar, 2025). This intercepted water is then evaporated, contributing to atmospheric moisture instead of overland flow. Vegetation also improves soil water retention and the capacity to adsorb microelements, enhancing the purification of groundwater as it filters through the soil (Alivio et al., 2025; Berland et al., 2017; Liu and Zhang, 2025). Riparian zones, with their distinct vegetation, are essential for groundwater recharge and demonstrate a clear relationship between their complexity and the reduction of peak flows, which aids in flow regulation and provides essential ecosystem services like discharge control and flood prevention. Forested watersheds are particularly effective in maintaining base streamflow during dry spells, helping to mitigate drought impacts (Dosskey et al., 2010; Swanson et al., 2017; Dinca et al., 2025).

Incorporating plant-based strategies into water resource management yields significant environmental, social, and economic advantages. Key management strategies include restoring riparian zones, which serve as ecological engineers by stabilizing stream banks, buffering pollutants, and mitigating erosion (Khan et al., 2025; Olajide et al., 2025).

Ecological engineering principles inform the design and implementation of constructed wetlands, which are engineered systems that utilize vegetation, soil, and microbial activity to effectively treat wastewater by removing pollutants like nitrogen, phosphorus, and organic matter (Abonyi et al., 2024; Guo and Guo, 2025; Merouane et al., 2025). These systems are valued for their cost-effectiveness and ease of maintenance. Furthermore, watershed management strategies prioritize the protection and restoration of vegetation cover as a key adaptation measure to address both water scarcity and excess water events (Abonyi et al., 2024; Kumari et al., 2025; Mitsch et al., 2002).

This review aims to thoroughly examine the diverse impacts of plant life on water quality and quantity and to explore optimal management approaches within the context of sustainable clean water resource management. The goal is to highlight the critical importance of plant-based strategies and propose actionable solutions to current water management challenges, thereby contributing to a more resilient and sustainable water future.

MATERIAL AND METHODS

The literature review for this article concentrated on English-language academic publications. It was conducted using external academic search engines and scientific databases with the "Web" context tag. The search strategy involved various combinations of keywords and phrases, such as "sustainable clean water management," "plant flora water quality," "vegetation water quantity," "phytoremediation water," "riparian zone management," "ecological engineering water," "constructed wetlands water purification," "plant ecosystem services water," "challenges in sustainable water management policies related to plant flora," "future research directions for plant-based water purification ecosystem services," "climate change effects on plant-mediated water quality," "integrated water resource management and vegetation," "economic valuation of ecosystem services from plant flora for freshwater quality and quantity," "community involvement in vegetation-based water management projects," and "climate change impacts on riparian vegetation's effectiveness in regulating water quality."

The searches specifically targeted studies published after 1997 to gather the most relevant and current information. The articles obtained were evaluated for their relevance to the impacts of plant flora on water quality, water quantity, and overall water resource management. The literature selected explored how vegetation interacts with the water cycle, its capacity for pollution reduction, and various plant-based management techniques, including experimental studies, review articles, and conceptual frameworks that highlight the effectiveness of these methods. This approach aimed to

provide a well-rounded understanding of the crucial role of plant flora in the sustainable management of clean water resources.

Impacts of Plant Flora on Water Quality

Plant flora plays an essential role in enhancing water quality in freshwater ecosystems through various mechanisms. Riparian (stream-side) and wetland vegetation are particularly effective in reducing pollution.

Filtration and Pollution Reduction

Riparian buffer vegetation is vital for reducing surface runoff from agricultural lands, as it filters sediments, nutrients, and other pollutants before they reach water bodies (Hou et al., 2019; Locke and Winter, 2024). This vegetation helps improve river water quality by preventing upstream pollution from entering the river (Hou et al., 2019). It can significantly lower pollution levels in both surface water and groundwater by filtering, absorbing, retaining, and accumulating contaminants (Hou et al., 2019). A notable increase in pollution can occur when the amount of natural vegetation drops below certain thresholds (Locke and Winter, 2024). Additionally, vegetation serves important environmental functions by reducing soil erosion from rain and addressing the harmful effects of pollutants (Bertini et al., 2015; Sun et al., 2021; Yang et al., 2023; Dahanayake et al., 2024).

Nutrient Removal and Phytoremediation

Plants have a remarkable ability to clean up polluted water by absorbing and metabolizing excess nitrogen and phosphorus. This natural process reduces the concentration of nutrients that lead to eutrophication, a phenomenon that can choke life out of water bodies. For example, a single hectare of wetland plants can absorb up to 100 kilograms of nitrogen and phosphorus from agricultural runoff, preventing it from entering nearby waterways (Wu et al., 2024; Yu et al., 2019).

Phytoremediation, the practice of using plants to remove pollutants from the environment, is a cost-effective and sustainable technology. It involves using plants to absorb, degrade, or stabilize pollutants like heavy metals, pesticides, petroleum waste, and even radioactive materials. This technology has been successfully used to clean up contaminated soil and water, as shown by studies such as Delgado-González et al. (2021), Khan et al. (2022), Wang et al. (2024), and Wentzell et al. (2025).

The process of phytoremediation is fascinating. Plants use their roots to absorb pollutants from the soil and water, storing them in their tissues or breaking them down through various mechanisms. For instance, some plants can filter out heavy metals from contaminated water using their roots, a

process called rhizofiltration (Bartucca et al., 2023). Others can break down pesticides and other pollutants through a process called phytodegradation (Uturunco et al., 2024).

Some plants are particularly adept at removing pollutants from water. The water hyacinth, for example, can absorb up to 70% of metals like copper, aluminum, lead, mercury, cadmium, and metalloids like arsenic from contaminated water (Monroy-Licht et al., 2024; Sayago et al., 2024). This remarkable ability makes phytoremediation a valuable tool in the fight against water pollution.

Bioindicators and Ecosystem Health

Aquatic plants are reliable bioindicators of water quality and can detect even slight hydro-morphological changes, thanks to their sensitivity to pollution and altered conditions in freshwater ecosystems. As shown by Ceschin et al. in 2020 and Ebling and Padial in 2024, these plants respond rapidly to changes in their environment. Moreover, freshwater macrophytes deliver essential ecosystem services, including nutrient cycling and habitat provision, while also contributing to water purification and disease control, as highlighted by Thomaz in 2023.

Impacts of Plant Flora on Water Qality, Quantity and the Hydrological Cycle

Vegetation's impact on water quantity and the hydrological cycle is multifaceted, with far-reaching consequences for water management. For instance, during the dry season, trees like the baobab in Africa can tap into groundwater reserves, releasing water vapor into the air through transpiration, and creating a local rainfall effect.

In regions like the Mississippi River Basin, the health of vegetation cover directly affects water quality. A dense cover of vegetation helps to absorb excess nutrients and sediments, preventing them from entering waterways and causing harm to aquatic life. Conversely, bare or degraded lands can lead to soil erosion, resulting in the deposition of pollutants into water bodies.

Plant flora also plays a crucial role in regulating the water cycle by influencing the rate of evaporation and runoff. In urban areas, the lack of vegetation can exacerbate flood risks, as paved surfaces and buildings increase runoff rates, putting pressure on drainage systems. By contrast, green infrastructure, such as parks and green roofs, can help to absorb rainfall, reducing the burden on urban water management systems.

Understanding the intricate relationships between vegetation, water quality, and the hydrological cycle is vital for effective water management. By preserving and restoring natural habitats, and incorporating green

infrastructure into urban planning, we can better mitigate the impacts of water scarcity and flood risks.

Infiltration and Groundwater Recharge

Dense vegetation plays a crucial role in maintaining healthy soil ecosystems, which in turn, supports the replenishment of groundwater reserves. When dense vegetation covers the soil, it improves the soil's structure, allowing it to hold more water and air. This, consequently, increases the soil's organic matter content, making it more conducive to water infiltration. As a result, water seeps into the soil at a faster rate, reducing the likelihood of surface runoff (Hao et al., 2020; Hidayat et al., 2024). This process is vital for recharging groundwater reserves, which are essential for meeting the world's growing water demands. For instance, in areas with dense vegetation, such as forests or grasslands, the soil can absorb rainwater quickly, reducing the risk of flooding and preventing pollutants from entering waterways. On the other hand, areas with sparse vegetation, like urban landscapes or degraded lands, often experience increased surface runoff, leading to erosion and decreased groundwater recharge. By understanding the intricate relationship between vegetation, soil, and water, we can better manage our natural resources and ensure a sustainable future for generations to come.

