AGRICULTURE AND ENVIRONMENT 2

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PREFACE

Rapid urbanization and industrialization have resulted in a number of environmental issues that define our time. The sustainability of our planet and the future of humanity depend on how these processes affect agriculture. One industry that directly utilizes our natural resources and is essential to maintaining the equilibrium of the ecosystem is agriculture. Given the vital role that agriculture plays in providing for humanity's basic necessities, efforts to promote sustainable farming methods and raise environmental consciousness should be prioritized. Building a prosperous and sustainable future in this process requires the active participation and support of individuals and societies.

The purpose of this book is to increase understanding of how agriculture affects the environment and to highlight the actions that must be taken to create a more sustainable world. It contains important research that will direct society toward the agricultural and environmental policies required to accomplish the Sustainable Development Goals of the United Nations, which include eradicating hunger, reducing poverty, and providing access to clean water and sanitary facilities.

We would like to express our gratitude to the writers who contributed to the book because we firmly believe that minor adjustments can result in major changes that will enable us to coexist peacefully with the natural world in the future.

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CHAPTER 1

CARBON FOOTPRINT OF ANIMAL PRODUCTION – OVERVIEW

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INTRODUCTION

Climate change refers to significant, long-term shifts in weather patterns and temperatures. These changes are driven by both natural processes and human activities, especially greenhouse gas (GHG) emissions (IPCC, 2021). Human activities like burning fossil fuels, deforestation, and agricultural production account for over 90% of total GHG emissions (UNEP, 2022). This increase in emissions is accelerating global warming, leading to temperature rises in terrestrial regions at roughly double the global average (IPCC, 2021). The consequences include desertification, extreme heatwaves, forest fires, severe storms, and increased evaporation (NASA, 2023). While these changes cause serious harm to human health, agriculture, and natural ecosystems (WHO, 2021), animal production—a key component of the agricultural sector—plays a critical role in global GHG emissions. Animal production is a major contributor to total food-related emissions and is at the heart of agriculture's environmental pressure (Flachowsky & Kamphues, 2012; Grossi et al., 2019). A 2006 FAO report stated that the livestock sector was responsible for about 18% of global GHG emissions, a figure higher than the transportation sector (Steinfeld et al., 2006). More recent data indicates this share is around 14.5% (Cheng et al., 2022; Barthelmie, 2022). The carbon footprint (CF) is a key metric that measures the direct or indirect GHG emissions caused by an individual, business, or production process (Polat & Tuncel, 2021). Since gases like methane (CH_4) and nitrous oxide (N_2O) have a much higher global warming potential than carbon dioxide (CO_2), ruminant livestock, in particular, stands out for its environmental impact (Koneswaran & Nierenberg, 2008; Grossi et al., 2019). The carbon footprint of animal production varies significantly by species and production system. For instance, beef production generates emissions ranging from 8 to 25 kg of CO_2 equivalent (CO_2e) per kilogram of live weight (De Vries & De Boer, 2010; Gerber et al., 2013). The main reasons for these high values are the energy needs during the growth phase of young animals and methane emissions from enteric fermentation in ruminants (Opio et al., 2013). Pork and poultry production generally have a lower carbon footprint than beef and sheep production (MacLeod et al., 2013). For example, chicken meat has lower GHG emissions due to its shorter production cycle and a lower feed conversion ratio. The carbon footprint of products like milk, eggs, and cheese varies depending on production methods, feed composition, and geographical location (Flachowsky & Kamphues, 2012; Röös & Nylinder, 2013). Over the last three decades, significant reductions in the carbon footprint have been achieved through genetic improvements, advancements in feeding techniques, and sustainable land management practices. In Canada, for example, the carbon footprint of beef production dropped from 18.2 kg CO_2e in 1981 to 9.5 kg CO_2e in 2006 (Legesse et al., 2016). Rising GHG concentrations are accelerating climate change, leading to reduced yields in pastures and grasslands—the primary feed sources for livestock. This threatens the sector's sustainability. At the same time, heat stress in animals lowers production performance and negatively affects their health (Çam et al., 2024). It's necessary to improve animals' climate adaptability by identifying heat-tolerant gene regions, implementing appropriate nutrition programs, and making environmental improvements. Selecting and breeding climate-resilient animal breeds is critical for the future sustainability of animal production (Çam et al., 2024). Adopting responsible and sustainable practices in production and consumption is essential for environmental protection. Key steps to reduce the carbon footprint include increasing efficiency, optimizing manure management, and using feed resources effectively (Gerber et al., 2013). However, environmental assessments shouldn't be limited to the carbon footprint; they should also include multi-dimensional sustainability analyses considering other indicators like water usage, soil health, and biodiversity (FAO, 2010). Additionally, land-use changes, deforestation, and the environmental impacts of feed production increase the environmental burden of animal agriculture (Bayır & Kıyak, 2022; Ağır et al., 2023). For example, about 70% of deforestation is caused by the land needs of livestock (Koneswaran & Nierenberg, 2008). Transformations in consumption habits and policy regulations have significant potential to reduce this impact (Barthelmie, 2022; Chen & Qi, 2025).

1. APPROACHES AND CHALLENGES IN CARBON FOOTPRINT CALCULATIONS

Calculating the carbon footprint of animal production is a technically complex field due to the intricate nature of production processes and the multidimensionality of environmental interactions. The most widely used method for this is Life Cycle Assessment (LCA), which aims to evaluate the greenhouse gas emissions that occur at every stage of a product's life, from raw material sourcing to its use and disposal by the consumer (De Vries & De Boer, 2010; Flachowsky & Kamphues, 2012).

1.1. Calculation Approaches

Generally, two methodological approaches are adopted in carbon footprint assessments: "top-down" (macro-level, based on national data and emission factors) and "bottom-up" (micro-level, based on farm or product-specific calculations). The top-down approach provides a general profile of emissions at a regional or national scale, while the bottom-up method can more precisely measure product-based differences (Barthelmie, 2022). The LCA approach, in particular, relies on ISO 14040 and 14044 standards, which require a clear definition of system boundaries and the accurate allocation of emissions (Uysal et al., 2022). For example, considering only on-farm processes for milk production yields different results than including milk processing and distribution as well (Flachowsky & Kamphues, 2012). Carbon footprint calculations are typically based on the greenhouse gas inventory methods developed by the IPCC (Intergovernmental Panel on Climate Change) (IPCC, 2019).

1.2. Uncertainties and Variability

Key factors that complicate carbon footprint calculations in animal production include:

- Data uncertainty: Parameters like feed content, animal numbers, and energy consumption vary geographically and over time (Röös & Nylinder, 2013).
- Modeling uncertainty: Microbial activities in processes like nitrous oxide (N_2O) emissions cannot be directly reflected in models (Grossi et al., 2019).
- System boundary selection: Some analyses only consider the production phase, while others also include packaging, transportation, and retail processes (Wróbel-Jędrzejewska et al., 2025).
- Allocation of by-products: Deciding how to allocate emissions when both milk and meat come from the same production system is a significant source of uncertainty (Flachowsky & Kamphues, 2012).

These uncertainties can be tested with statistical tools like stochastic simulation and sensitivity analysis. Stochastic simulation uses the distribution of input variables to create a confidence interval for the carbon footprint, while sensitivity analysis measures the effect of a specific variable on the calculations to identify the model's weak points (Röös & Nylinder, 2013).

1.3. Product Definition and Functional Unit Issues

For carbon footprint analysis comparisons to be meaningful, it's essential to correctly define the product and choose the right functional unit. For directly consumable products like milk and eggs, the calculation of CO_2e per kilogram of product is relatively straightforward. However, for meat products, different criteria like live weight, carcass weight, or animal-based protein lead to different results (Flachowsky & Kamphues, 2012; De Vries & De Boer, 2010). This requires that species-based product efficiency be considered in low-carbon footprint goals.

1.4. The Need for Multidimensional Assessment

The carbon footprint is only one dimension of environmental impact. For a holistic assessment of sustainability, other criteria must also be considered, such as water footprint, land use, eutrophication potential, energy consumption, social impacts, and economic costs (Röös & Nylinder, 2013; Uysal et al., 2022; Alltech, 2021).

2. CARBON FOOTPRİNT BY TYPE OF ANİMAL PRODUCT

The carbon footprint for different types of animal products is shown as a bar chart in Figure 1.

2.1. Beef and Dairy Production

2.1.1. The Importance of Ruminant Systems in Terms of Carbon Footprint

Beef and dairy production are among the animal production activities with the highest carbon footprint (CF). The main reason for this is that cattle are ruminant animals that produce a high amount of methane (CH_4) gas during the process of enteric fermentation. Methane is 28 to 84 times more potent than carbon dioxide in terms of its global warming potential (Grossi et al., 2019;

Koneswaran & Nierenberg, 2008; Boran & Serbester, 2022). In this context, agricultural systems focused on cattle farming have become one of the most debated agricultural practices in terms of climate change.

2.1.2. Emission Sources and Distribution

Figure 2 shows that beef and dairy production have individually significant shares of the total greenhouse gas emissions from animal production. Globally, 57.2% of CO_2 equivalent emissions from animal production come from beef, and 21% come from dairy (Sarıözkan et al., 2024). Similarly, according to Cheng et al. (2022), cattle account for 62% of total emissions across all animal species. This rate is far greater than that of pigs (7–11%), chickens (7–11%), and other small ruminants (7–11%). The main sources of emissions that make up the carbon footprint are as follows:

- Enteric fermentation (39%): The production of methane from the digestive systems of cattle (Grossi et al., 2019; Boran & Serbester, 2022), as schematized in Figure 1.

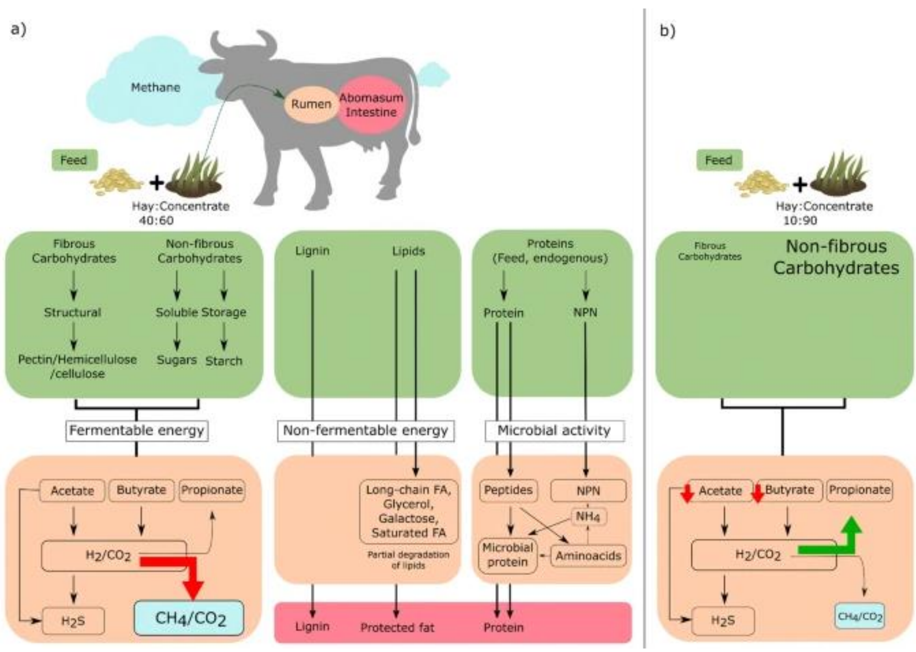


Figure 1. Enteric fermentation cycle in cattle (McCauley et al., 2020)

- Feed production and transportation (45%): CO_2 and N_2O emissions from fertilizers and fuels used for feed crops (Flachowsky and Kamphues, 2012; Montagnon, 2025)
- Manure management (10%): Methane and nitrous oxide emissions under anaerobic conditions in the barn environment (Kahraman and Yılmaz, 2024)
- Energy consumption and processing (6%): CO_2 emissions from processes such as milking, cooling, and transportation (Cheng et al., 2022).

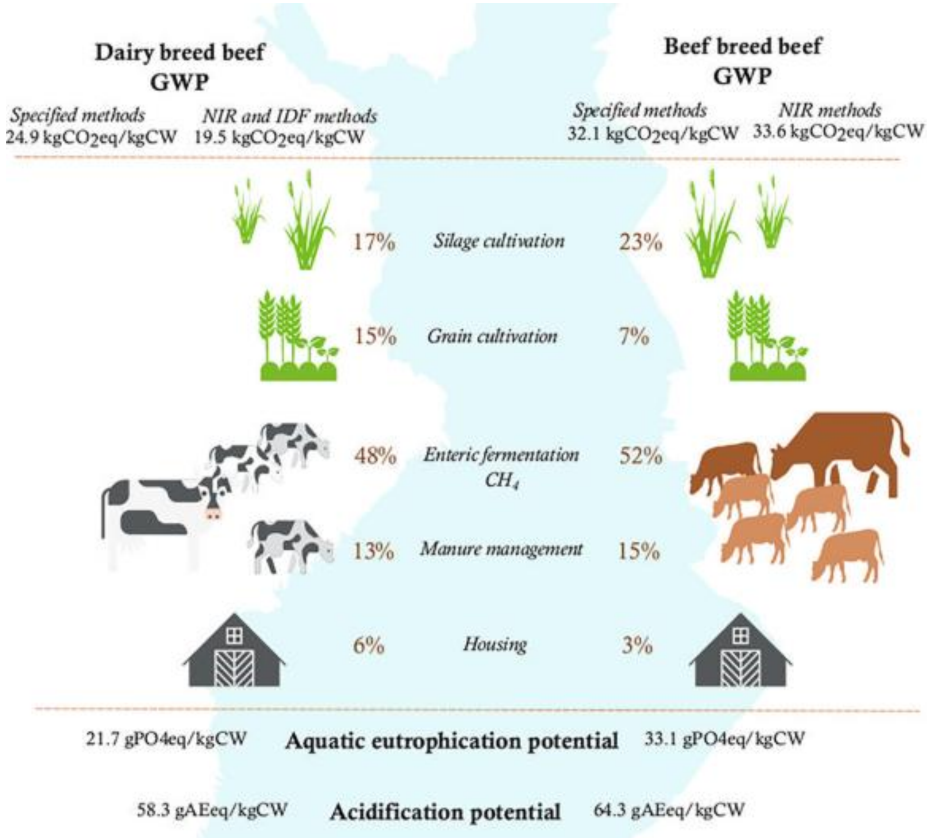


Figure 2. Distribution of emission sources caused by dairy and beef cattle (Hietala et al., 2021)

2.1.3. Carbon Footprint Values: Global and Turkey Comparison

The livestock sector holds a significant share of global greenhouse gas (GHG) emissions. Worldwide, enteric fermentation from ruminant animals accounts for approximately 14.5% of total GHG emissions (McCauley et al., 2020). The majority of these emissions are in the form of methane (CH_4) gas, which has a global warming potential about 25 times greater than carbon dioxide (McCauley et al., 2020). The carbon footprint (CF) of animal products varies significantly based on both the production system and regional conditions (Table 1). For example, the average global carbon footprint for beef production ranges from 28.3–94.6 kg CO_2e/kg of product (Barthelmie, 2022; Sarıözkan et al., 2024). In Canada, this value is reported as 9.5 kg, in the UK as 33.85 kg, and in the USA as 94.6 kg CO_2e/kg (Wróbel-Jędrzejewska et al., 2025). In Turkey, the carbon intensity of beef has been calculated at around 10.6 kg CO_2e/kg, which is below the global average (Sarıözkan et al., 2024). These differences depend on many factors, including the efficiency of production systems, the type of feed sources, the level of genetic improvement, and climatic conditions (Dakora et al., 2025). Similarly, milk production also shows regional differences. While the carbon footprint for milk produced in Europe ranges from 0.8–1.4 kg CO_2e/liter, this value can increase to 2.4–7.5 kg CO_2e/liter in Africa due to lower efficiency (Flachowsky & Kamphues, 2012). In Turkey, the carbon footprint of milk production is at lower levels, with average values calculated at 0.6–0.95 kg CO_2e/liter (Sarıözkan & Küçükoflaz, 2020). Studies specific to Turkey have detailed carbon footprint values at a regional level. Research in the Karapınar district of Konya calculated the annual increase in carbon footprint from dairy cattle farming activities as 426.4 kg CO_2e, including data on enteric fermentation and manure management. This emission accounts for about 2% of Turkey's total (Erzurum, 2024). Another study in İzmir found the total carbon footprint to be 2,826,500 tons CO_2e, with 53% of these emissions from enteric fermentation and 39% from manure management (Dağlıoğlu et al., 2024). In sheep farming, emission values also vary depending on the production system. A study in Diyarbakır found that the CO_2e per product was 46.2 kg in a nomadic system, while in a semi-intensive system, this value was 56.5 kg. Similarly, the carbon footprint per unit of live weight was lower in nomadic systems (20.8 kg CO_2e) (Yetişgin et al., 2022).

These results demonstrate that the production system is a determining factor in reducing environmental impacts. Among global strategies for reducing the carbon footprint, feed additives are a significant component. Algae-based additives, such as red macroalgae, have the potential to reduce enteric methane production by 80–99% (McCauley et al., 2020). In Turkey, regional suggestions include methods like biogas production, feed optimization, animal welfare practices, and genetic selection (Dağlıoğlu et al., 2024). The widespread adoption of such practices both increases production efficiency and provides significant contributions to sustainability.

Table 1. Global and National Carbon Footprint Values

Indicators / Regional Values	Carbon Footprint	Source
Ruminant-sourced GHG ratio (global)	14.5%	McCauley et al., 2020
Global warming potential of methane gas	25 times more than CO_2	McCauley et al., 2020
Beef carbon footprint (global range)	28.3–94.6 kg CO_2e/kg	Barthelmie, 2022; Sarıözkan et al., 2024
Beef carbon footprint (Canada)	9.5 kg CO_2e/kg	Wróbel-Jędrzejewska et al., 2025
Beef carbon footprint (UK)	33.85 kg CO_2e/kg	Wróbel-Jędrzejewska et al., 2025
Beef carbon footprint (USA)	94.6 kg CO_2e/kg	Wróbel-Jędrzejewska et al., 2025
Beef carbon footprint (Turkey)	10.6 kg CO_2e/kg	Sarıözkan et al., 2024
Milk carbon footprint (Europe)	0.8–1.4 kg CO_2e/liter	Flachowsky & Kamphues, 2012
Milk carbon footprint (Africa)	2.4–7.5 kg CO_2e/liter	Flachowsky & Kamphues, 2012
Milk carbon footprint (Turkey)	0.6–0.95 kg CO_2e/liter	Sarıözkan & Küçükoflaz, 2020
Karapınar dairy cattle CO_2e increase	426.4 kg CO_2e/year	Erzurum, 2024
İzmir total carbon footprint	2,826,500 tons CO_2e	Dağlıoğlu et al., 2024
İzmir enteric fermentation ratio	53%	Dağlıoğlu et al., 2024
İzmir manure management ratio	39%	Dağlıoğlu et al., 2024
Sheep nomadic system CO_2e (per product)	46.2 kg CO_2e/product	Yetişgin et al., 2022

Sheep semi-intensive system CO_2e (per product)	56.5 kg CO_2e/product	Yetişgin et al., 2022
Sheep nomadic system CO_2e (per live weight)	20.8 kg CO_2e	Yetişgin et al., 2022
Potential for methane reduction with algae additives	80–99%	McCauley et al., 2020

2.1.4. Animal-Sourced Protein and Efficiency Criteria

In carbon footprint analysis, emissions calculated per unit of animal-sourced protein are also an important comparison tool, not just those per kilogram of product. In this context, Flachowsky and Kamphues (2012) reported that producing 1 kg of animal-sourced protein releases 55–110 kg CO_2e for beef and about 16 kg CO_2e for milk. This finding shows that milk is more environmentally advantageous, but due to its high total production volume, it holds a significant place in absolute emissions.

2.1.5. Reduction Strategies

Numerous strategies are suggested to reduce the environmental impacts of beef and dairy production. These can be grouped under four main headings:

Feed Optimization: Formulating feed with a higher proportion of starch, fat, and legumes can reduce ruminal methane production (Grossi et al., 2019; Boran & Serbester, 2022). Additionally, feed additives like Bio-Mos® and Excential Energy Plus improve feed efficiency, which in turn reduces carbon emissions (Montagnon, 2025; Alltech, 2021).

Manure Management: Methods such as solid-liquid separation, anaerobic digester systems (biogas production), and prompt removal of manure can significantly reduce CH_4 and N_2O emissions (Grossi et al., 2019; Kahraman & Yılmaz, 2024).

Genetic Improvement and Increased Efficiency: The livestock sector is a major source of GHGs, and strategies to reduce these emissions are becoming increasingly important. Among these strategies, genetic improvement and increased efficiency offer powerful and lasting solutions for both environmental sustainability and economic viability (Mekonnen, 2023; Khan et al., 2023).

Genetic improvement is an approach aimed at producing more with fewer resources. In this context, selection for traits such as feed efficiency, growth rate, carcass quality, fertility, and health reduces the carbon footprint per unit of product while providing long-term genetic gains (Barwick et al., 2019; Scholtz et al., 2012). Efficiency indicators like residual feed intake (RFI) make it possible to select animals that achieve the same performance with less feed. Animals with a low RFI consume less dry matter, producing 15–25% less methane, and are estimated to emit 16,100 liters less methane per year on average (Basarab et al., 2013; Scholtz et al., 2012). In the USA between 1990 and 2020, live weight gain per beef cow increased by 47.5%, while CO_2e emissions per kg decreased by 4.4% (Crawford et al., 2022). This shows that increases in production efficiency provide direct environmental benefits. To reduce the environmental impacts of genetic progress in livestock, it is recommended to focus on multiple traits, not just one. Genetic selection based on multiple criteria—such as feed intake, live weight, fertility, and carcass yield—both improves economic performance and reduces emissions (Barwick et al., 2019). For example, where the carbon price is $10–40 per ton of CO_2e, a 1.1–2.6% reduction in total GHG emissions can be achieved per generation (Barwick et al., 2019). Not only animal genetics, but also the breeding of forage crops is an important factor in reducing environmental impact. Genetically improved forages provide a more balanced carbohydrate-protein ratio in the rumen, reducing methane production while also allowing animals to get more out of their feed (Kingston-Smith et al., 2013). This dual breeding strategy (animal and plant) reduces the overall environmental burden of the system by decreasing the amount of land, water, and energy required for feed production. In addition to traditional selection methods, genetic engineering applications also play an important role in reducing the environmental impacts of animal production. Techniques like CRISPR-Cas9 have made it possible to directly obtain high-yielding, low-emission individuals (Khan et al., 2023). In particular, identifying genetic variants that reduce methane production in ruminants and integrating them into genomic selection programs contributes to a reduced carbon footprint. Increased efficiency plays an important role in reducing environmental impact. Well-managed systems supported by feeding, health management, housing conditions, and digital technologies improve animal welfare while reducing emission intensity (Mekonnen, 2023). In this context, genetic improvement creates a holistic sustainability model by reducing not only production efficiency but also environmental externalities like nitrogen and phosphorus waste (Khan et al., 2023; Priyadharsini et al., 2022). Genetic improvement and increased efficiency are among the most effective strategies for reducing the carbon footprint of animal production. Tools such as residual feed intake, multi-trait selection, forage breeding, and genetic engineering both lower production costs and reduce greenhouse gas emissions. Therefore, promoting and scientifically supporting genetic improvement policies is of great importance for achieving environmental sustainability in animal production systems.

Digitalization and Smart Farming Technologies: With big data and sensor technologies, energy and resource use per animal can be optimized, which in turn reduces the environmental burden (Kahraman & Yılmaz, 2024).

2.1.6. Discussion on Sustainability

Although beef and dairy production are criticized for their high carbon footprint, their high bioavailability and micronutrient density mean these products maintain their strategic importance in nutritional systems (Bayır & Kıyak, 2022). Therefore, holistic assessments should be made that consider not only climate but also nutritional quality, food security, and socioeconomic contexts (Chen & Qi, 2025; Barthelmie, 2022). Additionally, because there is high potential for improvement in production systems, the carbon intensity of properly managed cattle-based systems can be significantly reduced.

2.2. Sheep and Goat Products

Globally, the sheep population, at approximately 1.01 billion, makes up a significant portion of small ruminants (FAOStats, 2024). As shown in Table 2, the goat population is around 1.145 billion, and these animals contribute about 4.9% of total global enteric methane emissions (FAO, 2024). However, according to the data shared, the number of sheep is greater than that of goats; goats produce less methane per unit of body weight and have higher feed conversion efficiency (Kerven, 2024). According to official data, China is the world leader with approximately 194 million sheep, followed by India (75 million), Australia (70 million), Iran (55 million), and Turkey (44–45 million) (FAOStats, 2024). The Situation in Turkey: According to TÜİK 2024 data, the total number of small ruminants is 53.9 million head, with sheep accounting for 43.4 million and goats for 10.5 million (TÜİK, 2024). Compared to the previous year, the number of sheep increased by 4.8% and goats by 5% (TÜİK, 2024).

According to red meat production statistics, in 2023, sheep, goat, and buffalo meat constituted 23.9% of total red meat production (TÜİK, 2023b).

Table 2. Methane Emissions by Population, Global and Turkey

Region/Species	Number (approx. - million head)	Description / Percentage
Global sheep population	1,010	Small ruminant population; contributes about 4.9% of enteric methane
Global goat population	1,145	Contributes 4.9% of enteric methane emissions
Turkey sheep population	43.4	4.8% increase in 2024
Turkey goat population	10.5	5% increase in 2024
Turkey small ruminant total	54.9	Total of sheep + goats

2.2.1. The Role of Small Ruminants in Sustainability

Small ruminant livestock, especially sheep and goat farming, are widespread production systems in many geographies due to their ability to adapt to harsh environmental conditions and low-quality pasture areas. However, because these animals are ruminants, their high production of enteric methane is a notable dimension in carbon footprint discussions (Grossi et al., 2019; Sarıözkan et al., 2024). Still, their ability to produce with low inputs presents both an opportunity and a challenge in terms of carbon footprint efficiency (Bayır & Kıyak, 2022).

2.2.2. Emission Sources and Characteristics

The largest contribution to the carbon footprint of sheep and goats again comes from enteric fermentation. Although the digestive system of small ruminants can ferment low-quality fibrous feed, the methane gas produced during this process can account for up to 60% of total emissions (Grossi et al., 2019). Additionally, because these animals are mostly raised in extensive systems, other emission sources like feed production and energy use are limited; however, this also increases carbon intensity due to low efficiency per unit of product (Flachowsky & Kamphues, 2012). Depending on system boundaries, manure management and processing also contribute to the carbon footprint. However, these factors are lower in sheep and goat production compared to cattle (Boran & Serbester, 2022; Sarıözkan et al., 2024).

2.2.3. Carbon Footprint Values: Global and Turkey Data

In global comparative studies, the carbon footprint of sheep meat is reported to be around 39–40 kg CO_2e per kilogram (Barthelmie, 2022; De Vries & De Boer, 2010). This value is similar to that of beef and significantly higher than that of chicken and pork. However, when viewed on a per-unit animal-sourced protein basis, sheep meat releases 50–90 kg CO_2e per kilogram of protein (Flachowsky & Kamphues, 2012). In the case of Turkey, the average carbon footprint calculated for sheep meat varies between 7.2–10.5 kg CO_2e/kg of carcass (Sarıözkan et al., 2024). While these values are lower than those in some EU countries, they also have the potential to increase depending on efficiency. In Turkey, production is more dependent on pasture-based systems, which keeps external inputs low and limits total emissions (Bayır & Kıyak, 2022). While there is a lack of data on the carbon footprint of goat meat and milk, the average emission for goat milk production is reported to be 1.4–1.7 kg CO_2e/liter (Flachowsky & Kamphues, 2012). The advantages of goats in terms of adaptability and sustainability rather than high yield enable them to form environmentally suitable production systems, especially in marginal areas.

2.2.4. Reduction Potential and Strategies

Key strategies that can be developed to reduce the carbon footprint in sheep and goat production are summarized below:

Increased Efficiency and Breeding Efforts: Selecting genetic lines that provide higher carcass and milk yield can reduce emissions per unit of product (Flachowsky & Kamphues, 2012). Selective breeding programs carried out on native breeds in Turkey, in particular, show promise in this direction (Sarıözkan & Küçükoflaz, 2020).

Feed Optimization and Feed Quality. Using feeds with a low fiber content and high starch and fat content can reduce enteric methane emissions. Additionally, studies on anti-methanogenic feed additives (e.g., garlic, certain essential oils) are ongoing (Grossi et al., 2019; Boran & Serbester, 2022).

Manure Management and Biogas Use: Processing organic fertilizers in anaerobic systems to produce biogas prevents methane emissions and also generates renewable energy (Kahraman & Yılmaz, 2024).

System Transformation and Integrated Models: Making extensive systems more efficient, for example, by increasing production per animal through pasture management, can reduce the environmental burden. The use of goat systems within an agricultural-livestock integration is also valuable for environmental sustainability (Bayır & Kıyak, 2022).

2.2.5. Discussion: The Importance of Local Systems

While the carbon footprint of small ruminant livestock is high, its advantages—such as the ability to produce with low inputs and provide animal protein in difficult geographies should not be overlooked (Bayır & Kıyak, 2022; Li et al., 2021). Furthermore, because sheep and goat systems are integrated with the local economy and cultural heritage, they are strategically important for food security within the context of socio-ecological systems (Chen & Qi, 2025). In this sense, small ruminants should be evaluated within the framework of sustainability principles rather than a narrow, carbon-emission-focused perspective.

2.3. Pork

2.3.1. The Role of Monogastric Systems in the Carbon Footprint

Pork production, within monogastric animal systems, offers a highly advantageous structure in terms of energy and protein conversion efficiency. The absence of enteric fermentation compared to ruminant species places pigs among the species with lower methane emissions (Grossi et al., 2019). However, due to the prevalence of intensive production systems, the carbon footprint is not negligible because of feed production, manure management, energy use, and processing stages (De Vries & De Boer, 2010; Kahraman & Yılmaz, 2024).

2.3.2. Emission Sources

The main emission sources that contribute to the carbon footprint in a pig production system are as follows:

Feed production (50–60%): CO_2 and N_2O are released during the production, transportation, and processing of feed ingredients (especially corn, soy, etc.) (Montagnon, 2025).

Manure management (up to 30%): Pig manure has a high nitrogen content and causes significant N_2O and CH_4 emissions under anaerobic conditions (Kahraman & Yılmaz, 2024).

Energy use and thermal comfort systems (10–15%): The ventilation, heating, and water systems used in modern pig farms cause CO_2 emissions from fossil fuel consumption (Barthelmie, 2022).

Enteric fermentation is minimal in pigs, so methane emissions are very low. However, the total carbon footprint is noteworthy due to the energy intensity of other production stages (Flachowsky & Kamphues, 2012).

2.3.3. Carbon Footprint Values

In pork production, the global average carbon footprint per kilogram of carcass weight ranges from 3.8–6.1 kg CO_2e (De Vries & De Boer, 2010; Barthelmie, 2022). This value is significantly lower compared to beef and lamb. In Turkey, local studies on the carbon footprint of pork production are limited due to its lack of prevalence. LCA analyses conducted in European countries show that feed production is responsible for about 60% of the carbon intensity in pork (Montagnon, 2025). It has also been reported that in high-efficiency lines, the CO_2e emissions required to produce 1 kg of carcass meat can be reduced to levels of 2.5–4.8 kg (Flachowsky & Kamphues, 2012).