Evapotranspiration

The evapotranspiration process, which recycles soil moisture back into the atmosphere, relies heavily on plants to function effectively. This crucial process has a significant impact on the local climate and regional water cycle (Li et al., 2025; Zhang et al., 2024). In urban areas, forests play a vital role in managing stormwater runoff, alleviating pressure on drainage systems and reducing the risk of flooding (Chianese and Motlagh, 2025; Marrazzo and Raimondi, 2025). This is especially important in cities like Tokyo, where rapid urbanization has put a strain on water resources.

Flood and Flow Regulation

Forests and natural vegetation serve as a natural barrier against floods, reducing peak flows and maintaining base flows during dry periods (Anjinho et al., 2024; Campos et al., 2018). The relationship between vegetation cover and flood control is straightforward: the more complex the vegetation, the more effective the flood regulation. This is evident in micro-basins with dense vegetation, such as those found in the Congo Basin, where natural cover helps to regulate water flow and prevent devastating floods.

Plant Flora Management Strategies in Water Resources Management

To optimize the benefits of plant flora in water resource management, several strategies have been developed. One approach is to restore degraded watersheds by replanting native vegetation, which helps to rebuild natural buffers against flooding and erosion. Another strategy is to incorporate green roofs and walls into urban planning, reducing stormwater runoff and alleviating pressure on drainage systems. By adopting these strategies, communities can ensure a sustainable supply of clean water while protecting the environment.

Riparian Zone Restoration and Management

Riparian zones, the interface between land and water, are crucial ecosystems that support a wide range of plant and animal life. These areas perform essential ecological functions, including stabilizing stream banks, filtering pollutants from water, reducing erosion, and recharging groundwater (Majumdar and Avishek, 2023; Naiman and Décamps, 1997). The restoration of riparian vegetation is a key strategy for improving river health, promoting biodiversity, and maintaining water quality (Gu et al., 2025; Özgenç, 2024). In fact, healthy riparian zones can act as natural buffers, protecting aquatic ecosystems from the impacts of human activities. Bioengineering techniques, such as restoring natural hydrological processes and promoting riparian vegetation growth, offer a more effective approach to managing rivers than traditional fixed riverbeds. For example, these techniques have been shown to remove significantly more nitrogen and phosphorus from river loads, leading to improved water quality and ecosystem health (Symmank et al., 2020; Chi et al., 2024).

Ecological Engineering and Constructed Wetlands

The innovative approach of constructed wetlands is revolutionizing wastewater treatment. By harnessing the natural purification powers of vegetation, soil, and microorganisms, these artificial ecosystems effectively remove pollutants like nitrogen, phosphorus, and organic matter from wastewater (Ferreira et al., 2023; Siddha and Kumar, 2023; Vymazal, 2010). Constructed wetlands have been shown to be particularly effective in removing nitrogen, with some studies demonstrating a removal rate of up to 98% (Babaniyi et al., 2025; Guerrero et al., 2020). The benefits of constructed wetlands extend beyond pollution reduction, offering a cost-effective and low-maintenance solution that can be implemented globally (Kataki et al., 2021).

Phytoremediation Applications

Phytoremediation, the use of plants to clean contaminated water, is a burgeoning field with vast potential. By carefully selecting plant species, researchers can target specific pollutants and remove them from water (Kafle et al., 2022; Pang et al., 2023). Advanced technologies like nanotechnology are being explored to enhance phytoremediation's effectiveness, increasing the bioavailability and degradation of pollutants (Aryal, 2024; Das et al., 2023; Kafle et al., 2022). For instance, researchers have found that certain plant species can remove heavy metals like lead and mercury from industrial wastewater (Wentzell, 2025).

Watershed Management

Vegetation plays a vital role in regulating water cycles, making it a cornerstone of effective watershed management. By preserving and restoring vegetation cover, we can significantly reduce the risk of water scarcity and excess water problems, which can have far-reaching consequences for ecosystems and human societies alike. For instance, research has shown that every 10% of forest cover lost results in a 10% decrease in water yield, highlighting the critical importance of vegetation in maintaining healthy water cycles (Amparo-Salcedo et al., 2025). Similarly, studies have demonstrated that restored vegetation in urban areas can reduce stormwater runoff by up to 40%, minimizing the likelihood of flooding and landslides (García-Ávila et al., 2026a).

In addition to these benefits, vegetation also helps regulate water flows, mitigating the impact of extreme weather events like floods and droughts. Imagine a sponge, soaking up excess water during heavy rainfall events and slowly releasing it during dry spells – this is essentially the role that vegetation plays in maintaining stable water flows. By prioritizing vegetation preservation, we can create a more resilient environment, better equipped to withstand the challenges of a rapidly changing climate.

RESULTS AND DISCUSS1ON

The complex and multifaceted role of plant flora in maintaining clean water resources is crucial for sustaining ecosystems and human societies. The mechanisms outlined above demonstrate the profound impact of vegetation on water quality and quantity, underscoring the need for sustainable management practices. However, the widespread adoption of nature-based solutions also poses significant challenges that must be addressed.

Integrated Approaches

Combining nature-based solutions with green infrastructure can foster a more sustainable approach to water resource management, balancing human

needs with environmental conservation. This holistic strategy can lead to multiple benefits, including improved financial, produced, social, human, and natural capital, as demonstrated by Dale et al. (2021) and Vörösmarty et al. (2021). For example, investing in green water supply infrastructure can not only ensure water security but also stimulate local economic growth and carbon sequestration, as shown by McMahon et al. (2022).

Economic and Social Benefits

Nature-based solutions can provide significant economic returns through long-term savings on flood damage, water treatment, and recreational benefits. By valuing ecosystem services economically, policymakers can better understand the critical link between the environment and the economy, as emphasized by Koundouri et al. (2022) and Romañach et al. (2018). This approach can help policymakers make informed decisions about water management, as García-Ávila et al. (2026) have demonstrated.

Research Areas

Future research should delve into the intricacies of microalgae-macrophytes-plant interactions to revolutionize water treatment systems. By examining the interplay between these organisms and critical environmental factors, such as pH, dissolved oxygen, and nutrient cycling, researchers can uncover novel ways to enhance pollutant removal and biomass productivity. This knowledge can be leveraged to develop innovative methods for biomass separation and valorization, generating high-value products. Additionally, the role of regional endemic species in water resources must be elucidated, particularly their adaptability to local conditions and potential to support sustainable water management. For instance, studying the unique traits of endemic species can reveal their capacity to tolerate pollutants and inform strategies for bioremediation. It is also crucial to investigate the ripple effects of human activities, such as deforestation, dam construction, and climate change, on water resources and identify adaptive solutions to mitigate these impacts. By identifying the most effective wetland community designs and species combinations for pollutant removal, researchers can create tailored solutions for upgrading water treatment efficiency, preserving ecosystem health, and ensuring sustainable water resource management.

CONCLUSION

Plant flora is essential for the sustainable management of clean water resources. It provides vital ecosystem services, such as enhancing water quality, regulating water quantity, and supporting hydrological processes, which are crucial for both human well-being and ecosystem health. Through

natural processes like filtration, phytoremediation, and nutrient removal, plants deliver effective and cost-efficient solutions for reducing pollution in aquatic ecosystems. Strategies such as riparian restoration, constructed wetlands, and watershed-based management, when integrated into water management practices, can yield significant environmental, social, and economic benefits.

However, the increasing impacts of climate change, gaps in existing policy and legal frameworks, and challenges in scaling up implementation limit the full realization of this potential. Future research should focus on understanding the complexities of plant-water interactions, modeling the effects of climate change on these systems, and developing innovative technologies to enhance the effectiveness of nature-based solutions. Policies need to encourage intersectoral collaboration and establish incentives that recognize and support the ecosystem services provided by plant flora. Public awareness and local engagement are crucial for the successful implementation of these strategies.

In conclusion, sustainable clean water resource management requires a comprehensive approach that fully leverages the natural capabilities of plant flora. This will provide resilient solutions to current water challenges and ensure healthy and safe water resources for future generations.

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How To Cope Wıth The Effects Of Global Warmıng On Agrıculture?

Erkan YASLIOGLU[1]

Ercan SİMSEK[2]

1- Prof. Dr.; Bursa Uludağ Üniversitesi Ziraat Fakültesi Biyosistem Mühendisliği Bölümü. yasli@uludag.edu.tr ORCID No: 0000-0002-3865-7863

2- Prof. Dr.; Bursa Uludağ Üniversitesi Ziraat Fakültesi Biyosistem Mühendisliği Bölümü. esimsek@uludag.edu.tr ORCID No: 0000-0001-9979-5496

ABSTRACT

The increase in human-caused greenhouse gas emissions since the Industrial Revolution has led to a rise in the average surface temperature of the Earth. The ever-increasing greenhouse gas emissions have pushed this temperature increase to levels that threaten human life. Global warming tremendously effects life on Earth in recent years, particularly through rising temperatures and extreme events such as droughts and floods. Increased industrialization efforts worldwide have amplified this effect day by day. Recognizing the severity of the situation, global efforts to find solutions is increased. The Kyoto Protocol was signed 1997, 15th Conference of the Parties held in Copenhagen, the capital of Denmark in 2009, and the Paris Agreement was signed in 2015. At the 15th Conference of the Parties a text called the "Copenhagen Accord" was signed, supported by 140 countries but without imposing any legal obligation; it aimed to keep the global temperature increase below 2°C. Then, 2°C global temperature increase target is reduced to 1.5°C with the Paris Agreement. Within the context of Paris Agreement, China, the leading emitter countries of greenhouse gases, along with the US and India is also joined in, all countries have committed to reducing greenhouse gas emissions below a set level by 2030. This study examines the effects of global warming on agriculture and the required mitigation measures.

Keywords – Global warming, drought, greenhouse gases, mitigation, carbon footprint

1. INTRODUCTION

Nowadays, the effect of global warming on life, especially agriculture is increasing tremendously. First of all it should be clearly understood the global warming to cope with it, appropriately. Global warming is recently discussed phenomenon worldwide since last century resulted from human activities such as fossil fuels (coal, oil and gas) burning, large-scale deforestation caused by forest fire and mining etc., which resulted increase in greenhouse gases emissions into the atmosphere, mostly carbon dioxide. The atmospheric Carbon Dioxide (CO_2) concentration increased from 277 ppm in the beginning in industrial era to 422.8 ppm in 2024 (Anonymous, 2025a:1).

Greenhouse gases absorb infrared radiation emitted by the Earth's surface, and also act as a blanket over the surface, which is known as the greenhouse effect. Therefore earth's surface temperature is higher than it would otherwise be. One of the main observed impact of global warming is global climate change which deeply effect of all biological life on the earth. Considering the potential global climate change pattern in the twenty-first century, in case of taking no additional mitigation activities; global mean

temperature and sea level are likely to rise by about 1.5 to 5.5°C, 0.5 metre (range 0.1–0.9 m), respectively. Some significant changes in hydrological cycles such as more frequent and more intense floods and droughts likely to be occurred, the rate of climate change is likely to be considerably greater than experienced over the last ten thousand years. It is crystal-clear fact that most of the warming over the last 50 years has been caused by humans(IPCC, 2007:112).

Several scientist noticed the greenhouse effect earlier. Jean-Baptiste Fourier, French scientist, was expressed it in 1827. Then, around 1860, the absorption of infrared radiation by carbon dioxide and water vapour was measured by John Tyndall. According to the findings, he suggested that the ice ages might be resulted from a decrease in the greenhouse effect of carbon dioxide. Another scientist, Svante Arrhenius(Swedish chemist) firstly calculate the effect of increasing concentrations of greenhouse gases in 1896. He estimated that doubling the concentration of carbon dioxide would increase the global average temperature by 5–6˚C. Surprisingly it is not too far from present estimates(Mudge, 1997:13).

According to the European Environment Agency (EEA 2017) the key observed and projected climate change and its impacts in southern Europe as follows:

1.Substantial increase in heat extremes, 2. Decrease in precipitation and river flow, 3. Increase in drought risk, 4. Increase in biodiversity loss risk, 5. Increasing risk of forest fires, 6. Increased competition between different water users, 7. Increasing water demand for agriculture, 8. Decrease in crop yields, 9. Increasing risks for livestock production, 10. Increase in mortality from heat waves, 11. Expansion of habitats for southern disease vectors, 12. Decreasing potential for energy production, 13. Increase in energy demand for cooling, 14. Decrease in summer tourism and potential increase in other seasons, 15. Increase in multiple climatic hazards, 16. Most economic sectors negatively affected and 17. High vulnerability to spill over effects of climate change from outside Europe.

2. IMPACT OF GLOBAL WARMING ON AGRICULTURAL PRODUCTION

In recent years, despite all mitigation measures, global warming threatens plant and animal production and leads to yield losses. Regular rainfall and adequate soil moisture are key to agricultural production. As has been the case in recent years, erratic rainfall patterns, coupled with a lack of adequate soil moisture at the right time, threaten agricultural productivity, leading to a decline in food production.

Global warming will lead to negative impacts on agricultural resources, such as the decrease in water resources, the change and transformation of arable land assets, the increase in pollution load and the accumulation of toxic substances in the food chain (Srivastav 2019:94).

Changes in climatic factors such as temperature, humidity, insolation, and precipitation, as well as variations in the frequency and intensity of extreme events like drought, floods, and storms, directly affect productivity in both crop and livestock production. Although plant and livestock production are complementary components, it is beneficial to examine them separately in order to more clearly reveal their effects.

2.1.Impacts on Crop Production

Although temperature increases can have both positive and negative effects on crop yields, it has generally been found that temperature increases reduce the yield and quality of many crops, most notably grain and forage crops. Although it is thought that the increase in the amount of CO_2 accumulated in the atmosphere will increase the temperature on the one hand and the product yield on the other hand, this increase will not be enough to compensate for the harmful effects of the temperature increase on the yield, and the positive effect of CO_2 on the increase in yield will not be seen in important crops (Wali et al., 1999:24).

Wali et al. (1999) stated that pollination is the most sensitive period in a plant's life cycle, and that the world's three staple foods (rice, wheat, and corn) are particularly sensitive to this process. They reported that pollen from its tassels must land on the fine tassel fibers attached to the grain nests at the tip of each corn cob for corn to reproduce. For grains to develop in the nests, pollen must transport from the tassel fibers to the seed nest. When temperatures are above normal, the tassel fibers quickly dry out, turn brown, and cannot function during the fertilization process. (Pollen can survive for 3 days, and stigmas for 4 days.)

Global warming also leads to indirect effects such as changes in the incidence and distribution of pests and pathogens (Sutherst et al. 1995:60), increased rates of soil erosion and degradation, and increased tropospheric ozone levels due to rising temperatures (Adams, 1986:466).

Increases in precipitation can benefit semiarid and other water-scarce areas by increasing soil moisture, while they can exacerbate problems in water-excessive areas. Reductions in precipitation can have the opposite effect. Increased atmospheric CO_2 concentrations will lead to higher net photosynthesis rates (Cure and Acock, 1986:128, Allen et al. 1987:1).

Lesk et. al., (2016:1), determined that there was a 9–10% decrease in national cereal production in the UK associated with extreme heat events between 1964 and 2007 due to a decrease in harvested area and productivity.

Extreme temperatures and weather events caused by global warming have led to a significant decrease in agricultural production, which in turn has restricted local food supplies and caused prices to rise (Escalante and Maisonnave, 2022:1; Solaymani, 2018:1590; Yen et al., 2019:16). Climate change-induced productivity drops can undermine people's economic investment capacity including farm inputs, technology, labor, and equipment for future production and adaptation measures.

The most vulnerable community to climate change is the rural population in low- and middle-income countries. Climate change will affect rural populations directly through reduced agricultural incomes and indirectly through off-farm income and food prices. Discriminatory social norms, along with differences in socioeconomic assistance and access to services and institutions, make some people more vulnerable to climate change than others.

2.2.Impacts on Livestock

Nowadays, most significant constraint to the global sustainability of livestock production systems is climate change. Adaptation and mitigation approaches to the negative impacts of climate change on animals play an important role in the struggle (Sejian et al., 2015:142).

In addition to the direct effects of global warming, such as heat stress due to increasing temperatures, indirect effects such as water scarcity, decrease in roughage/concentrate feed production and pathogens will have a much more negative impact on livestock production.

High temperature, nowadays frequently observed as a result of global warming, accompanied by high relative humidity cause heat stress in livestock. Under the heat stress conditions livestock escalate the efforts to dissipate body heat, causing the increase in body temperature, respiration rate, water consumption and a decrease in feed intake.

Increasing temperatures, lead to decreased production (reduced grazing areas, decreased live weight growth, decreased milk production, decreased fertility), behavioral problems, and increased animal mortalities in addition to heat stress. Livestock animals perform best between 10-30°C. It is stated that every 1°C increase in ambient temperature above 30°C results in an average 3-5% decrease in feed consumption for cattle, sheep, goats, and chickens (NRC, 1981:14).

The problems that climate change will cause in animal husbandry include increased susceptibility to diseases, the emergence of mutations in disease and parasite agents, an increase in animal-borne diseases, and the emergence of previously unseen animal diseases. Livestock production systems worldwide will be affected by this situation, and the demand for animal products will increase in the future. Food and water security will be among humanity's most important priorities in the 21st century. Furthermore, local and global climate changes are expected to impact agriculture worldwide this century.