2.3.4. Reduction Methods and Advanced Applications

Various technical and managerial strategies have been developed to reduce the environmental impacts of pork production:

Improving Feed Efficiency: The Feed Conversion Ratio (FCR) expresses the amount of meat, milk, or eggs an animal produces in relation to the amount of feed it consumes, and as this ratio decreases, emission intensity also decreases. Reducing FCR lowers both the amount of feed needed and the emissions from the production of that feed. New-generation feed additives (e.g., enzyme complexes, prebiotics) can increase nutrient absorption rates (Montagnon, 2025; Alltech, 2021).

Manure Treatment Systems: Using pig manure for biogas production through anaerobic fermentation both reduces methane emissions and provides energy (Kahraman & Yılmaz, 2024). Additionally, N_2O emissions can be limited through manure drying, composting, and pH regulation methods.

Energy Efficiency and Renewable Energy Use: The CO_2e burden from on-farm energy consumption can be reduced with technologies such as solar panels, biogas, and waste heat recovery systems (Barthelmie, 2022).

2.3.5. Evaluation in the Context of Nutritional Systems

Pork, thanks to its improved feed conversion ratio and low enteric methane production, is a globally preferred source of animal protein in terms of its carbon footprint (Grossi et al., 2019). The low environmental burden in intensive production systems, especially in countries like China, Germany, Brazil, and the USA, is related to good practices in this area (Wróbel-Jędrzejewska et al., 2025). However, pork consumption is limited in many countries due to religious and cultural reasons. Therefore, when comparing carbon footprints, it is important to consider socio-cultural factors like consumption habits (Chen & Qi, 2025).

2.4. Poultry Meat and Eggs

2.4.1. Carbon Efficiency in Monogastric Systems

Poultry production, especially broiler chickens, is among the species with the lowest carbon footprint in the context of animal protein production (Flachowsky & Kamphues, 2012; De Vries & De Boer, 2010). The main reasons for this include poultry's high feed conversion ratios, short production cycles, and low live weight and energy needs. Furthermore, the absence of enteric fermentation minimizes methane emissions in these systems (Grossi et al., 2019).

2.4.2. Emission Sources

The main factors contributing to the carbon footprint in poultry meat and egg production are:

Feed production (60–70%): The largest portion of the carbon footprint comes from the production and transportation of feed ingredients with high energy and protein content (corn, soy, etc.) (Montagnon, 2025).

Energy use (10-15%): Heating, ventilation, and lighting systems used in broiler houses are significant sources of CO_2 (Barthelmie, 2022).

Manure management (10-15%): Limited methane and nitrous oxide emissions can occur from the anaerobic decomposition of chicken manure (Kahraman & Yılmaz, 2024).

In general, the emission profile of poultry systems is much lower and more homogeneous than that of cattle and sheep systems (Flachowsky & Kamphues, 2012; Wróbel-Jędrzejewska et al., 2025).

2.4.3. Carbon Footprint Values

According to global averages:

The carbon footprint for broiler chicken meat is reported to be 1.6–4.5 kg CO_2e/kg of carcass.

For egg production, this value is around 1.1–1.9 kg CO_2e/dozen (12 eggs) or 1.3–1.5 kg CO_2e/kg of product (De Vries & De Boer, 2010; Flachowsky & Kamphues, 2012; Sarıözkan et al., 2024).

In Turkey, the carbon footprint of broiler meat is calculated to be between 1.65–2.25 kg CO_2e/kg, and egg production between 1.15–1.60 kg CO_2e/kg (Sarıözkan & Küçükoflaz, 2020). These values are consistent with global data and show that Turkey's poultry sector has significant potential for low-emission animal production.

2.4.4. Reduction Strategies

Some strategies to further reduce the carbon footprint in poultry production are summarized below:

Feed Formulation and Local Sources: Using alternative protein sources (e.g., sunflower meal, legumes) instead of soy reduces both import dependency and feed-related emissions (Bayır & Kıyak, 2022; Montagnon, 2025).

Enzyme and Additive Use: Additives like feed enzymes (phytase, protease, cellulase) increase digestive efficiency, leading to more live weight gain with less feed, which in turn reduces emissions (Alltech, 2021).

Energy Efficiency and Renewable Systems: Carbon emissions from energy can be reduced with technologies like heat recovery systems, LED lighting, photovoltaic panels, and automation systems (Barthelmie, 2022).

Waste Management and Manure Recovery: The prompt removal and drying of chicken manure and its use as organic fertilizer reduce both carbon and nitrogen losses (Kahraman & Yılmaz, 2024).

2.4.5. Nutrition and Sustainability Perspective

Poultry meat and eggs, with their low carbon footprint and high bioavailability, hold a significant place in sustainable diets (Chen & Qi, 2025). Models like the "planetary health diet" are suggested to meet a large portion of animal protein needs from low-emission species (Grossi et al., 2019). However, the rapid growth and intensification in the sector carry the risk of increasing indirect emissions, especially from feed ingredients. Therefore, the carbon footprint should not be evaluated solely on a production basis but together with environmental factors such as the global feed supply chain, land use, and biodiversity impacts (Flachowsky & Kamphues, 2012; Röös & Nylinder, 2013).

2.5. Dairy Products

2.5.1. The Carbon Profile of Dairy Products

Dairy products form a significant subset of animal production systems. This includes varieties such as cheese, yogurt, butter, and cream, each with a different carbon footprint due to the varying energy and resource use required during processing and preservation (Flachowsky & Kamphues, 2012). Beyond the carbon footprint of raw milk, the processing, transportation, packaging, and energy consumption in the cold chain for these products significantly affect total emissions (Röös & Nylinder, 2013).

2.5.2. Emission Profile of Production and Processing Stages

The carbon footprint of dairy products is generally generated in four main stages:

Milk production: Animal husbandry, feed production, manure management, milking.

Processing: Energy and water use in processes like pasteurization, fermentation, cheesemaking, and cream separation.

Packaging and cold chain: The packaging material and constant cooling needs, especially for short-shelf-life products like yogurt and milk, cause significant CO_2 emissions (Barthelmie, 2022).

Transportation and distribution: The carbon footprint of refrigerated distribution increases, especially when it extends beyond the local consumption chain (Kahraman & Yılmaz, 2024).

Each of these stages contributes to the carbon footprint at varying rates depending on the product type. Cheeses, in particular, which require high energy and a long maturation period, are more carbon-intensive products (Flachowsky & Kamphues, 2012).

2.5.3. Carbon Footprint Values

Carbon footprint values vary depending on both the product type and the processing method. Some average values reported in the literature are:

Hard cheese: 8.5–13.5 kg CO_2e/kg of product.

Yogurt: 1.2–2.0 kg CO_2e/kg of product.

Butter: 9.0–12.0 kg CO_2e/kg of product.

Powdered milk: 10.0–15.0 kg CO_2e/kg of product.

Milk (raw or pasteurized): 0.8–1.4 kg CO_2e/liter (Flachowsky & Kamphues, 2012; Sarıözkan et al., 2024; De Vries & De Boer, 2010).

Studies conducted in Turkey show that the average carbon footprint values for dairy products are similar to those in Europe, with an average of 9.2–11.6 kg CO_2e/kg for cheese production and 1.3–1.8 kg CO_2e/kg for yogurt (Sarıözkan & Küçükoflaz, 2020; Kahraman & Yılmaz, 2024).

2.5.4. Cheese: The Effect of Concentration and Processing

Cheese is one of the products with the highest carbon footprint among raw milk products. The main reasons for this are:

The use of an average of 10 liters of milk to produce 1 kg of hard cheese.

The need for continuous refrigeration during a long maturation period (3–12 months).

Intensive packaging and transportation requirements.

Therefore, when comparing the carbon footprints of yogurt and cheese obtained from the same amount of milk, for example, the emission value for cheese can be 6–8 times higher (Flachowsky & Kamphues, 2012).

2.5.5. Reduction Strategies

Strategies to reduce the carbon footprint of dairy products can be grouped under the following headings:

Efficient Processing Systems: Emissions can be reduced by lowering energy intensity with techniques like high-yield pasteurization systems, heat recovery, and energy optimization (Barthelmie, 2022).

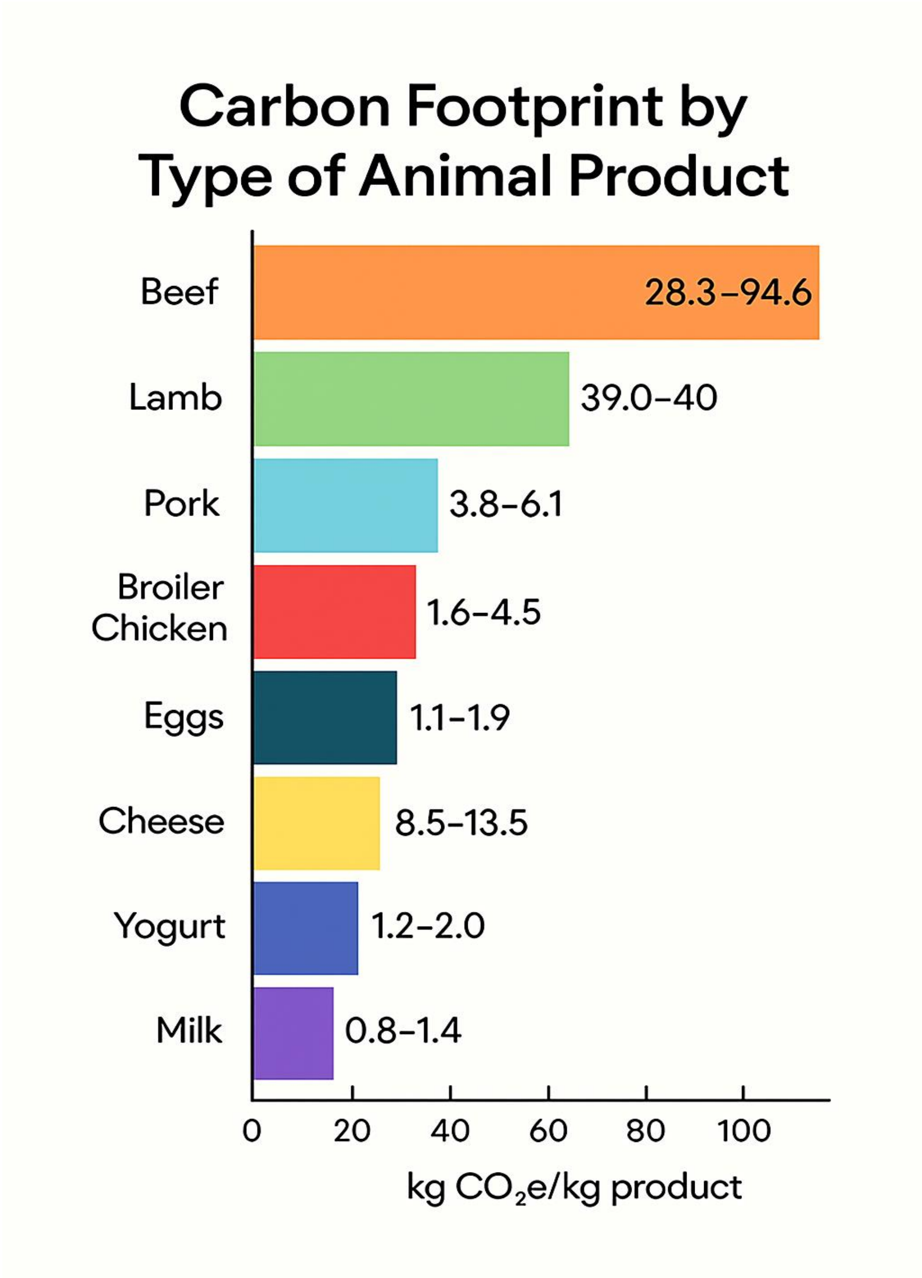
Packaging Alternatives: Using biodegradable materials instead of petroleum-derived packaging reduces carbon emissions during both the production and disposal stages. Reducing packaging (light-packaging) is also important in this context (Kahraman & Yılmaz, 2024).

Local Consumption Chains: Consuming dairy products in local markets instead of transporting them long distances within the cold chain reduces CO_2 emissions from transportation (Chen & Qi, 2025).

Increased Conversion Efficiency: By improving the efficiency of dairy cattle breeds and milk-to-cheese conversion ratios, less milk and energy can be consumed for the same amount of product (Crawford et al., 2022; Alltech, 2021).

2.5.6. Evaluation and Nutrition Perspective

While dairy products are an important nutritional component with high calcium and protein content, they are also the group with the highest carbon footprint among processed animal products. Therefore, when planning consumption, the carbon footprint of dairy products should be considered, and balanced and sustainable nutrition recommendations should be developed (Grossi et al., 2019; Röös & Nylinder, 2013). Choosing less-processed dairy products, in particular, offers an eco-friendly approach from both a carbon footprint and nutritional integrity perspective. Increasing milk efficiency will also reduce emission intensity, and reducing emission intensity can help reduce absolute emissions (Bateki et al., 2023).



Graph 1. Carbon footprint by animal product type

3. COMPARATIVE ASSESSMENT AMONG SPECIES

The carbon footprint of animal production systems should be evaluated not only by the total amount of CO_2e but also in conjunction with factors such as product type, feed conversion ratio, emissions per unit of animal-sourced protein, and the intensity of processing stages (Dakora et al., 2025). A correct understanding of the differences in carbon footprint among species is critical for developing sustainable nutrition strategies and environmentally friendly production policies (Grossi et al., 2019; Flachowsky & Kamphues, 2012; Barthelmie, 2022).

3.1. Comparison of Average Carbon Footprint per Product

The average carbon footprint values for the meat, milk, and egg products of different species are summarized below in Table 3.

Table 3. Carbon Footprint Values of Animal Products

Animal Product	Average Carbon Footprint (kg CO_2e/kg product)
Beef	28–95
Mutton/Lamb	30–40
Goat Meat	10–15 (estimated)
Pork	3.8–6.1
Chicken Meat	1.6–4.5
Eggs	1.1–1.9/kg or 1.2/dozen
Cow's Milk (raw)	0.8–1.4
Goat's Milk	1.4–1.7
Yogurt	1.2–2.0
Cheese	8.5–13.5
Butter	9.0–12.0

(Sources: Flachowsky and Kamphues, 2012; De Vries and De Boer, 2010; Sarıözkan et al., 2024; Kahraman and Yılmaz, 2024; Barthelmie, 2022)

This table shows that beef and sheep have the highest emissions in terms of carbon footprint, while poultry and eggs have the lowest. The low emissions profile of egg production is associated with high-yield animal genetics, short production cycles, and efficient feed conversion ratios. Dairy products, on the other hand, vary depending on their processing intensity (Grossi et al., 2019).

3.2. Carbon Footprint Per Unit of Animal-Sourced Protein

Evaluating the environmental impact of animal products in terms of CO_2e per unit of animal-sourced protein is of great importance for analyzing both nutritional value and environmental impact together (Flachowsky & Kamphues, 2012; Röös & Nylinder, 2013). This approach more accurately reveals the environmental footprint of species with low protein efficiency.

Ruminant animals cause more carbon emissions due to their low feed conversion ratio and high enteric methane production (Weindl et al., 2020). For example, this value ranges from 55–110 kg CO_2e/kg protein for beef, while for mutton/lamb it is reported to be in the range of 50–90 kg CO_2e/kg protein (Flachowsky & Kamphues, 2012). In contrast, products from monogastric animals like chicken meat and eggs have a lower carbon footprint due to their higher feed conversion ratios (De Vries & De Boer, 2010). Chicken meat, in particular, with only 7-11% of total emissions, is considered one of the most sustainable animal protein sources from both an environmental and economic perspective (Cheng et al., 2022). Milk and cheese production, while variable depending on the milk production system, feed sources, and processing stages, are considered products with a high carbon footprint (Dunne, 2020). Table 4 provides the emissions per kilogram of animal-sourced protein in CO_2e. These differences show how effective factors like rational planning of animal production systems, optimization of feed sources, and genetic efficiency can be in reducing the carbon footprint.

An increase in greenhouse gas emissions from animal production is observed in developing countries. The main reasons for this increase include population growth, rapid urbanization, and a continuous rise in demand for animal protein. This trend is expected to continue in the African region until 2050, where the livestock sector plays a critical role for both rural livelihoods and food security (Bateki et al., 2023).

Table 4. Emissions per 1 kg of Animal-Sourced Protein (kg CO_2e)

Product	Emissions per 1 kg of Animal-Sourced Protein (kg CO_2e)
Beef	59.6
Mutton/Lamb	24.5
Fish	5.1

(Source: Poore and Nemecek, 2018)

3.3. System Efficiency and Feed Conversion Ratios

Biological efficiency parameters such as feed conversion ratio (FCR) and life cycle duration are determinants of the carbon footprint (Table 5):

Table 5. Feed Conversion Ratio, Age, and Emission Impact by Species

Species	Average FCR (kg feed / kg live weight)	Slaughter Age (days)	Emission Impact
Chicken (broiler)	1.5–1.8	40–45	Low
Pork	2.5–3.0	160–180	Medium
Sheep	4.0–6.0	180–365	High
Cattle	6.0–10.0	365–720	Very High

(Sources: Grossi et al., 2019; Montagnon, 2025; Barthelmie, 2022)

This table clearly shows that as an animal's growth period and feed conversion ratio increase, its carbon footprint also increases. Therefore, monogastric species like chickens and pigs are part of production systems with a lower environmental impact.

3.4. Comprehensive Sustainability Assessment

When assessing the carbon footprint across different species, the analysis should not be limited to emission quantities alone; it should also include these aspects:

Nutrient density: For example, beef is rich in iron and B12.

Socio-cultural factors: Pork is not consumed in many societies.

Suitability for farming systems: Sheep and goats are well-suited for production on marginal agricultural lands.

Ecosystem services: Pasture-based livestock farming can increase soil carbon (Bayır & Kıyak, 2022).

Therefore, animal production systems should be evaluated holistically, considering environmental, nutritional, and cultural criteria, not just carbon data (Chen & Qi, 2025). When consumers consider the carbon footprint of meat and dairy products in their choices, it increases the effectiveness of labeling strategies (Ang et al., 2024).

4. DETAILED ANALYSIS OF EMISSION SOURCES

The carbon footprint in animal production systems comes from both direct, animal-based biological processes and indirect operational stages like feed production, energy consumption, and waste management. This section provides a detailed analysis of the four most critical emission sources: enteric fermentation, manure management, feed production and transport, and energy use and processing (Grossi et al., 2019; Sarıözkan et al., 2024).

4.1. Enteric Fermentation

Enteric fermentation is a biological process that occurs in the rumen of ruminant animals during the microbial digestion of cellulosic materials. This digestive process results in the formation of methane (CH_4) gas, which is released into the atmosphere through the animal's exhaled gas (Flachowsky & Kamphues, 2012). This process is one of the largest components of methane emissions in animal production systems and holds a significant share of total greenhouse gas emissions. For ruminant species like cattle, sheep, and goats, enteric methane production is a serious sustainability issue in terms of both environmental impact and energy loss. To address this, various approaches have been developed to reduce enteric methane production, including feed formulation, genetic selection, microbial modification, and the use of additives.

Species-Based Emissions

Cattle: Approximately 60–65% of total methane emissions come from enteric fermentation. This makes cattle the species with the highest enteric methane emissions (De Vries & De Boer, 2010). The long breeding period and low feed conversion ratios of cattle are the main reasons for this difference.

Sheep and Goats: While not as high as cattle, enteric fermentation contributes 50–60% to their total carbon footprint (Bayır & Kıyak, 2022).

Pigs and Poultry: As they are monogastric, their enteric methane production is negligible (Grossi et al., 2019).

Reduction Methods

Feed additives (nitric acid, oils, saponins)

Use of high-quality roughage

Developing low-methane-emitting breed variants through genetic selection (Barthelmie, 2022)

4.2. Manure Management

Emission Types

When animal manure ferments in the open, anaerobic conditions are created, which increase methane (CH_4) and nitrous oxide (N_2O) emissions. Because it is rich in nitrogen and carbon, manure can release methane (CH_4) and nitrous oxide (N_2O) under anaerobic conditions. These gases have a much higher global warming potential compared to CO_2: $N_2O \approx 298\ CO_2e$, and $CH_4 \approx 25\ CO_2e$. Nitrous oxide (N_2O) is a greenhouse gas 265 times more potent than CO_2 (Bateki et al., 2023; Kahraman & Yılmaz, 2024).

System-Based Differences

Liquid manure systems (cattle, pigs): Produce more methane due to anaerobic conditions.

Solid manure systems (sheep, goats, poultry): Are generally kept in the open and produce lower emissions under aerobic conditions (Sarıözkan et al., 2024).

Improvement Methods

Methane recovery with anaerobic biogas systems

Manure drying and composting

Lowering manure pH (Bayır & Kıyak, 2022)

4.3. Feed Production and Transport

Feed Sourcing and Impact

In animal production, the largest share of the carbon footprint is typically from feed. During the cultivation of feed crops, agricultural machinery, nitrogen fertilizers, irrigation, and pesticide use cause CO_2 and N_2O emissions (Montagnon, 2025).

Species-Based Differences

Monogastrics (pigs, poultry): Have higher feed requirements, but their conversion efficiency is high.

Ruminants (cattle, sheep): Can use low-quality roughage, but their feed-to-protein conversion rate is low (Grossi et al., 2019).

Transportation Impact

Imported feed ingredients (e.g., soybeans) create a high carbon footprint during transport. Soy production also causes indirect emissions through land-use change (Röös & Nylinder, 2013). A large portion of feed ingredients like soy and corn used in Turkey are imported, which increases indirect emissions from transportation (Sarıözkan et al., 2024). Utilizing food waste like bread scraps provides environmental advantages in the context of feed alternatives (Tiwari et al., 2024).

Reduction Methods

Using local protein sources (legumes, sunflower meal)

Low-input feed systems and nature-friendly farming methods

Efficiency optimization in feed formulations (Alltech, 2021; Bayır & Kıyak, 2022)

4.4. Energy Use and Processing

Energy Consumption

The use of electricity and fossil fuels is common in some stages of animal production (milking, ventilation, heating, cooling, lighting). This is particularly prominent in intensive systems like dairy and poultry production (Barthelmie, 2022). The electricity and fossil fuels used during the processing, cooling, and distribution of meat and dairy products can account for 10–15% of total production emissions (Flachowsky & Kamphues, 2012).

Processing Emissions

The processing and shelf-life extension of products like cheese, powdered milk, and butter are energy-intensive processes. Cold chain applications (especially for yogurt and milk) cause high CO_2 emissions (Kahraman & Yılmaz, 2024).

Reduction Strategies

Using renewable energy (solar panels, biogas systems)

Heat recovery technologies

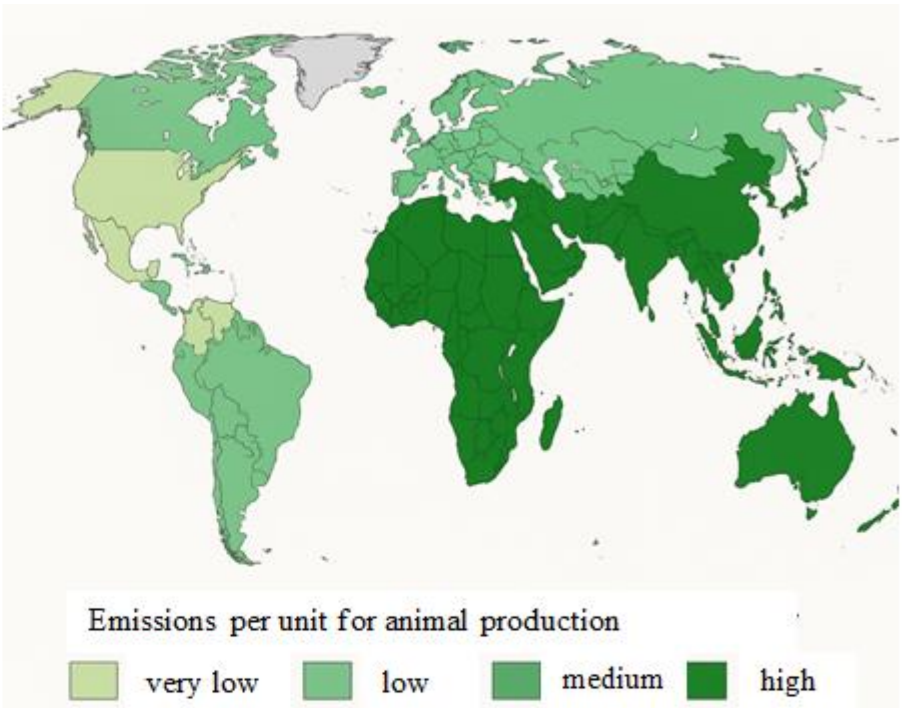
Low-energy consumption processing machinery (Flachowsky & Kamphues, 2012; Li et al., 2021)

5. REGIONAL COMPARISONS AND THE SITUATION IN TÜRKİYE

5.1. Global Emission Intensities

The carbon footprint of animal production varies significantly depending on the structure of production systems, feed sources, technological level, and geographical conditions. According to current FAO data from 2000-2022, agri-food systems cause a total of 16.2 billion tons of CO_2e emissions annually, with approximately 7.8 billion tons coming directly from agricultural production (FAO, 2022). A large portion of these emissions originates from animal production processes, especially enteric fermentation, manure management, feed production, and energy consumption. Globally, greenhouse gas emissions from animal production show significant differences between developed and developing countries (Bateki et al., 2023). In developed countries, the carbon footprint per unit of product is lower due to high efficiency, the prevalence of intensive systems, and advanced environmental management techniques. For example, in European Union countries, greenhouse gas emissions per unit of protein have been reduced through efficient feed conversion ratios and well-structured manure management systems (Flachowsky & Kamphues, 2012; Röös & Nylinder, 2013). In contrast, in regions like Africa, Asia, and Latin America, animal production is often based on low-efficiency, traditional systems, leading to very high greenhouse gas emissions per unit of product (Grossi et al., 2019). The global emission intensity for animal production is shown on the map in Figure 2. For instance, in Africa, the amount of CO_2e

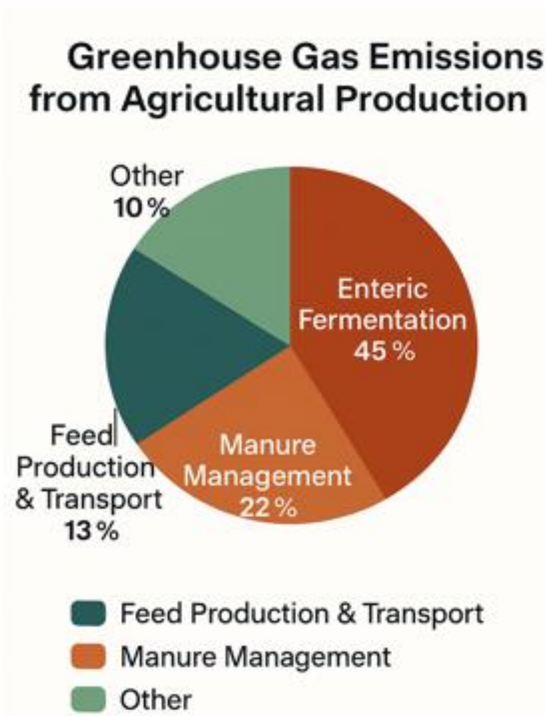
produced during the production of 1 kg of beef can be about 2–3 times higher than in Europe (Li et al., 2021). Furthermore, in these regions, the quality of feed is low, the yield per animal is small, and infrastructure is limited, which makes emission control difficult (Barthelmie, 2022; Chen & Qi, 2025).



Graph 2. Global emissions intensity for animal production

5.2. Distribution of Greenhouse Gas Emissions from Animal Production in Turkey

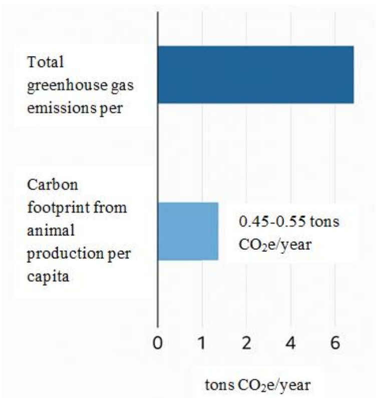
According to data from the Turkish Statistical Institute (TÜİK, 2023a), agricultural production accounts for approximately 13–15% of total greenhouse gas (GHG) emissions. In Turkey, GHG emissions from animal production processes largely stem from biological processes like enteric fermentation (45–50%) and manure management (20–25%) (Kahraman & Yılmaz, 2024; Sarıözkan et al., 2024). Cattle and sheep production make up the majority of total animal-sourced emissions in Turkey, which is directly linked to the high methane production of ruminant animals (Bayır & Kıyak, 2022). Specifically, the conventional production systems used for beef and dairy production lead to a higher carbon footprint due to low feed conversion ratios and limited use of technology (Sarıözkan & Küçükoflaz, 2020). Furthermore, a significant portion of feed ingredients commonly used in animal production in Turkey are imported. Inputs like soy and corn also cause indirect emissions from transportation (Röös & Nylinder, 2013). Feed production and transport stand out as a major source of emissions, especially for monogastric species like poultry and pigs (Grossi et al., 2019; Alltech, 2021). Feed production and transport account for approximately 10–15% of total emissions, while processing and energy use range from 8–12% (Grossi et al., 2019; Montagnon, 2025). The distribution of GHG emissions from animal production in Turkey is presented in Figure 3. Strategies such as using domestic feed ingredients, processing manure, and supporting energy use with renewable sources will play a crucial role in reducing the environmental impacts of animal production (Montagnon, 2025).



Graph 3. Greenhouse gas distribution from animal production in Turkey

5.3. Per Capita Carbon Footprint Data

The total per capita GHG emission in Turkey is approximately 6–6.5 tons of CO_2e/year. Of this, about 0.7–0.9 tons are from agricultural emissions, and 60% of those are from animal production (FAO, 2022). Based on these figures, the per capita carbon footprint from animal production in Turkey is around 0.45–0.55 tons of CO_2e/year. Per capita carbon footprint data for Turkey is shown in Graph 4. The per capita carbon footprint from animal production is directly related not only to the level of consumption but also to the efficiency of production systems and environmental management policies. For example, despite the per capita consumption of meat and dairy products being much higher in EU countries than in Turkey, their carbon footprint is lower due to the use of more advanced technological systems and the prevalence of sustainable production practices (Flachowsky & Kamphues, 2012; Röös & Nylinder, 2013). Improving production systems in Turkey, especially in areas like feed and manure management, is critically important for reducing emissions. Reducing per capita emissions from animal production is a strategic necessity, not only for combating climate change but also for Turkey's alignment with the European Green Deal (Sarıözkan et al., 2024; Bayır & Kıyak, 2022).



Graph 4. Carbon footprint data per capita in Türkiye

6. EMISSION REDUCTION STRATEGIES

Reducing the carbon footprint caused by animal production systems is strategically important not only for environmental sustainability but also for economic efficiency, social acceptance, and compliance with international trade standards. The emission reduction strategies developed in this context are based on integrated approaches that cover all components of production. This section discusses multidimensional strategies, ranging from feed optimization to genetic selection, and from digital solutions to consumer behavior.