Agricultural commodity prices are also affected by the strategies producers adopt to cope with climate-related stresses. For example, small-scale producers with limited access to functional insurance markets may sell their livestock to compensate for lost income and facilitate consumption (Assan et al., 2018:2; Mishra and Mishra, 2010:177; Wouterse et. al., 2022:1-2). These sales can lead to rapid drops in livestock prices in local

markets. For example, forced livestock sales following adverse weather events in northwestern China led to a 60% drop in livestock prices, approximately (Zhang et al., 2022:5).

To meet the nutritional needs of the growing global population, animal production will also increase relatively. It is estimated that the world population will reach 9.3 billion in 2050, with more than 60% of this population living in cities. Herein, to achieve a balance between livestock production and animal products consumption, either the number of animals or productivity per animal must be increased. To ensure the sustainability of livestock farming, water use efficiency must be increased to counter the expected decrease in water quantity and quality (Koyuncu, M., 2017:101).

To mitigate the effects of global warming, the following measures, which will have short-term and long-term effects, can be taken at the farm level(Koyuncu, M., 2017:104).

- Adjusting the planting dates of forage crops considering changing climate conditions.
- Selecting suitable plant varieties in terms of growing requirements and water usage and adaptation capability to abnormal temperature and humidity conditions.
- Using water more efficiently and ensuring water recycling or storage through reducing water losses, improving irrigation practices.
- Improving soil management practices that increase water holding capacity to conserve soil moisture, and adopting land management approaches that facilitate the sustainability of animal's vital activities.
- Improving the effectiveness of pest and disease control, for example through better monitoring, diversified crop rotations, or improved integrated pest management methods,
- Introducing high temperature-tolerant animal breeds and adapting the ration models for animals in a way that will relieve them under heat stress conditions.
- Technical solutions for animal house indoor climate control to protect animals from extreme cold or heat.

3. GLOBAL WARMING INDUCED DROUGHT

The problem to cope with is substantially difficult created by global warming is global climate change. Global climate change also causes various problems in different sectors at the international level, such as drought. Drought is defined as a period of prolonged moisture deficit and divided into four categories as meteorological, hydrological, agricultural, and socioeconomic drought (Heim Jr., 2002:1149; Mukherjee et al., 2018:145).

Climate change-related disasters pose the highest risk to agriculture and livelihoods for rural areas especially in developing countries. Ashraf et. al. (2021:2127) stated that frequent droughts observed in the arid and semiarid region of Pakistan is due to changing rainfall pattern. Farming

communities are affected by drought disasters that cause serious threats to livelihood, global food crises, environmental migration, and sustainable development.

Measurements of drought-related variables such as humidity, precipitation, winds, runoff, cloud cover, and surface radiation have become more widespread and recorded since 1950. It is observed that global surface temperature, atmospheric CO_2, and other greenhouse gases were rapidly increased, since 1950. Therefore, changes in drought over the last 75 years revealed by detailed analyses of these data may bring out whether global warming induced droughts will become more frequent and widespread in the coming decades.

Oguntunde et al. (2017:121) found that drought frequency and magnitude under climate change in the Volta River Basin increased in 2046-2065 and 2081–2100 compared to 1970–2013, based on standardized precipitation index (SPI), standardized precipitation and evapotranspiration index (SPEI) and standardized runoff index (SRI) time series and the relationships among these indices.

Nowadays, changes in the precipitation regime and amount due to climate change lead to the problem of not only meeting agricultural irrigation water needs but also domestic water use needs. At the societal level, drought causes loss of plant and animal production, and at the advanced level, it leads to chronic food shortages and famine. The migration of people living in regions face with famine and drought from rural areas to cities getting food and employment will cause new social problems and pressure on urban resources.

The effects of drought on livestock generally include a decrease in meat, milk and egg production, significant losses in body condition and weight, irregularities in the immune system, increased susceptibility to diseases, and long-term drought negatively impacts reproductive performance.

The effects of drought on agriculture can be briefly summarized as follows:

- Decrease in plant and animal product productivity, loss of quality and increase in costs,
- Increase in pest and diseases,
- Decrease in quality soils required for agricultural production,
- Water and wind erosion of soils,
- Reduction in irrigation water supply and quality,
- Losses in agro-industries,
- Risk of food security,
- Reduction in farmer income.

4. MITIGATION EFFORTS

Since the 1970s, countries around the world have been seeking solutions to environmental problems through global collaboration. These efforts, which began with the 1972 Stockholm Conference under the auspices of the United Nations, manifested themselves primarily in the climate meetings held in Rio in 1992 and Kyoto in 1997. While the first international meeting and agreement directly related to climate took place in Rio in 1992, this meeting lacked clarity on concrete commitment criteria and the extent to which countries would be held accountable. The Kyoto Protocol, signed in 1997, was a milestone because it included, for the first time, a commitment to reduce carbon emissions to specified levels (Sinn, 2012:35). The Kyoto Protocol set a target for 38 developed countries to reduce emissions by 5.2% compared to 1990 levels. While global greenhouse gas emissions increased by 44% until 2012, countries covered by the protocol achieved reductions of between 7% and 12.5% (Anonymous, 2022:1). Although global climate meetings within this framework continued regularly until the 2015 Paris Climate Summit, no solution was reached, and environmental problems and global warming continued to escalate. The Paris Agreement aims to limit the global temperature increase to below 2°C and, if possible, to 1.5°C compared to pre-industrial levels. Countries update their greenhouse gas reduction targets every 5 years (Anonymous, 2025b:1). While the Paris Climate Agreement represents a much more significant milestone, no concrete developments have yet been seen that would change the outcome, apart from the commitments and strong will of countries. The most important reason for this was the reluctance of global capitalism and capitalist state forms, which underlie the problem, to compromise their existing institutional structures, commodity-based economic approaches, and political preferences.

Morrison et. al. (2025:1) stated that wine grape, coffee, and cocoa production is becoming increasingly unstable endangering the livelihoods of millions of farmers due to global warming. The research team focused on stratospheric aerosol injection, a geoengineering technique that has been heavily debated in recent years. This method aims to cool the planet by releasing particles into the upper atmosphere that reflect sunlight. In the study 18 major agricultural regions in Western Europe, South America, and West Africa for the years 2036-2045 were modeled. The results showed that while stratospheric aerosol injection lowered temperatures, it failed to stabilize critical variables such as rainfall, humidity, and disease risk. Only six regions showed a significant improvement compared to areas where stratospheric aerosol injection was not applied. They concluded that lowering the temperature alone was not enough. Plants like cocoa, coffee, and grapes are affected not only by heat but also by humidity and rainfall. It's impossible to balance such a complex system with a single method.

Local adaptation strategies, sustainable practices, and international solidarity are needed to secure the future of agriculture.

5. CONCLUSIONS

Taking measures related to agricultural activities alone will not be sufficient to mitigate the effects of global warming on agriculture. These efforts must be carried out in coordination with other sectors contributing to global warming, and measures taken in a specific region must be implemented from a global perspective.

The carbon footprint and water footprint should be calculated for each agricultural activity, and solutions to mitigate the problem should be developed in areas where deemed necessary, based on the findings.

To effectively implement these measures, appropriate policy tools must be developed, and farmer awareness and training programs organization is needed to maximize success.

It should never be forgotten that both academic and industrial technology will make significant contributions to finding solutions to adaptation and mitigation problems.

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Volume Calculation from Digital Elevation Models: A Practical Application Using QGIS

Mehmet ŞENER[1]

1- Prof.Dr.; Tekirdag Namik Kemal University, Faculty of Agricultre, Biosystem Eng. Dept. msener@nku.edu.tr ORCID No: 0000-0002-6736-0567

ABSTRACT

Digital Elevation Models (DEMs) function as basic GIS elements which allow users to view three-dimensional land surfaces through Geographic Information Systems (GIS) (Guth et al., 2021). The main use of DEMs involves volume calculation which serves multiple fields including earth science and civil engineering and mining operations and environmental management and urban planning (Hengl & Reuter, 2009). The paper describes a complete method to extract volumes from DEMs through QGIS which operates as an open-source GIS software system. The research investigates DEM-based volume calculation theory while showing users how to apply the method and explaining its measurement precision and operational constraints. The research presents a complete method for volumetric analysis which practitioners and researchers can use to perform measurements in their respective fields. The results show that QGIS enables users to perform volume calculations through an easy-to-use interface which delivers precise results at no cost to users.

Keywords –Volume Calculation, QGIS, Geospatial Analysis, Terrain Analysis, Cut and Fill Analysis

INTRODUCTION

The measurement of terrain volumes stands as a basic necessity which multiple scientific fields and engineering specialties need to function. The requirement for exact volume measurements from topographic data has become vital for both construction earthwork quantity estimation and water resource management reservoir capacity evaluation in modern geospatial technology. Digital Elevation Models (DEMs) introduced a modern approach to this field because they create exact terrain surface models which allow scientists to perform complex volume calculations (Smith et al., 2011; Wilson & Gallant, 2000; QGIS Development Team, 2023).

The cross-section methods and contour-based approaches which are traditional volume calculation methods remain useful but they consume excessive time and fail to deliver the needed accuracy for modern uses. Users can now perform complex spatial analysis through GIS technology which operates through QGIS and other user-friendly systems that experts used to handle (Albut, 2025; Hengl & Reuter, 2009).

The research investigates DEM-based volume calculation methods in QGIS through an analysis of built-in algorithms which enable users to perform accurate volume measurements. The methodology presented here is applicable to diverse scenarios including cut-and-fill analysis for construction sites, stockpile volume estimation in mining operations, erosion and deposition studies in environmental science, and flood inundation volume

calculations in hydrology (Merwade, 2009; Tarboton, 2003). The general process for DEM-based volume calculation appears in Figure 1 which shows the steps used in GIS environments. The diagram in Figure 1 shows the complete process for calculating volumes.

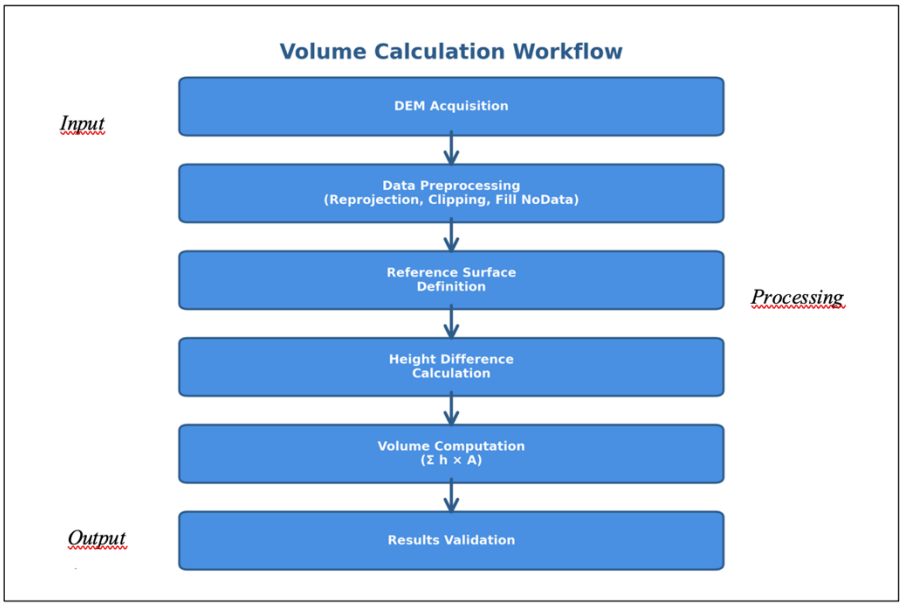


Figure 1: General workflow for DEM-based volume calculation in QGIS

THEORETICAL BACKGROUND

Digital Elevation Models

A Digital Elevation Model is a digital representation of terrain surface topography. DEMs exist as raster datasets which use elevation values to show height differences from a reference datum that is mean sea level. The quality and resolution of a DEM determines how accurately volume calculations will be produced from this data (Guth et al., 2021; Zhou & Liu, 2004).

The generation of DEMs occurs through different techniques which include photogrammetry and LiDAR (Light Detection and Ranging) scanning and radar interferometry and field surveying. The choice of DEM source affects both the horizontal and vertical accuracy of the model. The accuracy of volume calculations depends on vertical precision because it determines how well volumetric measurements will turn out (Liu, 2008; Zhou & Liu, 2004). The table 1 shows a comparison between different DEM sources which includes their main features.

Table 1: Comparison of DEM sources for volume calculation applications

DEM Source	Resolution	Vertical Accuracy	Coverage	Best Application
SRTM	30m	±16m	Global	Regional studies
ASTER GDEM	30m	±20m	Global	General mapping
Airborne LiDAR	0.5-2m	±0.15m	Local	Engineering projects
UAV Photogrammetry	0.05-0.5m	±0.05m	Site-specific	Small-scale detailed analysis
Ground Survey	Variable	±0.01m	Site-specific	High-precision engineering

Volume Calculation Principles

The process of volume calculation from DEMs requires users to establish the volume difference between two surfaces which include the reference surface and the actual terrain surface from the DEM (Hengl & Reuter, 2009). The fundamental mathematical procedure includes:

The area of interest needs to be divided into individual cells which function as elements for analysis. The DEM system uses each cell to represent a straight vertical space.

• The height difference needs to be calculated for each cell by comparing the reference surface to the DEM surface.

The calculation of individual cell volumes requires multiplying the height difference by the cell area.

• Summing all cell volumes - To obtain the total volume

The mathematical expression for volume calculation can be represented as: $V = \Sigma(h \times A)$, where V is the total volume, h represents the height difference at each cell, and A is the area of each cell. The cut-and-fill analysis needs volume data to be separated into two parts which include cut volumes for removing materials and fill volumes for adding materials. The conceptual framework appears in Figure 2.

The text preserves its original language structure while developing a human-like writing style. The output maintains a ratio between its length and the input material while preventing detailed explanations when working with short inputs (Wilson & Gallant, 2000).

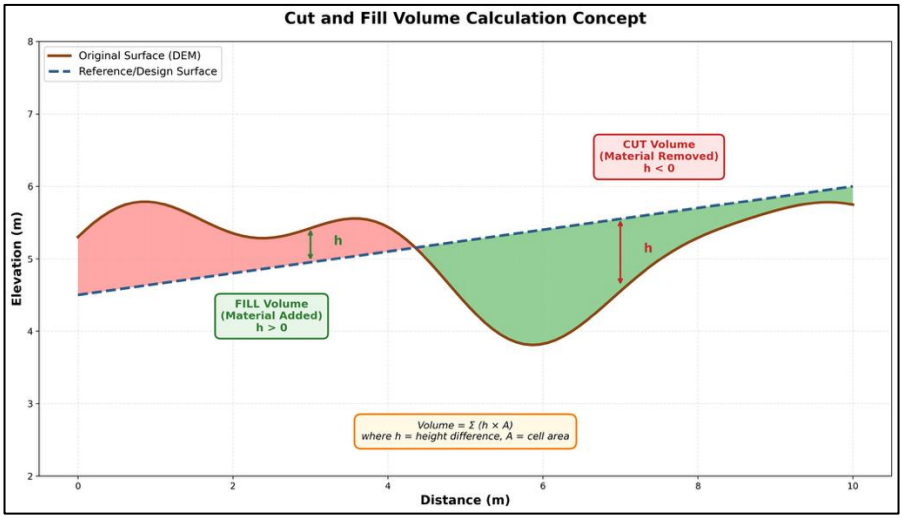


Figure 2: Conceptual framework of cut and fill volume calculation from DEMs

Applications of Volume Calculation

Real-world applications benefit from three fundamental advantages which DEM-derived volume measurements offer (Smith et al., 2011).

• Civil Engineering and Construction: The process of calculating earthwork amounts for grading work and excavation and embankment construction requires determining necessary materials and total project expenses.

• Mining and Quarrying: The system enables stockpile volume measurement and extraction rate tracking and excavation sequence planning.

• Environmental Management: The assessment of erosion and sedimentation volumes and reservoir storage capacity determination and landslide volume evaluation makes up the Environmental Management section (Merwade, 2009).

• Hydrology: The process involves three main steps which include flood inundation volume determination and depression water storage calculation and watershed property evaluation.

• Agriculture: The system performs three main tasks which include computing irrigation pond capacities and planning land leveling operations and estimating terrace volumes.

METHODOLOGY: QGIS IMPLEMENTATION

Software Requirements

QGIS (Quantum GIS) is a free and open-source Geographic Information System that provides comprehensive functionality for spatial data analysis (QGIS Development Team, 2023). The recommended version for volume calculation from DEMs is QGIS 3.0 or later because it provides better

raster processing functions and superior calculation methods. The software supports Windows, macOS and Linux operating systems which provides users with platform flexibility.

The Processing Toolbox in QGIS provides users with multiple tools and algorithms which enable volume calculation operations (GDAL/OGR Contributors, 2023). The necessary QGIS tools for volume calculation operations are listed in Table 2.