6.1. Feeding Optimization and Feed Additives

Animal feeding strategies play a critical role in controlling the carbon footprint, as they directly influence methane production and nitrogen emissions. In ruminants, methane emissions from enteric fermentation vary depending on the quality of roughage, the starch/cellulose ratio, and the type of microbial fermentation in the rumen (Flachowsky & Kamphues, 2012; Grossi et al., 2019).

Diet Balancing: Optimizing the energy and protein balance in feed increases digestive efficiency and thus reduces methane production (Bayır & Kıyak, 2022).

Feed Additives: Additives like nitric acid, saponins, tannins, essential oils, and certain fatty acids suppress methane production by altering the rumen microbiota (Röös & Nylinder, 2013).

High-Quality Feeds: Highly digestible feeds both increase production efficiency and reduce emission intensity (Alltech, 2021). In developing countries, in particular, increasing the digestibility of roughage is considered one of the most effective methods for potential emission reduction (Barthelmie, 2022).

6.2. Management and Production System Improvements

The environmental performance of livestock systems is not only linked to feed efficiency but also to farm management and infrastructural organization. Sustainable management practices make significant contributions to reducing emissions per unit of product (Kahraman & Yılmaz, 2024; Sarıözkan & Küçükoflaz, 2020).

Manure Management: Processing solid manure under aerobic conditions, composting systems, methane recovery from liquid manure, and biogas systems minimize methane emissions (Bayır & Kıyak, 2022).

Energy Use: Using renewable energy (solar, biogas) for milking, lighting, and climate control systems helps lower energy-related emissions (Grossi et al., 2019).

Yield-Oriented Production: Increasing the yield per animal (e.g., milk yield) reduces the carbon footprint per unit of product (De Vries & De Boer, 2010; Röös & Nylinder, 2013). In this context, improving low-efficiency animals and systems is one of the intervention areas that can provide effective emission reduction in the short term (Flachowsky & Kamphues, 2012; Bateki et al., 2023).

6.3. Genetic Selection, Digitalization, and Technological Solutions

As a long-term and systematic reduction strategy, animal breeding, biotechnological interventions, and digital monitoring systems hold great potential.

Genetic Selection: Selecting genotypes that produce low methane emissions makes it possible to develop lines of ruminant animals with a lower environmental impact (Grossi et al., 2019). The long-term strategy involves prioritizing individuals with low methane emissions through genetic selection (Flachowsky & Kamphues, 2012).

Sensor and Monitoring Technologies: Monitoring parameters such as animal health, feed consumption, and behavior with sensors helps optimize feeding and environmental management decisions (Montagnon, 2025).

Artificial Intelligence and Data Analytics: Digital decision support systems enable accurate analysis of on-farm emission sources and effective implementation of interventions (Alltech, 2021; Kahraman & Yılmaz, 2024; Montagnon, 2025). Furthermore, carbon tracking and reporting software allow farms to document their sustainability performance and facilitate compliance with national and international standards (Sarıözkan et al., 2024).

6.4. The Impact of Consumption Habits and Sustainable Diets

It's important to remember that emission reduction strategies are shaped not only at the production level but also through consumer behavior. Demand-driven sustainability approaches in food systems are aimed at limiting the overconsumption of high-emission animal products (Röös & Nylinder, 2013).

Diet Diversification: Reducing the overconsumption of red meat and shifting to lower-emission alternatives like white meat, dairy products, and eggs lowers the carbon footprint (Flachowsky & Kamphues, 2012).

Sustainable Protein Sources: Alternative protein sources such as plant-based proteins (legumes, soy, peas) and microbial proteins (algae, yeast, bacterial biomass) are gaining prominence (Chen & Qi, 2025).

Reducing Food Waste: Food waste at the consumer level is associated with greenhouse gas emissions equivalent to 8–10% of the total food system (Barthelmie, 2022).

Sustainable diets not only reduce the burden on the environment but also offer significant benefits for public health. As highlighted in the EAT-Lancet report, promoting environmentally friendly dietary habits is vital (Willett et al., 2019).

7. SUSTAINABILITY PERSPECTIVE AND FUTURE DIRECTIONS

7.1. Beyond Carbon: Multidimensional Environmental Impacts

The evaluation of animal production from a sustainability perspective is not limited to its carbon footprint. Other environmental impacts like water consumption, land use, eutrophication potential, and biodiversity loss must also be considered (Flachowsky & Kamphues, 2012; Grossi et al., 2019). For example, producing 1 kg of beef requires approximately 15,000 liters of water, whereas the same amount of chicken meat requires 4,300 liters, and eggs require only 3,300 liters (Reynolds, 2019; Dunne, 2020). Effects like eutrophication and acidification, especially from the intensive use of fertilizers and over-cultivation of feed crops, put serious pressure on water ecosystems. Şahin and Avcıoğlu (2016) emphasize that agricultural production in Turkey contributes to eutrophication, particularly through nitrogen and phosphorus emissions, highlighting the need to evaluate agricultural activities from a holistic environmental perspective, not just in terms of greenhouse gases. Similarly, it has been reported that increased livestock activities in the Qinghai-Tibet Plateau over the last 30 years have led to land degradation and water stress in addition to carbon emissions (Li et al., 2021). This suggests that animal production can weaken regional ecosystem resilience alongside climate change.

7.2. Alternative Protein Sources: Plant-Based, Microbial, and Lab-Grown

Reducing the environmental impact of animal production is possible not only by improving existing systems but also by developing alternative protein sources. Plant-based proteins (legumes, soy, peas), proteins of microbial origin (algae, yeast, bacterial biomass), and in vitro meat products developed in a laboratory setting are prominent in this context (Chen & Qi, 2025; Bateki et al., 2023). Plant protein production is highly advantageous in terms of both energy and water efficiency. The greenhouse gas emissions required for the same amount of protein are up to 90% lower compared to meat products (Dunne, 2020). Furthermore, in vitro meat technologies aim to produce animal products by culturing muscle cells and have the potential to significantly reduce land use and emissions in the long term (Tiwari et al., 2024). However, factors like the high energy requirements, production costs, and level of social acceptance of these systems make it difficult for them to completely replace conventional animal production in the short term (Reynolds, 2019). Nevertheless, it is anticipated that the commercialization and scalability of these alternatives will lead to radical transformations in future food systems (Ang et al., 2024).

7.3. Policies, Labeling, and Consumer Behavior

One of the key dynamics that will determine the sustainability of animal production in the future is consumer behavior and the policy tools that guide it. Mechanisms like carbon footprint labeling, environmentally friendly production certifications, and food taxation systems have the potential to encourage sustainable consumption (Ang et al., 2024; Flachowsky & Kamphues, 2012). Ang et al. (2024) studied the effect of carbon footprint labels on consumer choices and showed that they contribute to reducing animal product consumption, especially among environmentally conscious individuals. Such labeling not only increases producer responsibility but also supports the spread of conscious consumption behaviors. When evaluated from a consumer behavior perspective, economic constraints, cultural habits, and a lack of information play a significant role in the adoption of sustainable diets in Turkey and similar developing countries (Sarıözkan et al., 2024; Özsalmanlı, 2024). However, initiatives like the European Green Deal and the Global Methane Pledge show that these behaviors can be reshaped through policy-based transformations (Reynolds, 2019). Additionally, global carbon pricing, linking agricultural production incentives to green production criteria, and strategies to reduce food loss and waste will play a key role in achieving sustainability goals (Dakora et al., 2025; Bateki et al., 2023).

8. CONCLUSION AND POLICY RECOMMENDATIONS

Animal production is a major source of greenhouse gas emissions globally and nationally, placing it at the center of climate change mitigation policies. The assessments within this book chapter show that the environmental impacts of animal production systems are not limited to the carbon footprint alone; they also create multidimensional environmental pressures such as water use, land cover change, and eutrophication. Species-based analyses have demonstrated that the environmental impacts of animal production are not uniform. Beef and dairy production have the highest carbon footprint due to methane emissions from enteric fermentation, while chicken meat and egg production have lower environmental impacts per unit of product. This makes it essential to conduct disaggregated, species-based analyses when evaluating the sustainability of production systems. Emission reduction is possible only through integrated strategies that are considered within the entire system, not just through individual interventions. Feed optimization, the use of efficient genetic lines, manure management, energy efficiency, digital monitoring technologies, and sustainable consumption models are all holistic components that must be implemented together to improve the environmental performance of animal production. Similarly, the integration of renewable energy sources, increased domestic feed production, and waste management strategies must also be part of this whole. In the future, strategic policy recommendations and research priorities can be summarized as follows:

- Carbon and environmental footprint maps for animal production systems should be created on a species basis, and this data should be integrated with national greenhouse gas inventories.
- Diversification of local feed sources should be supported to reduce emissions related to imports.

- Carbon footprint labeling should be promoted to increase producer and consumer awareness.
- Low-cost, local solutions for low-income and subsistence livestock systems should be developed, and adaptive strategies should be supported.
- Public-private partnerships and R&D investments should be increased for the adaptation of climate-friendly technologies in animal production.
- Integrated sustainability models that prioritize the protection of water and land resources should be widely adopted, especially in developing countries.

In conclusion, reducing the impact of animal production on climate change is not just a technical issue; it is a necessity for a multidimensional transformation with socio-economic, cultural, and political aspects. The success of this transformation will depend on planning based on scientific data, a holistic management approach, and the level of societal participation.

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CHAPTER 2

GIS–BASED MORPHOMETRIC ANALYSIS: EASTERN BLACK SEA TÜRKİYE (RİZE AND ARTVİN) CATCHMENTS

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1. INTRODUCTION

The Eastern Black Sea Region, situated in the northeast of Türkiye, is one of the most dynamic hydro-geomorphological areas in the country, characterized by its steep topography, intense precipitation regime, and complex geological structure. The region's characteristic features–deep valleys, dense drainage networks and high stream energy–cause variation in the surface formation and hydrographic system. This situation requires an examination of the morphometric features of the catchments in the area, which should be interpreted alongside the quantitative results. The physical characteristics of the catchments underpin this requirement, as they form the scientific basis of management plans, such as those for water and basins (Tekin and Çan, 2022).

Morphometry is the dimensional measurement and quantitative expression of the Earth's surface structure and shape (Hajam et al., 2013). In catchment-scale hydrological studies, GIS-based morphometric analyses offer a faster and more reliable alternative to traditional methods (Yıldırım, 2021a). These results were accepted as indicators of geological, geomorphological, and climatic processes (Özdemir and Akbaş, 2023; Shekar and Mathew, 2024; Topsakal et al., 2025). This acceptance has been emphasized in many studies since earlier studies dealing with basin morphometry (Horton, 1945; Strahler, 1952; Schumm, 1956; Mueller, 1968; Shreve, 1969; Merritts and Vincent, 1989; Oguchi, 1997; Özdemir and Bird, 2009; Altın, 2014; Özsayın, 2016; Yıldırım, 2021b; Dutal, 2023; Çorapcı and Özdemir, 2024; Topsakal et al., 2025).

Various parameters were used to conduct a morphometric analysis of catchments. This study employed the widely used parameters, such as drainage density, stream frequency, drainage texture, surface flow length, shape factor and extension rate.

2. STUDY AREA

The study area encompasses 18 river basins within the borders of Rize and Artvin provinces in northeastern Türkiye. The study area is located between latitudes 40°39'0" – 41°31'0" and longitudes 40°21'0" – 41°39'0" (Figure 1). This area is bordered by Trabzon province to the west, the provinces of Bayburt and Erzurum to the south, Georgia to the east, and the Black Sea to the north. The rivers, which originate in the Eastern Black Sea Mountains, flow from south to north and empty into the Black Sea. The coastline length of Rize province is 80 km (Rize Valiliği, no date), while that of Artvin is 34 km (Artvin Valiliği, no date). The area, elevation and flow path length values of the river basins are presented in Table 1.

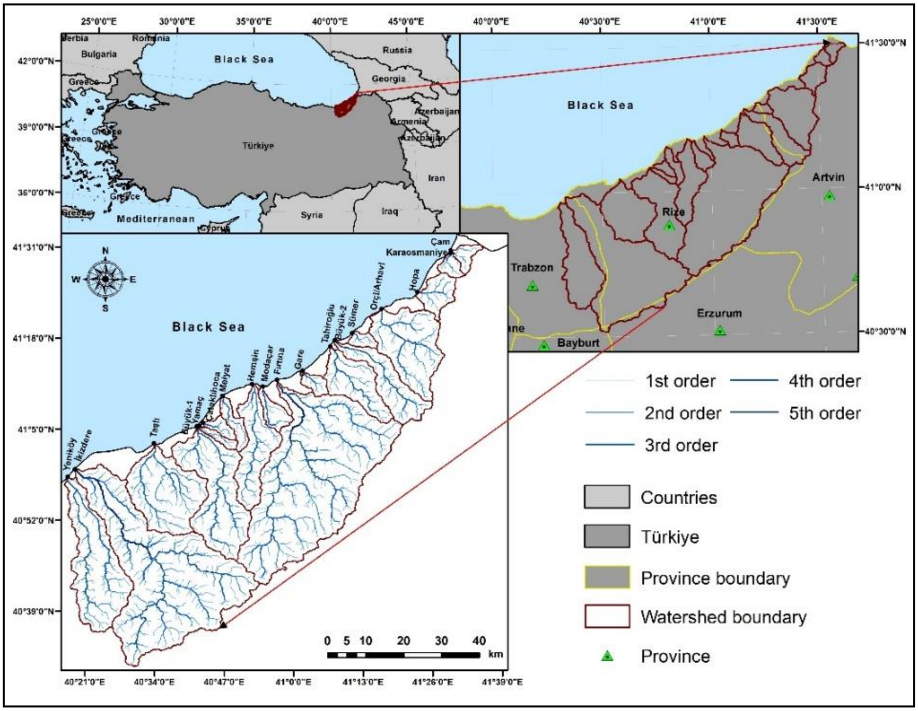

Figure 1: Location Map of the Study Area.

Table 1: Area, Elevation, and Flow Path Length Values of Catchments.

Name	Area (km^2)	Elevation (m)		Slope (°)		LFP (km)
		Max.	Mean	Max.	Mean	
Yeniköy	380	1480	511	68	27	53.6
İkizdere	1053	1460	593	60	28	82.3
Taşlı	326	1860	473	69	26	36.5
Büyük-1	378	3320	1121	77	28	51.0
Yamaç	21	1234	295	58	21	13.5
Çataklıhoca	26	3330	1558	73	30	12.8
Melyat	45	3100	1036	74	28	21.7
Hemşin	203	1180	446	60	24	41.4
Modaçar	49	3922	1914	76	29	19.4

Table 1: Continued.

Fırtına	1155	1030	437	63	25	72.1
Gare	29	2470	837	66	27	10.9
Tahiroğlu	172	1390	557	66	27	34.0
Büyük-2	176	1220	201	61	24	38.7
Sümer	24	1390	508	60	25	10.2
Orçi/Arhavi	299	3350	1329	69	28	36.9
Hopa	75	2450	849	68	27	14.1
Karaosmaniye	27	3420	1828	76	26	11.4
Çam	31	3110	1585	65	23	11.3

LFP: Longest flow path

The catchments are located in an area of very steep and rugged terrain. These catchments range in altitude from sea level to 3,922 m (Figure 2a). The catchments' high slope degree reflects the region's topographic features. The mountains rising immediately from the coastline have caused the slope to increase. This situation is explained by the fact that the coastal areas have a very narrow plain. The slopes of river basins range from 0° to 77° (see Figure 2b). In the higher regions of catchments (>2,000 m), the slope decreases. In these regions, glacial plateaus and plains cover large areas.

The study area has a humid and rainfall-rich climate, influenced by its coastal location and the orographic complexity of the North Anatolian Mountains. Notably, Rize province has the highest average annual rainfall of any province in Türkiye, at 2,301 mm (MGM, 2025). The amount of precipitation observed in Rize Province is approximately four times higher than the average for Türkiye (Gürgen, 2004). In Artvin Province, the average annual rainfall is 695 mm, there are an average of 137 rainy days per year (MGM, 2025). These figures, released by the General Directorate of Meteorology, represent the mean values recorded between 1928 and 2024.