Table 2: Key QGIS tools for DEM-based volume calculation (QGIS Development Team, 2023)

Tool Name	Primary Function	Location in QGIS
Raster Surface Volume	Direct volume calculation from single DEM	GDAL > Raster analysis
Raster Calculator	Calculate height differences between DEMs	Raster > Raster Calculator
Raster Layer Statistics	Compute statistical summaries for volume	Processing Toolbox > Raster analysis
Fill Nodata	Interpolate missing elevation values	GDAL > Raster analysis
Warp (Reproject)	Transform DEM to appropriate projection	GDAL > Raster projections
Clip Raster by Extent	Extract DEM for specific area of interest	GDAL > Raster extraction

Data Preparation

The process of volume calculation requires several essential steps which need to be completed before starting (Hengl & Reuter, 2009).

DEM Acquisition and Quality Assessment

The first requirement demands access to appropriate DEM data which covers the specific region of interest. The data sources include national mapping agencies together with satellite-based datasets from SRTM and ASTER GDEM and aerial LiDAR surveys and specific survey operations. The DEM requires assessment of its spatial resolution and vertical accuracy and its extent of coverage. Volume measurement accuracy improves when using DEMs with high resolution but these models require advanced computing power to operate (Liu, 2008; Guth et al., 2021; Zhou & Liu, 2004).

Coordinate System Verification

The DEM needs to exist within a suitable projected coordinate system because this ensures proper results for area and volume measurements. The implementation of geographic coordinate systems which use latitude and longitude values leads to incorrect area measurements (Hengl & Reuter, 2009). Therefore, the DEM should be reprojected to a suitable projected

coordinate system, preferably one specific to the region of interest, such as Universal Transverse Mercator (UTM) or a local state plane coordinate system.

DEM Preprocessing

The DEM source and quality determine if preprocessing operations need to be performed. The process requires three main steps which involve sink depression treatment and noise reduction and DEM area restriction for the specific study area. The Processing Toolbox in QGIS offers multiple tools which enable users to perform these operations through its Fill Nodata and GDAL Warp and Clip Raster by Extent functions (Arun, 2013; GDAL/OGR Contributors, 2023).

Volume Calculation Procedure in QGIS

Users can calculate volumes from DEM data through QGIS because the software provides different methods for performing this operation. The most common methods are described below:

Method 1: Using Raster Surface Volume Tool

The Raster Surface Volume tool in QGIS allows users to perform volume calculations directly from DEM data because of its dedicated functionality (GDAL/OGR Contributors, 2023). The following steps need to be followed in order:

Step 1: Load the DEM - Users can access the Add Raster Layer function through Layer > Add Layer > Add Raster Layer (or use Ctrl+Shift+R) in QGIS. Browse to select your DEM file and click Open. The DEM will be displayed in the map canvas with a default grayscale visualization.

Step 2: Access the Processing Toolbox - Users can access the Processing Toolbox through two available methods which include selecting Processing menu > Toolbox or using the keyboard combination Ctrl+Alt+T. Users can view the Processing Toolbox panel after they access it through QGIS interface and it will display on the right side of the interface.

Step 3: The user needs to access the Raster Surface Volume Tool through the Processing Toolbox search function which enables them to locate the tool. The tool becomes accessible through GDAL > Raster analysis > Raster surface volume. Double-click to open the tool dialog.

Step 4: Configure Tool Parameters –

• Input layer: The first step requires users to select their DEM from the available options which appear in the dropdown selection.

• Band number: The system operates with Band 1 as its pre-installed default configuration.

• Base level: Enter the reference elevation for volume calculation

• Output file: The system requires users to select both the output directory and the desired file name for their HTML report file.

Step 5: Execute the Tool - Click the Run button. QGIS will process the DEM and generate an HTML report containing the volume statistics.

Step 6: Interpret Results - Open the generated HTML report in a web browser. The report shows volume measurements in cubic units which follow the DEM coordinate system and elevation measurement system.

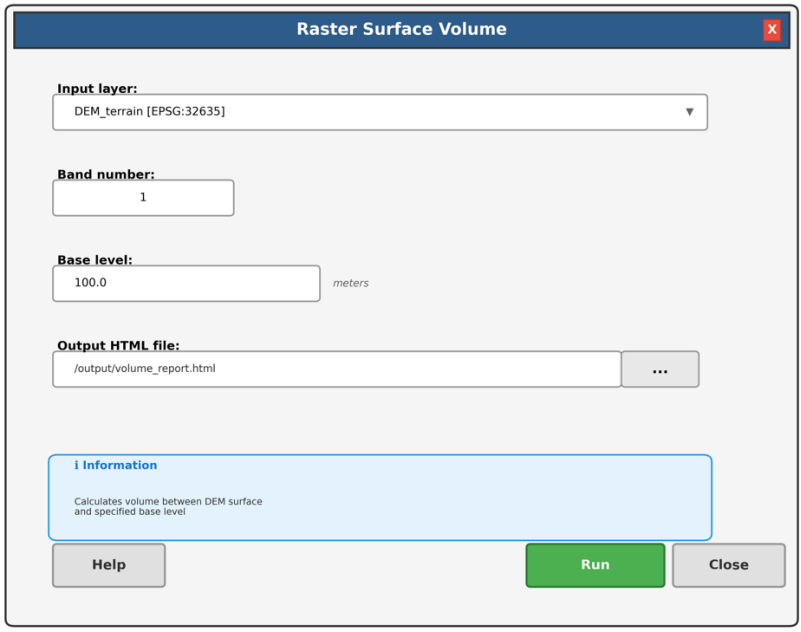


Figure 3: QGIS Raster Surface Volume tool interface and parameter configuration

Method 2: Manual Calculation Using Raster Calculator

For more control over the calculation process, particularly when working with two different surface models (cut-and-fill analysis), the Raster Calculator provides a flexible approach (Wilson & Gallant, 2000):

Step 1: Load Both DEMs - Load both the original surface DEM and the proposed/design surface DEM into QGIS. Ensure both rasters have the same spatial extent, resolution, and coordinate system (Hengl & Reuter, 2009).

Step 2: Calculate Height Differences - Open the Raster Calculator (Raster menu > Raster Calculator). Create an expression to subtract one surface from another.

Step 3: Separate Cut and Fill Areas - Use the Raster Calculator to create separate rasters for cut and fill volumes.

Step 4: Calculate Cell Area**s** - Determine the area of each raster cell based on the DEM resolution.

Step 5: Compute Total Volumes - Use Raster Layer Statistics to obtain sum of cell values, then multiply by cell area.

Method 3: Integration with External Plugins

The QGIS plugin collection includes multiple tools which enable users to perform volume calculations (Chen et al., 2015). The Volume Calculator plugin allows users to run cut-and-fill analysis through its simple interface. Users can access plugins through the Plugins menu which leads to Manage and Install Plugins where they search for volume-related plugins before installing their chosen plugin and executing its dedicated installation process.

The three volume calculation methods in QGIS receive evaluation through Table 3 which shows their benefits together with their constraints.

Table 3: Comparative analysis of volume calculation methods in QGIS

Method	Advantages	Limitations	Best Use Case
Raster Surface Volume	Quick, direct calculation; Automated HTML report	Single reference plane only; Limited visualization	Reservoir capacity, simple excavation
Raster Calculator	Maximum flexibility; Separate cut/fill analysis; Custom calculations	Multiple processing steps; Requires more expertise	Complex earthwork, cut-fill balance
External Plugins	User-friendly interface; Enhanced visualization; Automated workflows	Requires installation; May not be actively maintained	Routine projects, repetitive analyses

Quality Control and Accuracy Assessment

Ensuring the accuracy of volume calculations requires attention to several factors (Zhou & Liu, 2004):

• DEM Resolution: Higher resolution DEMs provide more accurate results but require more computational resources (Guth et al., 2021).

• Vertical Accuracy: Understanding the vertical accuracy specification of the DEM is crucial (Liu, 2008).

• Edge Effects: Areas at the boundaries of the DEM may exhibit artifacts or reduced accuracy (Arun, 2013).

• Validation: Where possible, validate volume calculations against known volumes.

• Uncertainty Quantification: Consider propagating the DEM's vertical uncertainty through the volume calculation (Zhou & Liu, 2004).

RESULTS AND DISCUSSION

Practical Application Example

The practical application of volume calculation in QGIS becomes clear through the examination of earthwork data which construction sites need to analyze. A construction company needs to estimate the volume of material to be excavated and filled for site preparation. Two DEMs are available: the existing ground surface and the proposed design surface.