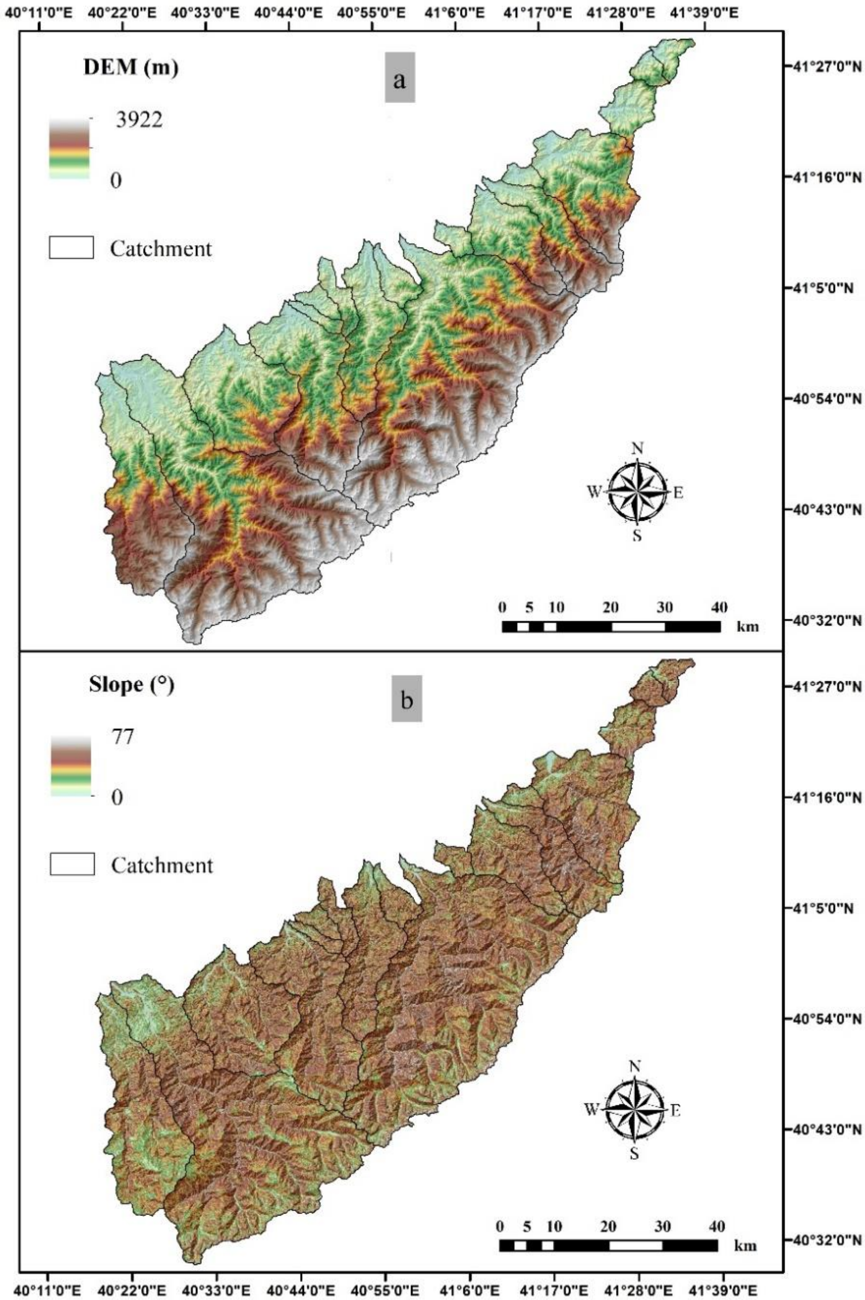

Figure 2: (a) Digital Elevation Model (DEM) and (b) Slope Map of the Study Area.

The mountainous and rugged terrain of the study area is mostly covered by forests. These areas are home to over 20 tree species in these areas, including spruce, fir, Scots pine, beech, oak, chestnut, and alder. Tea and hazelnut cultivation are common in the study area, where agriculture is limited by the topography. In Rize Province, tea cultivation accounts for 92% of existing agricultural land (ÇŞİDM, 2025a). In Artvin province, approximately 18% of the total agricultural land in Artvin province is used for hazelnut cultivation and 13% for tea cultivation (ÇŞİDM, 2025b). These agricultural activities make a significant contribution to the regional economy.

The Black Sea Basin is characterized by four Pontide belts (south, west, middle, and east) due to its diverse geological and tectonic features (Yılmaz, 1997; Softa et al., 2019). The study area is located in the Eastern Pontides mountain belt. The Eastern Pontides' oldest unit, forming the central part of the Alpine-Himalayan Mountain Belt, consists of Jurassic-Cretaceous volcano-sedimentary rocks and neritic limestones (MTA, 2002). These units are followed by dacite, rhyolite, rhyodacite, clastic and carbonate rocks (Cretaceous–Paleocene); granitoid; diorite; quartz diorite; and tonalite (Paleocene–Eocene); volcanics (Eocene); and clastics and alluviums (Pliocene–Quaternary) toward the younger units (MTA, 2002). The Quaternary alluvium, the youngest unit, is primarily found at the base of slopes (Softa et al., 2019). Although there are no active faults in the Eastern Pontides, normal faults are present in the southern part of the study area (Figure 3a). Much of the catchment area consists of volcanic sediments and granitoid units (Figure 3).

Land use/land cover (LULC) data were obtained from the 2018 CORINE inventory database (CORINE, 2018) and integrated and revised for the study area. Nine LULC classes were created and are visualized in Figure 3b. The LULC class “forests” covers the largest area in the study area (46.69%). The remaining classes are grasslands (25.72%), crops (13.72%), bare rocks (8.15%), agricultural areas (4.27%), pastures (0.69%), inland waters (0.49%), urban areas (0.14%), and industrial areas (0.13%) (Figure 3b).

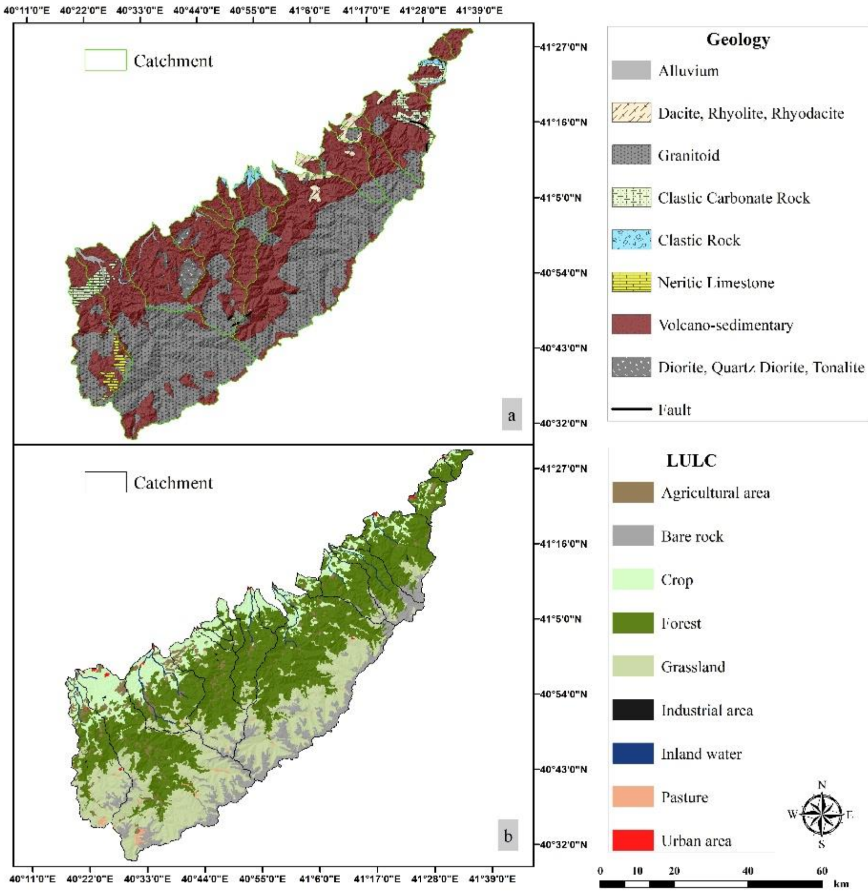

Figure 3: (a) Geology Map (MTA, 2002) and (b) LULC Map (CORINE, 2018) of Catchments.

3. MATERIALS AND METHODS

We used 1:50,000-scale topographic maps, ArcGIS software, and the ArcHydro tool to create the data necessary to determine the morphometric parameters of the catchments. The entire catchment morphometry study was conducted within the ArcGIS environment.

The study was conducted using the Universal Transverse Mercator (UTM) and World Geodetic System (WGS 1984) Zone 37N coordinate systems. The digital elevation model (DEM) of the study area was produced at a resolution of 10 m by digitizing the contour lines on topographic maps. The "Topo to Raster" tool in ArcGIS was then used to create the DEM. Catchment boundaries and drainage networks were generated using the fill DEM, flow direction, flow accumulation, stream order, stream to feature, and watershed plugins, respectively, utilizing ArcHydro tool. The flow sequence was determined according to the method suggested by Strahler (1964).

The analysis of morphometric parameters is conducted using basic parameters, including catchment area, perimeter, and length. In this regard, the morphometric parameters used and produced in the study were divided into two groups: "basic" and "characteristic". Table 2 presents descriptive information of morphometric parameters.

Table 2: Descriptive Information of Parameters used in Morphometric Analyses.

		Unit/Formula	**Reference**
Basic Parameter	Catchment area (A)	km^2	Arc measurement plugin
	Catchment perimeter (P)	km	Schumm, 1956
	Catchment length (L_b)	km	Schumm, 1956
	Stream order (U)*		Strahler, 1964
	Stream number (N_u)		Horton, 1945
	Total stream length (L_u)	km	Horton, 1945
Characteristic Parameter	Drainage density (D_d)	L_u/A	Horton, 1932
	Stream frequency (F_s)	N_u/A	Horton, 1945
	Drainage texture (D_t)	N_u/P	Horton, 1945
	Length of overland flow (L_g)	$1/2D_d$	Horton, 1945
	Form factor (R_f)	$A/{L_b}^2$	Horton, 1932
	Elongation ratio (R_e)	$\frac{\sqrt[2]{A/\pi}}{L_b}$	Schumm, 1956

* Hierarchical order

4. RESULTS AND DISCUSSIONS

4.1. Basic Parameters

Table 3 presents data on the basic morphometric parameters of river basins. Catchment area (A) plays a crucial role in runoff and erosion processes and is a significant hydrological feature because it determines the amount of water that can be sourced from precipitation (Karataş, 2017; Obeidat et al., 2021). The perimeter length (P), which is used to determine the drainage texture of river basins, can also provide preliminary information about the catchment roughness (Karataş, 2017). While the basin with the smallest area in the study area is the Yamaç catchment, the catchment with the shortest perimeter is the Sümer catchment (Table 3). The largest catchment in area is the Fırtına catchment, and the longest catchment in perimeter is the İkizdere catchment (Table 3).

The catchment length (L_b), which reflects the characteristic features of the surface flow, is defined as the length of the line drawn parallel to the main stream. (Schumm, 1956). This length is inversely proportional to the slope, with longer streams indicating a flatter topography (Christopher et al., 2010; Taha et al., 2017; Obeidat et al., 2021). The length of the studied catchments ranges from 8.7 to 74.8 km (Table 3). The Fırtına catchment has the longest length and the largest area.

The stream order (U), which represents the hierarchical order of the catchments, varies from the second degree to the fifth degree (Table 3). Catchments with large stream numbers (N_u) exhibit high surface runoff and fast peak flows compared to catchments with smaller stream numbers (Bhat et al., 2019). In this study, stream numbers ranging from 9 to 599 were determined. The stream numbers of Fırtına (1155 km^2) and İkizdere (1053 km^2) catchments, which have significantly different catchment areas compared to the others, are 599 and 550, respectively (Table 3). The Yamaç catchment with the smallest area has the lowest flow rate (Table 3).

The long stream lengths indicate low infiltration capacity and high flow generation potential (Strahler, 1952). Total stream length (L_u) ranges from 15.6 km (Sümer) to 718.0 km (Fırtına) within the study area.

Table 3: Basic Morphometric Parameter Values of Catchments.

Name	A (km^2)	P (m)	L_b (km)	U	N_u	L_u (km)
Yeniköy	380	117	43.9	4	203	246.5
İkizdere	1053	202	69.4	5	550	687.8
Taşlı	326	87	29.6	4	157	229.2
Büyük-1	378	115	40.6	5	213	251.2
Yamaç	21	29	12.2	2	9	17.0
Çataklıhoca	26	27	10.9	3	13	16.4
Melyat	45	42	17.8	3	17	29.6
Hemşin	203	93	37.0	4	111	132.1
Modaçar	49	37	14.5	3	25	32.5
Fırtına	1155	193	74.8	5	599	718.0
Gare	29	26	10.2	3	17	19.4
Tahiroğlu	172	70	27.7	4	89	107.0
Büyük-2	176	86	34.9	4	95	112.4
Sümer	24	23	8.7	3	13	15.6
Orçi/Arhavi	299	85	30.8	4	177	192.1
Hopa	75	43	13.3	3	41	52.7
Karaosmaniye	27	25	8.9	3	9	19.1
Çam	31	29	9.8	3	15	19.5

Table 3: Continued.

4.2. Characteristic Parameters

In this section, parameters that provide information about the hydrological, geomorphological, and physiographic characteristics of catchments (Yıldırım, 2021a) are mentioned. The numerical values of these parameters (drainage density (D_d), stream frequency (F_s), drainage texture (D_t), length of overland flow (L_g), form factor (R_f), and elongation ratio (R_e)) are presented in Table 4.

Catchments with low drainage density (D_d) are characterized by dense vegetation, low relief, and a permeable soil structure (Harlin and Wijeyawickrema, 1985; Kelson and Wells, 1989). However, the drainage density values of the catchments with a high degree of fragmentation by the river are also high (Özdemir, 2011). The drainage density values of catchments vary between 0.62 and 0.81 (km/km^2) (Table 4). The low values of the stream frequency (F_s), which represents the ratio between the total number of streams and the area, together with the drainage density, indicate that the runoff is slow (Taha et al., 2017). Flood risk is lower in basins where these two parameters are low (Carlston, 1963). At the same time, low F_s values reflect that the geology of the catchment is permeable (Özdemir, 2011). In the study area, the lowest F_s value was observed in the Karaosmaniye catchment (0.33), while the highest value was observed in the Orçi/Arhavi and Gare catchments (0.59).

Drainage texture (Dt) is an index obtained by dividing the total number of streams by the perimeter of the catchment. Smith (1950) divided the catchment texture into five classes using the following index values: very fine (Dt >8), fine (8>Dt >6), medium (6>Dt >4), coarse (4>Dt >2), and very coarse (2>Dt). Of the catchments examined, the Orçi/Arhavi, Fırtına, and İkizdere catchments are coarse–textured, and all the remaining catchments are very coarse–textured. (Table 4). The length of the path that the flowing water travels before reaching the channels is defined as the length of overland flow (L_g) (Horton, 1945). Geology, soil, climate, vegetation, and relief are key parameters that influence the length of overland flow (Youssef et al., 2009). Especially circular and drainage–dense catchments have low L_g values. Catchments with high L_g values are also more susceptible to floods (Obeidat et al., 2021). The study yielded L_g values ranging from 0.62 to 0.80 (Table 4). While Fırtına and Tahiroğlu catchments have the highest L_g values, the catchment with the lowest L_g value is the Yamaç catchment (Table 4).

The form factor (R_f) is a parameter that determines the flow in terms of both time and quantity. Long-term high flows occur in catchments with low form factor (R_f) values. According to Özdemir (2011), catchments where short-term peak flows occur have high R_f values. The R_f values of the studied catchments range from 0.14 (Büyük-1) to 0.43 (Hopa). As the elongation ratio (R_e), a measure of catchment shape (Horton, 1932), approaches unity, the catchment's shape approaches a circle (Abdel-Latif and Sherif, 2012). Especially the catchments with R_e values between 0.6 and 0.8 have high relief and steep topography (Obeidat et al., 2021). However, it is stated that there is an inverse proportion between flood potential and extension rate (Obeidat et al., 2021). Catchments with high extension rates have intense erosive activities and high sediment transport (Reddy et al., 2004). Hopa catchment has the highest R_e value with 0.74 (Table 4). The Melyat catchment is the most elongated catchment (0.42) in the study area (see Table 4).

Table 4: Characteristic Morphometric Parameter Values of Catchments.

Name	D_d (km/km²)	F_s	D_t	L_g	R_f	R_e
Yeniköy	0.65	0.53	1.74	0.77	0.20	0.50
İkizdere	0.65	0.52	2.72	0.77	0.22	0.53
Taşlı	0.70	0.48	1.80	0.71	0.37	0.69
Büyük-1	0.66	0.56	1.85	0.75	0.23	0.54
Yamaç	0.81	0.43	0.31	0.62	0.14	0.42
Çataklıhoca	0.63	0.50	0.48	0.79	0.22	0.53
Melyat	0.66	0.38	0.40	0.76	0.14	0.42
Hemşin	0.65	0.55	1.19	0.77	0.15	0.43
Modaçar	0.66	0.51	0.68	0.75	0.23	0.55
Fırtına	0.62	0.52	3.10	0.80	0.21	0.51
Gare	0.67	0.59	0.65	0.75	0.28	0.60
Tahiroğlu	0.62	0.52	1.27	0.80	0.22	0.53
Büyük-2	0.64	0.54	1.10	0.78	0.14	0.43
Sümer	0.65	0.54	0.57	0.77	0.32	0.64
Orçi/Arhavi	0.64	0.59	2.08	0.78	0.32	0.63
Hopa	0.70	0.55	0.95	0.71	0.43	0.74
Karaosmaniye	0.71	0.33	0.36	0.71	0.34	0.66
Çam	0.63	0.48	0.52	0.79	0.32	0.64

Table 4: Continued.

5. CONCLUSION

This study quantitatively revealed the hydro-geomorphological character of the region by examining the morphometric properties of 18 catchments in Rize and Artvin provinces, located in the Eastern Black Sea Region, using GIS-based analyses. The steep topography, high relief, and heavy rainfall regime of the study area are directly reflected in the morphometric indicators of the catchments. Particularly, drainage density, stream frequency, and length of overland flow values have been determinants of rapid surface flow and erosional processes in the region.

It is understood that the drainage texture in most catchments falls into the "very coarse" class, which is related to lithological permeability, slope, and topographic fragmentation. The elongation ratio (R_e) and form factor (R_f) values show that most of the catchments have an oval and elongated form. Therefore, the flow can quickly reach the main channel during flood formation processes. The high drainage density and low surface flow length of the Yamaç and Karaosmaniye catchments, in particular, pose a flood risk.

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CHAPTER 3

THE USE OF SMART FARMING TECHNOLOGIES AND ARTIFICIAL INTELLIGENCE IN MEDICINAL AROMATIC PLANTS

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INTRODUCTION

Plants that contain certain bioactive compounds such as alkaloids, terpenoids, or phenolic compounds in any or all of their organs—such as leaves, flowers, roots, bulbs, tubers, bark, seeds, and fruits—and are used as medicine are defined as medicinal plants. Medicinal and aromatic plants consist of one or more plants that contain compounds with therapeutic properties and health benefits (Bayram et al., 2010; Marshall, 2011).

The term "medicinal aromatic plants" has no particular meaning.In order to create a meaningful whole, the phrases "medicinal," which means healing and therapeutic, and "aromatic," which means a plant that has a pleasing taste and smell, are combined to produce this name. Aromatic plants are utilized to flavor food and give the atmosphere a pleasant scent, whereas medicinal plants are preferred for food, cosmetics, physical health, and ambient odor. Herbal pharmaceutical treatments and supplements have become increasingly popular in recent years due to their medical properties, low toxicity, accessibility, and affordability (Gerçek et al., 2022).

Aromatic medicinal plants are also added to cuisine. They are used for their coloring, sweetening, antioxidant, and preservation qualities. The active components of plant-based essential oils have been shown in numerous studies to possess a variety of qualities, including antibacterial, antioxidant, antifungal, and inhibitory actions. Additionally, some plants are used as colorants: paprika for red, saffron for yellow, tomato for red, marigold for yellow-orange, pomegranate for red-purple, annatto (bixa orellana tree) for red, safflower for red and yellow, and turmeric for yellow (Toker et al., 2015; Göktaş and Gıdık, 2019).

Herbal products have become more popular in recent years, and a lot of study has been done on their bioactive properties, which include anti-inflammatory, antioxidant, antibacterial, and anticancer benefits (Sefalı, 2023).

This study aims to highlight the significance of therapeutic aromatic plants, which are becoming more and more valuable economically, and to highlight the potential applications of artificial intelligence in this area. There are still few studies on the application of artificial intelligence in medicinal aromatic plants in the literature, according to research done for this study. As a result, this book chapter has been developed as a resource for further research on artificial intelligence in aromatic medicinal plants.

MEDICINAL AROMATIC PLANTS

Since the beginning of human history, medicinal and aromatic herbs have been utilized for the health of humans, animals, and even plants through trial and error and occasionally other means. Natural treatments have been supplanted by chemical drugs as industry has grown, and the demand for medications made from aromatic and medicinal plants has further decreased. Pharmacologists and molecular biologists have evaluated and approved a number of alternative medicine techniques, and people are once again using medicinal and fragrant plants. Additionally, the significance of aromatic and medicinal plants the active components of many medicines is growing in light of the detrimental effects of synthetic chemicals on health (Salehi Surmaghi, 2006; Arslan et al., 2015; Gıdık et al., 2019). The uses of certain medicinal aromatic plants are shown in Figure 1, 2, 3, and 4.

Aromatic medicinal plants are also added to cuisine. They are used for their coloring, sweetening, antioxidant, and preservation qualities. The active components of plant-based essential oils have been shown in numerous studies to possess a variety of qualities, including antibacterial, antioxidant, antifungal, and inhibitory actions. Additionally, some plants are used as colorants: paprika for red, saffron for yellow, tomato for red, marigold for yellow-orange, pomegranate for red-purple, annatto (bixa orellana tree) for red, safflower for red and yellow, and turmeric for yellow (Göktaş and Gıdık, 2019).

Vernacular names	Scientific name	Used parts	Preparation	Key cosmeceutical uses	Country
Apiaceae					
Addaryas	*Smyrnium Olusatrum* L.	L	Powder	Wound healing	Morocco
Accio	*Apium graveolens* L.	R, S	Decoction	Dandruff, bruises, contusions, wounds	Turkey
Pastenaca	*Daucus carota* L. subsp. *Sativus*	R	Raw	Pimples, wounds, dermatitis	
Fenucchiello	*Foeniculum vulgare* Mill	R	Fumigation of decoction	Eye pains	
Petrusino	*Petroselinum crispum* (Mill.) Fuss	AP, L	Decoction	Bruises, burns, pimples, wounds	
Araliaceae					
Ellera	*Hedera helix* L.	L	Decoction	Acne, hair loss, bruises, burns, skin rashes, wounds, varicose veins	Turkey
Apocynaceae					
Dafla	*Nerium oleander* L.	L	Decoction$^{\alpha}$, Infusion$^{\beta}$, poultice$^{\beta}$	Skin diseases$^{\alpha}$, dandruff$^{\beta}$, leprosy$^{\beta}$	Algeria$^{\alpha}$, Morocco
Asteraceae					
Chiba	*Artemisia absinthium* L.[a]	L	Infusion$^{\alpha}$, Powder mixed with oils$^{\beta}$	Otitis$^{\alpha}$, skin infections$^{\beta}$, anti-wrinkle$^{\beta}$	Morocco
Chih	*Artemisia herba-alba* Asso	L	Poultice	Wound healing	
Oum lbina	*Launaea arborescens* (Batt.) Murb	S	Latex	Wounds and acne, skin care	
Chbartu	*Senecio anteuphorbium* (L.) Sch.Bip	S	Poultice	Wound healing	
Qranfel	*Syzygium aromaticum* (L.) Merr. & L.M.Perry	Clo	Powder$^{\alpha}$, poultice$^{\beta}$, Decoction$^{\gamma}$	Toothache$^{\alpha}$, haircare$^{\beta}$, bad breath$^{\gamma}$	
Chih	*Artemisia herba-alba* Asso	L	Poultice	Wound healing	Morocco
Addad	*Atractylis gummifera* Salzm. ex L	R	Decoction$^{\alpha}$, poultice$^{\beta}$	Skin care$^{\alpha}$, hair care$^{\beta}$	
Tafsa	*Bubonium graveolens* (Forssk.) Maire	S	Raw	Dental hygiene (brushing)	
Oum lbina	*Launaea arborescens* (Batt.) Murb	S	Latex	Wounds and acne, skin care	
Chbartu	*Senecio anteuphorbium* (L.) Sch. Bip	S	Poultice	Wound healing	
Lmghayzli	*Volutaria crupinoides* (Desf) Maire	L	Powder	Jaundice	
L'jamra	*Calendula officinalis* L.	L	Powder	Wounds, burns	Morocco
Taymat	*Cynara humilis* L.	R	Powder	Wounds, burns	
Magraman	*Dittrichia viscosa* (L.) Greuter	L	Powder	Wounds, burns	
Khasse	*Lactuca sativa* L.	L	Mixed with cucumber, turnip, and carrots	Mask for face care	
Civanperçemi	*Achillea millefolium* L.	AP	Decoction	Wound healing	Turkey
Elbaboundj	*Matricaria chamomilla* L.	L	Infusion	Skin diseases	Algeria

Figure 1: The uses of certain medicinal aromatic plants (Menale et al., 2016; Belhaj et al., 2020; Mechaala et al., 2022; Bouissane et al., 2025)

Vernacular names	Scientific name	Used parts	Preparation	Key cosmeceutical uses	Country
Achiba	*Artemisia arborescens* L.	L	Powder	Wrinkles and skin infections	Morocco
Addad	*Atractylis gummifera* L.	R	Powder	Skin abscesses and warts	
Cardenzol	*Centaurea ornata* Willd	R	Decoction	Furuncles	Portugal
Erva-montã	*Pulicaria odora* (L.) Reichenb		Cataplasm	Wounds	
Erva-da-talasma	*Senecio jacobaea* L.	L	Cataplasm	Furuncles	
Seca-ossos					
Loloucha	*Calendula arvensis* M.Bieb	L, Fr	Cataplasm, infusion	Burns, wound healing	Algeria
Djamra					
Lappa	*Arctium lappa* L.	L	Leaves juice mixed with the juice of *Urtica* spp. whole plant	Acne, dry skin, pimples, hair loss, varicose veins	Italy
Servatica	*Cichorium intybus* L.	AP, L	Decoction	Acne, wounds	Italy
Cecoria					
Cardo	*Silybum marianum* (L.) Gaertn	WP, R	Decoction	Wounds	
Piscialietto	*Taraxacum campylodes* G.E. Haglund	L	Infusion	Skin inflammation, varicose veins, warts, varicose veins	
Cianfa	*Tussilago farfara* L.	R, L	Decoction with *Malva sylvestris* leaves	Acne, dry skin, skin infections, skin infections, pimples, wounds	
Tefaf	*Sonchus oleraceus* L.	L	Decoction	Warts	Algeria
Brassicaceae					
Çingirdak	*Capsella bursa-pastoris* (L.) Medik	Capit	Infusion	Wounds	Turkey
Şingirdak otu					
Tahtaci otu					
Eşekdikeni					
Vruoccolo	*Brassica oleracea* L.	L	Crushed leaves mixed with olive oil	Pimples, contusions, burns, skin inflammation, shoulder pains, varicose veins	Italy
Rafaniello	*Raphanus raphanistrum* L.	R	Raw	Greasy skin	
Al girjir	*Eruca sativa* Miller	WP	Lotion	Wounds	Morocco
Sibryan	*Sisymbrium irio* L.	LS	Poultice	Wound healing	
Cactaceae					
EL Hendi	*Opuntia ficus-indica* (L.) Mill		Cataplasm	Skin diseases	Algeria
Caprifoliaceae					
Fiocco 'e cardinale	*Centranthus ruber* (L.) DC	L	Infusion, decoction	Hair loss	Italy
Crassulaceae					
Basilios	*Umbilicus rupestris* (Salisb.) Dandy	L	Poultice$^{\alpha}$, infusion$^{\beta}$	Burns$^{\alpha}$, acne$^{\beta}$, warts$^{\beta}$	Spain
Vasillos					
Hoja de llaga					
Cucurbitaceae					
Cetrulo	*Cucumis sativus* L.	Fr	Raw	Skin diseases, wrinkles, pimples, face redness	Italy

Figure 2: The use of certain medicinal aromatic plants in the cosmetic field (Merzouki et al., 2000; Camejo Rodrigues et al. 2003; González et al., 2010; Bulut and Tuzlacı, 2013)

Vernacular names	Scientific name	Used parts	Preparation	Key cosmeceutical uses	Country
Ericaceae					
Sovera pelosa	*Arbutus unedo* L.	L, Fr	Decoction	Wounds	Italy
Fabaceae					
Retam	*Retama raetam* (Forssk.) Webb & Berthe	AP	Cataplasm	Wounds	Algeria
Feniello	*Trigonella foenum-graecum* L.	AP	Mixed with egg yolk	Dry skin, rashes, warts	Italy
Fagaceae					
Cerza	*Quercus pubescens* Willd	Bark	Decoction	Skin diseases, wounds, varicose veins	Italy
Geraniaceae					
Nicchinocco	*Pelargonium peltatum* (L.) L'Hér	L	Topic use	Wounds, burns, pimples, skin diseases	Italy
Nicchinocco	*Pelargonium zonale* (L.) L'Hér. ex Aiton	L	Topic use	Wounds, burns, bruises, pimples	
Globulariaceae					
Zriga	*Globularia alypum* L.	L	Crushed and mixed with milk as an ointment	Furunculosis	Tunisia
Lamiaceae					
Chendgura	*Ajuga iva* (L.) Schreb	L	Poultice[α], decoction[β]	Hair care[α], skin care (rinsing)[β]	Morocco
Lokhzama beldiya	*Lavandula dentata* L.	LS	Decoction	Bad breath	
Halhal	*Lavandula stoechas* L.	LS	Poultice	Hair loss	
Lmrot	*Marrubium vulgare* L.	L	Poultice	Wounds	
Timija	*Mentha suaveolens* Ehrh	L	Decoction	Toothache	
Manrubio negro *Manrubio fétido*	*Ballota nigra* L.	FAP	NS	Toothache	Spain
Alhucema *Espliego* *Alucemón*	*Lavandula latifolia* Medicus	Fr, FAP	NS	Wounds, ulcers, contusion, animal bites, eczema	Spain
Cantuezo *Tomillo* *Cantueso basto*	*Lavandula stoechas* L.	FAP, Fr	Infusion	Wounds, ulcers, contusion, animal bites, eczema	Spain, Morocco
Habaq *Kezouân* *Badrendjouya* *Turunjân*	*Melissa officinalis* L.	AP	NS	Halitosis	Morocco Spain
Narpuz *Yarpuz*	*Mentha pulegium* L.	AP	Infusion, decoction	Sunburn	Turkey
Biberiye	*Rosmarinus officinalis* L.	AP	Infusion	Wounds, anti-aging, skin diseases	
Almakeyik *Almageyik*	*Salvia fruticosa* Miller	L	Infusion	Skin diseases, burns	
karakekik *Peynir keki ̆gi* *Kekik*	*Satureja thymbra* L.	AP	Decoction	Gingivitis	
Taş nanesi	*Micromeria fruticosa* (L.) Druce subsp.*barbata* (Boiss. Et Kotschy) Davis	AP	Decoction	Inflamed or suppurating wounds	Turkey