The Raster Calculator method from Section 3.3.2 allowed users to perform surface difference calculations between the two datasets. The analysis revealed distinct zones of cut and fill across the 50,000 square meter site. The results from this case study appear in Table 4 which shows the complete volumetric analysis data.

Table 4: Volumetric analysis results for construction site earthwork (case study)

Parameter	Cut Volume	Fill Volume	Net Volume
Total Volume (m^3)	12,450	8,230	4,220
Affected Area (m^2)	28,350	21,650	50,000
Average Depth/Height (m)	0.44	0.38	0.08
Maximum Depth/Height (m)	2.85	1.92	-
Percentage of Total Area	56.7%	43.3%	100%

The cut and fill areas distribution across space became visible through a classification process which divided the difference raster into three zones that included cut areas with negative values and no change areas with near-zero values and fill areas with positive values. The visualization tool delivered vital value to construction planning because it enabled the project team to locate essential areas and create improved material transportation methods throughout the construction site (Smith et al., 2011).

Advantages of QGIS for Volume Calculation

The DEM-based volume calculations through QGIS offer users several essential advantages (QGIS Development Team, 2023; Chen et al., 2015).

- QGIS software operates as an open-source system which allows organizations to prevent expenses for licensing fees.
- The software QGIS allows users to work with multiple raster file formats which enable them to choose different methods for volume calculations.
- The system operates through complete integration which enables it to work perfectly with all existing geospatial applications and their associated databases.
- The system maintains an active user population which creates and maintains complete documentation and tutorial materials for system users.

The analysis process in QGIS becomes automated through Python scripting which enables reproducibility of results.

Limitations and Considerations

The volume calculation system based on QGIS operates with specific restrictions (Chen et al., 2015; Zhou & Liu, 2004; Arun, 2013; Hengl & Reuter, 2009).

- The system shows performance degradation when it needs to handle extensive high-resolution DEMs that cover extensive geographical areas.
- The results depend on the exact quality which the input DEM provides.
- The volume calculations depend on continuous surface connections between DEM cells according to interpolation assumptions.
- The user needs to understand GIS principles because QGIS provides an easy-to-use interface for volume calculation.

Best Practices

The following best practices emerge from practical experience and literature review (Guth et al., 2021; Hengl & Reuter, 2009; Arun, 2013):

- The selection of DEM resolution requires matching the needed precision level to the available processing power.
- The DEMs require verification of their coordinate systems which should use projected coordinate systems that match the particular area.
- The system requires users to track all processing operations together with their corresponding parameter values.
- The process needs verification of calculated volumes through alternative methods when such methods exist.
- The DEM needs to extend its boundaries past the study area borders because data becomes distorted when measurements reach the edge points.

FUTURE DEVELOPMENTS

The field of DEM-based volume calculation advances because of current technological developments. The field continues to advance through two main developments which involve machine learning algorithms for automatic feature detection and volume calculation and better approaches to determine volume measurement uncertainties and 3D visualization methods and augmented reality tools and cloud-based solutions for large DEM data processing and better UAV photogrammetry and LiDAR system integration (Crosetto et al., 2016; Chen et al., 2015; Liu, 2008).

The plugin system of QGIS together with its Python library integration enables users to access modern analytical tools which support open-source operations (QGIS Development Team, 2023).

CONCLUSION

The paper presents a complete procedure to extract volumes from Digital Elevation Models which users can perform using QGIS operations. The described methods offer simple and precise and budget-friendly methods for volumetric analysis which work for various engineering and environmental science and resource management needs. The step-by-step procedures enable practitioners to perform volume calculations with assurance through the accuracy discussion which helps them understand result limitations (Albut, 2025; Wilson & Gallant, 2000; Hengl & Reuter, 2009).

The open-source platform QGIS enables users to access complex geospatial analysis tools which expert users used to have exclusive access to. The software allows users to calculate volumes through its flexible interface which supports both large and small assessments through its powerful raster processing capabilities.

The volume calculation process will become more accurate and faster because GIS technology advances through improved DEM collection methods and enhanced computer processing capabilities. The research methods presented in this paper function as initial approaches which users can transform into new methods to handle their expanding project requirements and advancing technology (Guth et al., 2021).

The software QGIS provides researchers and engineers and environmental professionals with an efficient method to estimate volumes through its powerful flexible system which works for basic and advanced environmental assessments. Users can perform DEM-based volume calculations with confidence through the best practices in this paper which explains the method's limitations to enhance decision-making and project planning accuracy in different fields.

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The Relationship Between Animal Barns And Animal Productivity

Ercan ŞİMŞEK[1]

Erkan YASLIOĞLU[2]

1- Prof.Dr...; Bursa Uludağ Üniversitesi Ziraat Fakültesi Biyosistem Mühendisliği Bölümü. esimsek@uludag.edu.tr ORCID No: 0000-0001-9979-5496

2- Prof. Dr.; Uludağ Üniversitesi Ziraat Fakültesi Biyosistem Mühendisliği Bölümü. yasli@uludag.edu.trORCIDNo0000-0002-3865-7863:

ABSTRACT

The most important element of productivity in animal production is housing the animal in conditions suitable to its environment. It is important to understand that a suitable environment for the animal's needs and consideration of issues affecting animal welfare are necessary. Structural features of the shelter, floor arrangement, and ventilation, as well as climatic characteristics, are effective in animal welfare. Factors such as a suitable resting environment for animals, easy access to feeders and water, and their position during feeding reduce stress. At the same time, if the air quality inside the shelter is arranged according to the animal's needs, productivity can be achieved. This study emphasizes the importance of animal shelter design in terms of productivity, and explains the legal regulations regarding animal welfare in Turkey and the issues that should be considered in shelter design.

Keywords – Animal welfare, Barn, Dairy Cattle, Barn Floor Arrangement, Ventilation

INTRODUCTION

Today, animal production has become a strategic part of countries, not only meeting the basic nutritional needs of people but also providing raw materials to the industrial sector. Due to the increasing population in countries, the per capita need for animal-based food is also increasing day by day. To meet this need for animal production, livestock farming has become an industry, and the number of farms has begun to increase. In intensive cattle farming, productivity depends on various factors. Many factors, from housing to caretakers, from feeding to milking, affect productivity in cattle farming. Farm animals are social animals, and every factor in their social environment can be considered a source of stress or comfort for them (Estevez et al. 2007:189). Also, group or individual housing can affect their behavioral characteristics (Tapkı 2007, 57). Each animal species has specific behavioral patterns to perform certain functions, and these behavioral patterns are related to the animal's basic anatomy and life cycle.

Understanding and identifying animals, especially domestic farm animals, depends on studying their behavior. Behavior refers to observable body movements that occur throughout life, following birth, and are influenced by genotype and environment. Animal behavior is the physical reaction that animals exhibit to specific stimuli, influenced by heredity and the environment. The general aim of behavioral studies is to understand animals and maximize the benefits of their genetic characteristics. A cow will be productive as long as it is physically and psychologically

comfortable. Providing sufficient rest and freedom for cows in a herd prevents social stress and greatly facilitates rumination (Şahin 2008, Ertuğrul, 2025).

With livestock farming becoming an industry, the housing and feeding conditions of animals have begun to be neglected in the pursuit of housing more animals and achieving more economical production. In European countries, the environments in which animals are raised and the negative effects of modern methods on animals have begun to be debated by consumers, and consequently, the importance of the concept of "Animal Welfare" has increased.

Bracke et al. (2001:322) defined "welfare" for animals as their biological needs. The current definition of the concept of "Animal Welfare" was put forward by the Farm Animal Welfare Commission, formed by five different animal rights organizations in the UK.

Animal welfare is defined as the environmental conditions provided to animals so that they can exhibit all their natural behaviors in nature. Factors such as the size, location, lighting, and indoor environmental conditions of the barn directly affect the welfare of the animals. One of the most important reasons for the inability to achieve efficient production in livestock farming is that animals are removed from their natural habitats and housed in unsuitable barn conditions.

Botreau et al. (2007: 226) and the Welfare Quality Consortium (2009; 16) listed the factors affecting animal welfare under 4 basic principles and 12 criteria in order of importance (Table 1). When the specified criteria are examined, the importance of housing, i.e., barn conditions, in animal welfare ranks high. The comfort of the animals' resting place, the comfort of the indoor climate conditions, and the availability of sufficient roaming areas are fundamental factors affecting welfare.

Shelters are planned to eliminate the negative environmental factors affecting animals and to ensure productivity in production by creating a welfare environment. When selecting a location for the facility, the following factors should be considered: soil structure, topographical features of the land, location near roads, accessibility to water and electricity, and the location and arrangement (or usability) of other structures on the land. The floor layout and use of technology should be implemented to increase the work efficiency of the shelter's employees. Areas suitable for future expansion should be left to accommodate future developments. The shelter should be located in a way that allows for integration with other structures in the facility. The construction of the barns is expected to be simple, with sufficient air intake and exhaust openings, and suitable for comfortable and versatile use (Ekmekyapar 2001:45, Arıcı et al, 2001:8).

Various factors related to the shelter have an impact on animal welfare. These factors include microclimate conditions such as indoor temperature, air quality (humidity, air flow velocity, levels of various gases,

dust), and lighting; the space allocated per animal; indoor arrangements and equipment; the structure of the shelter floor and bedding; and the way the animals are tethered.

Table 1. Defining Animal Welfare in Barns with 12 Criteria within 4 Basic Components.

Conditions	Criteria
Nutrition	1- Prolonged fasting
	2- Prolonged thirst
Shelter	3- Resting place comfort
	4- Thermal comfort
	5- Freedom of movement
Health	6- Injury
	7- Illness
	8- Treatment
Behavior	9- Social behavior
	10- Other behaviors
	11-Caregiver-animal relationship
	12- General fear

Source: (Welfare Quality Consortium, 2009)

Barn Characteristics

To ensure animal welfare, shelter and herd management conditions must be suitable for the animals. Animals will experience stress if housed in unsuitable conditions. Therefore, the planning of shelters should be done taking into account the movements and environmental needs of the animals. Factors such as the size of the stalls where the animals will lie down, the structure of the feeders and waterers, the floor characteristics of the bedding, and the roaming areas directly affect animal welfare. In the planning of stables, it is first necessary to determine the dimensions of the facility according to the number of animals to be housed. After determining the number of animals to be housed in the facility, the selection of the location where the facility will be established is made. In site selection, the selected area should be large enough for the stable capacity and should allow for the future expansion of the facility's capacity (Simsek, 2013:).

In Turkey and worldwide, various barn models are used in dairy cattle farming. The vast majority of small-capacity businesses employing traditional production methods commonly utilize enclosed, tethered stalls. These types of businesses have very limited opportunities for capacity expansion and innovation. Operating these barns is quite difficult. Feed distribution, manure removal, milking, and care operations are time-consuming and tiring. Since the animals are constantly tethered, it is difficult to ensure their natural behavior and animal welfare. Furthermore, the unsuitable working environment for caretakers reduces productivity. The

free-standing open (semi-open) barn model, designed to suit the natural behavior of dairy cattle, allows animals to move freely (Arıcı et al., 2008). This barn type is implemented according to the region's climate conditions, with three sides enclosed and the south and east-facing sides open. Resting areas are freely provided for the animals, and exercise areas and feed troughs are arranged outside the barn. This structural model, designed with construction cost and animal welfare in mind, also has several drawbacks. Firstly, continuous use of bedding is required in the resting area, especially in winter. Since at least one side of the barn is open, regional winds directly affect the animals, leading to productivity losses. Therefore, this barn model may have limiting effects on its widespread use. In dairy cattle farming, the most common barn design today is the free-stall barn type. Free-stall barns can be arranged in various ways. In planning, various arrangements can be made according to the degree of protection of animals and workers from adverse external weather conditions, the amount of ventilation required, and the barn operating system. The basic functions that should be provided in system planning are to provide a healthy and comfortable environment for cows and workers, and to integrate the cattle shelters with the feeding, milking, and manure management systems within a functional planning framework (MWPS, 2000).

Cattle spend approximately 56% of their time lying down in their natural environment. Accordingly, planning stalls taking into account the animals' species, weight, body measurements, and lying positions is important for animal welfare (Koçak et al., 2015: 580). Cows need to rest at certain times of the day, and if their rest periods are insufficient, their resistance to certain diseases decreases along with stress. For this reason, the dimensions and floor characteristics of stalls allocated for animals to sleep and rest are very important.

Koçak et al. (2015: 579) examined the welfare levels of beef cattle farms with different barn characteristics using the Animal Needs Index (ANI) 35L method in their study. The farms examined were scored according to the criteria in the ANI 35 method for each farm, taking into account factors such as barn characteristics, bedding, feeding, and ventilation. According to the study results, animals in farms with free-stall systems scored higher in welfare levels because they have more freedom of movement compared to tethered systems.

Easy access to feed troughs and drinking water for animals within the barn also affects their productivity. It is generally recommended that dairy and feed cattle have access to feed for 21 hours a day. Health problems occur in animals if they are deprived of feed. In particular, feed troughs should be designed to allow animals' easy access to and consumption (Göncü et al, 2016: 15).

Barn Indoor Environmental Conditions

In barns, environmental conditions for animals can be categorized as climatic, physical, chemical, social, and microbiological. Environmental conditions affect the health and productivity of animals, as well as the structural characteristics and cost of barns for producers. Since environmental factors such as temperature, humidity, and air velocity directly affect the physiological structure of animals, these factors also affect water and feed consumption, causing changes in animal productivity (Kocaman et al., 2007:140).

The fundamental principle in barn construction is to create a living space for animals with optimal environmental conditions. No matter how good the barns where cattle are raised are, if the animals' desired environmental conditions are not provided, we cannot obtain the desired yield. Studies show that genotype has a 30% impact on animal yield, while environmental conditions account for 70% (Anonymous, 2013: 3). This is because environmental conditions constitute all external factors affecting the growth, development, and yield of animals.

For animal welfare and productivity, good air quality must be ensured within the barn environment. This requires good ventilation. Ventilation in animal barns has two main purposes: firstly, to meet the animals' oxygen requirements, and secondly, to remove heat, water vapor, CO2, ammonia, and other harmful gases, and to minimize the level of microorganisms and pathogens living in the barn's atmosphere (Noton, 1982: 140). Dairy cattle barns are classified as cold, adjustable, and hot barns according to the heat control provided by the insulation and ventilation system (MWPS, 2000:26).

In stables, the ventilation system should be designed taking into account the climatic conditions of the region in order to ensure optimum temperature and humidity conditions inside. The success of the ventilation system in the shelter's interior is measured by the air velocity inside. In stables, an air flow velocity of 0.2-0.5 m/s is desired. Furthermore, for the ventilation system to function effectively, the temperature difference between the indoor and outdoor environments should be between 5°C and 7°C (Ekmekyapar, 2001: 150; Usta, 2011:30).

Legal Regulations Regarding Animal Welfare in Turkey

In line with global developments in animal welfare, studies in our country have also gained momentum. According to Article 10 of the Regulation on General Provisions Regarding the Welfare of Farm Animals, published in the Official Gazette on November 22, 2014, the regulations for farms and internal farm arrangements are specified as follows (Anonymous 2014):

(1) The materials used for the construction of farms, and especially the enclosures containing equipment that animals may come into contact with, must be suitable for thorough cleaning and disinfection in a way

that will not harm the animals. (2) The sections where farm animals live are constructed in such a way that they can lie down, rest, stand up, defecate and urinate without any difficulty. (3) In farms where farm animals are kept, tools and equipment are properly cleaned and disinfected to prevent cross-contamination and the formation of disease-carrying organisms. Feces, urine, feed residues and scattered feed are; (4) On-site arrangements and installations for the safety of farm animals are constructed without any sharp edges or protrusions that could cause injury or suffering to the animals. The floor must be made of a hard, flat, and durable surface, and must be non-slip to prevent injuries and be suitable for the size and weight of the animals. The resting area must be comfortable and clean. Bedding suitable for the species and age of the animals is used. (5) The insulation, heating, and ventilation of the farm buildings; air circulation, dust levels, temperature, relative humidity, and gas concentrations are kept within limits that are not harmful to the animals. (6) Animals housed in farm buildings cannot be kept in continuous darkness or artificial lighting without sufficient rest periods. Arrangements are made to allow for natural or artificial lighting suitable for different climatic conditions to meet their behavioral and physiological needs. If the available natural light is insufficient to meet the animal's physiological and ethological needs, artificial lighting is provided for at least 8 hours, a duration equivalent to that of natural light.

CONCLUSION

Given the ever-increasing consumer demand for animal products, producers' desire for higher profits and criticisms of the environmental impacts of intensive production, animal welfare has become a current issue in Turkey. While legal regulations regarding animal welfare have been implemented in Turkey, European Union standards have not yet been reached in terms of barn design and hygiene.

In our country, where approximately 17 million cattle are raised today, barns need to be planned and designed taking environmental conditions into account, and existing barns need to be improved. In particular, in businesses that produce inefficiently in unsuitable environmental conditions, the housing conditions should be evaluated and suitable production conditions should be provided. During the planning and design phase of barns, considering the regional variations in climatic characteristics, the indoor environmental conditions should be planned according to the welfare level of the animals.

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