Figure 3: The uses of certain medicinal aromatic plants (González et al., 2010; Gürdal and Kültür, 2013; Güzel at al., 2015; Menale et al., 2016; Karous et al., 2021; Mechaala et al., 2022)

Vernacular names	Scientific name	Used parts	Preparation	Key cosmeceutical uses	Country
Khzâma	*Lavandula angustifolia* Mill	L	Powder	Wounds, hair loss	Morocco
Merdedouche	*Origanum majorana* L.	L	Powdered plant mixed with *Trigonella foenum-greacum*, *Peganum harmala*, and olive oil	Hair loss	
Rtaimya	*Sideritis incana* L.	AP	Bath	Skin allergy	Algeria
Liliaceae					
Rusco	*Ruscus aculeatus* L.	Rh	Decoction	Varicose veins	Spain
Cornicabra					
Lythraceae					
Henna	*Lawsonia inermis* Roxb	L	Mixed with water	Hair tonic	Morocco
Malvaceae					
Malva	*Malva sylvestris* L.	Fr, L	Cataplasm,	Wounds, furuncles	Portugal
Ebe gömeç	*Malva neglecta* Wallr	L	Crushed leaves mixed with milk	Wounds	Turkey
Gömeç					
Bissam	*Hibiscus sabdariffa* L.	Fr	Infusion	Hair care	Morocco
Oleaceae					
Zeytin	*Olea europaea* L.var. *europaea*	L	Mixed and cooked with olive oil	Wounds	Turkey
Poaceae خرطال	*Avena algeriensis* L.	Fr	Decoction	Skin whitening	Algeria
Tiliaceae ملوخية	*Corchorus olitorius* L.	FAP	Raw	Hair loss	Algeria

Figure 4: The use of certain medicinal aromatic plants in the cosmetic field (Merzouki et al., 2000; González et al., 2010; Benarba at al., 2015; Mechaala et al., 2022)

ARTIFICIAL INTELLIGENCE (AI)

The usage of information and communication technology has resulted in an exponential increase in data generation across all facets of society. Artificial intelligence technology, which has lately gained prominence, is used to process this massive volume of data. Artificial intelligence (AI) is a branch of computer science that studies and evaluates the mechanisms underlying intelligent behavior in humans and then uses those same mechanisms to mimic that behavior in machines (Nogales et al., 2021).

Artificial intelligence (AI) is the term used to describe machine intelligence. This phrase is used when a machine exhibits human-like cognitive behaviors, such problem-solving or machine learning. AI uses technologies like well-known machine learning to learn and anticipate new features. Specifically, the advancement of artificial intelligence has been made possible by the creation of artificial neural networks like recurrent neural networks (RNN) and deep neural networks (DNN). Artificial intelligence will inevitably be used in drug design as a result of these advancements. Molecular filters can be developed or discovered using models derived from MLT, such as Support Vector Machines (SVM), Random Forests (RF), and Bayesian Learning models, especially in virtual screening investigations (Gertrudeset al.,2012).

Data mining, modeling, and machine learning methods are combined to create artificial intelligence. Artificial intelligence, sometimes referred to as machine intelligence, is the capacity of computer systems to learn from inputs or historical data. When a computer imitates cognitive behavior linked to the human brain during learning and problem-solving, it is usually referred to as artificial intelligence (Gupta et al., 2021).

Artificial intelligence includes machine learning, deep learning, and neural networks. Without human help, machines can solve prediction issues by using data to train algorithms. Artificial intelligence is now acknowledged as an engineering field that uses novel ideas and approaches to tackle difficult problems. Computers may eventually surpass human intelligence due to continuous advancements in electronic speed, capacity, and software development. It is impossible to ignore the important role that modern cybernetics has played in the advancement of artificial intelligence (Hamet, 2017; Ossowska et. al., 2022).

THE USE OF ARTIFICIAL INTELLIGENCE TECHNOLOGY IN MEDICINAL AROMATIC PLANTS

Artificial intelligence technology enables the rapid processing of large data sets, providing a comprehensive and standardized approach to documenting collected data. This is also used to evaluate the process of productive agricultural areas from the past to the present (Al-Sammarraie et al.,2025).

Artificial intelligence has the potential to improve sustainability, efficiency, and creativity across a range of industries, including the food business. Artificial intelligence technologies in agriculture optimize crop cultivation methods, facilitate precision farming, and enhance product monitoring and disease detection procedures all of which are crucial for addressing global food security concerns (Nath et al., 2024; Pandey and Mishra, 2024; Al-Sammarraie et al.,2025).

Digital technology has been seen to have a significant impact on business advances in recent years (Sircar et al. 2021) because it uses machine learning, artificial intelligence, and robots to blur the boundaries between the biologic and physical fields.

It is possible to review studies conducted from the past to the present using smart farming applications and artificial intelligence. Thus, artificial intelligence is utilized to determine priority plants in research on medicinal aromatic plants and to establish preliminary information such as the areas of use of these plants. Additionally, artificial intelligence is being utilized in areas such as accelerating plant scanning processes and addressing issues like plant species facing extinction due to uncontrolled use (Al-Sammarraie et al.,2025).

Due to their bioactivities, which include antiviral, antiseptic, antiwormal, antibacterial, anti-inflammatory, antioxidant, and anticancer properties, medicinal and aromatic plants are widely used (Beg et al., 2017). Depending on their chemical makeup and geographical location, these activities differ from plant to plant.

In order to predict and categorize the biologic activities of medicinal and aromatic plants, an automated model that is computationally efficient is required. Having enough descriptive data to create an effective model would be a significant obstacle, though. Furthermore, it is clear from literature reports that model outputs may be impacted by biases in datasets, noise in data, or the requirement for feature selection in models (Jalali-Heravi and Parastar 2011).

To sum up, this thorough guide on realizing the potential of medicinal and aromatic plants has illuminated the important developments in recovery methods, contemporary inventions, legal frameworks, and AI integration in the industry. The guide has emphasized the potential for improving the efficacy and purity of medicinal and aromatic plants by highlighting the significance of quality control and investigating different extraction techniques and cutting-edge technology.

Furthermore, the growing breadth and potential of medicinal and aromatic plants have been highlighted by the discussion of contemporary technologies and their uses in sectors like food and personal care. Lastly, the investigation of AI integration has shown how technology can revolutionize the study, development, and decision-making of medicinal and aromatic plants. Exciting opportunities exist for investigating the untapped benefits of aromatic and medicinal plants in a variety of sectors, and ML integration can promote useful tools for both research and real world applications.

CONCLUSION

With growing economic importance and a wider range of applications, medicinal aromatic plants have emerged as a significant plant category. Even though there have been more research in this area recently, the majority of them concentrate on the plants' antioxidant activity, anticancer properties, active ingredient concentration, and essential oil content. Apart from all these applications, we also use medicinal aromatic plants as food on a daily basis. It is crucial to be able to scan investigations that simultaneously look into a wide range of characteristics of such precious plants.

Nowadays, the use of therapeutic aromatic herbs has increased as consumers switch from chemical-containing manufactured products to natural ones. These plants have been utilized in every part of our life from ancient times to the present, according to several research. Due to increasing demand, the collection, drying, storage, and use of these plants from nature must be carried out in a controlled manner. Additionally, the speed and accuracy of research carried out to identify the various characteristics of these plants are becoming increasingly significant.

Artificial intelligence and machine learning are among the most compelling research topics that have emerged in recent years. As in many other fields, the number of studies utilizing artificial intelligence and machine learning technologies in agricultural sciences is increasing. Artificial intelligence applications have been used to conduct comprehensive and rapid research on the various uses and characteristics of medicinal aromatic plants.

Collaborative work in the fields of artificial intelligence and agricultural sciences, which are expected to play a significant role among the interdisciplinary studies becoming widespread in the field of science, is also proving to be quite productive. It has been concluded that artificial intelligence applications can be utilized in studies related to medicinal aromatic plants due to positive outcomes such as achieving the desired result in a shorter time, enabling more comprehensive scans, and producing measurable results.

This study, which investigates medicinal aromatic plants and artificial intelligence science, examines the collaboration between the two fields. Previous studies on this subject are noteworthy. Although there are not many studies, the existing ones show that the use of medicinal aromatic plants in conjunction with artificial intelligence and new technological applications shortens the research period, enables more accurate results, and opens up new areas of research.

Despite the importance of artificial intelligence, machine learning, and medicinal aromatic plants, it is thought that there are gaps in the literature and that not enough scientific research has been done in these areas. It is thought that more research in this area is necessary to close these gaps in the literature and to provide a basis for future, more in-depth studies.

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CHAPTER 4

ENVIRONMENTAL APPROACHES IN SHEEP BREEDING: INTEGRATION OF BIOCAR-BASED FEEDING AND SMART AGRICULTURAL TECHNOLOGIES

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INTRODUCTION

Global climate change, the unsustainable use of natural resources, and the environmental pressure from agricultural activities have necessitated fundamental transformations in the livestock sector. Livestock activities within agricultural production systems pose a serious threat to environmental sustainability, particularly through enteric methane emissions from ruminant animals, nitrogen oxide emissions from manure management, and the disruption of the carbon cycle in grazing areas (Rodrigues et al., 2022; Osman et al., 2022). In this context, the impact of livestock on the climate crisis is not merely an environmental issue but a multidisciplinary problem that must be addressed from the perspectives of economic efficiency and social responsibility. Livestock-related emissions constitute approximately 14.5% of global greenhouse gas emissions, with a large portion of these emissions being in the form of methane (CH_4). Methane is a greenhouse gas 28 times more potent than CO_2 and is released from microbial fermentation processes in the digestive systems of animals (Rodrigues et al., 2022; Pepeta et al., 2024). Furthermore, enteric methane loss negatively affects the animal's energy efficiency, leading to a decline in production performance (Graves et al., 2022). To overcome these problems, the concept of sustainable livestock farming has evolved, emphasizing holistic approaches that aim to minimize environmental impacts while simultaneously increasing production efficiency and animal welfare (Graves et al., 2022; Schmidt et al., 2019). Among these approaches, two key technological areas have garnered attention in recent years: the use of biochar and the integration of smart farming technologies (e.g., IoT-based systems, sensor-based monitoring networks, and AI-supported analyses) into small ruminant systems (Caja et al., 2020; Rohan et al., 2024; Sadowski and Spachos, 2020). Biochar is a carbon-rich, porous product with a high potential for reducing environmental impacts, obtained by processing wood, agricultural waste, or organic materials through pyrolysis in an oxygen-free environment (Osman et al., 2022). When used as a feed additive, particularly in the diets of ruminant animals, it has been shown to have various effects on digestive system function, microbial balance, gut health, and methane production (Schmidt et al., 2019; Lind et al., 2024). Biochar can also alter the composition of enteric fermentation products, increasing fermentative efficiency and creating selective effects on the ruminal microbiota (Teoh et al., 2019). On the other hand, smart farming technologies offer the ability to monitor and analyze animal behavior, physiological parameters, and environmental interactions in real time. These technologies provide innovative solutions, especially for small ruminants, for predicting births, monitoring feeding behavior, detecting stress, and improving animal welfare (Gonçalves et al., 2024; Terence et al., 2024). Wearable sensors, rumen boluses, GPS tracking systems, camera-based behavior analysis, and machine learning-based decision support systems are some of the technological tools implemented in this field (Caja et al., 2020; Babar and Akan, 2024).

This review aims to provide a scientific foundation for future projections and strategic directions for environmentally friendly sheep farming by comprehensively evaluating the potential of biochar-supported feeding systems as a sustainability-oriented approach, along with smart farming technologies, and the impact of the integration of these two components on environmental and production outcomes.

1. BIOCHAR: DEFINITION, PRODUCTION, AND PROPERTIES

Biochar is a carbon-rich, porous material obtained by the thermal decomposition (pyrolysis) of organic biomass in a controlled, oxygen-free environment. Sourced from agricultural waste, forest products, industrial biomass, or animal residues, biochar is considered an eco-friendly material with both soil-improving and carbon sequestration capacities (Osman et al., 2022; Zhu et al., 2017).

1.1. Obtaining Biochar

Common raw materials used in biochar production include woody residues (e.g., pine shavings, corn cobs, palm fronds), agricultural residues (rice husks, wheat straw, miscanthus), and animal organic materials (Cabeza et al., 2018; Keba et al., 2023; Lind et al., 2024). The source of the raw material directly influences the nutrient content, porosity, pH, and surface area of the resulting biochar. Therefore, the selection of raw material is of great importance depending on the application area (Rodrigues et al., 2022; Graves et al., 2022).

1.2. Pyrolysis Process and Production Parameters

The primary method for biochar production is pyrolysis (Figure 1). In this process, biomass is subjected to thermal decomposition, typically at temperatures between 300–700 °C, in an oxygen-free or very low-oxygen environment. The pyrolysis temperature is a determining factor for the physical and chemical properties of the resulting product. Biochar obtained from low-temperature pyrolysis (350–500 °C) is rich in organic matter, while biochar processed at high temperatures (700–1000 °C) has a larger surface area and pore structure (Cabeza et al., 2018; Rodrigues et al., 2022). Additionally, biochar for different purposes can be obtained through alternative thermal processes such as hydrothermal carbonization and torrefaction (Osman et al., 2022). Activation methods are also applied depending on the production process. Physical activation (e.g., treatment with CO_2 or steam) increases pore volume, while chemical activation (e.g., acid/base treatment) modifies the surface structure to enhance the biochar's adsorption capacity (Graves et al., 2022; Zhu et al., 2017).

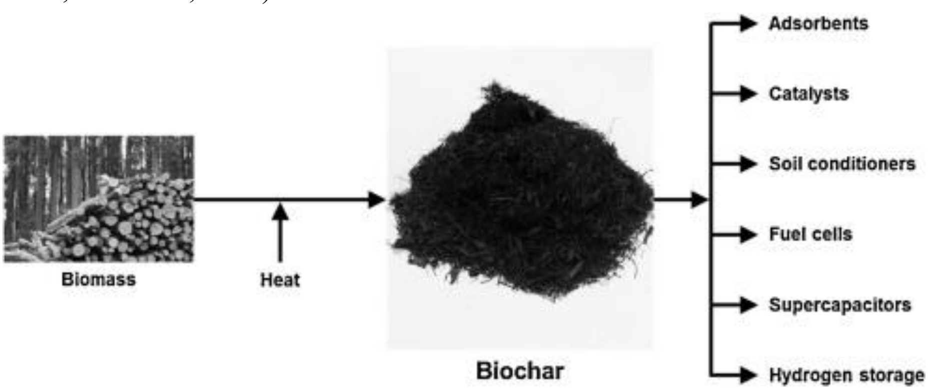

Figure 1. Biochar formation and usage area (Cha et al., 2016)

1.3. Physical and Chemical Properties

Biochar has a number of key properties, including a high surface area (400–1200 m²/g), microstructure, a variable pH (generally alkaline), high cation exchange capacity, electrical conductivity, and a rich organic matter content (Osman et al., 2022; Graves et al., 2022). These characteristics are important for both soil health and animal nutrition (Table 1). Specifically, the interaction of surface functional groups with hydrophilic and lipophilic substances provides advantages like mycotoxin adsorption and microbiota modulation (Schmidt et al., 2019; Zhu et al., 2017). The redox potential (tendency to accept electrons) of biochar enables it to support electron exchange, which can contribute to energy efficiency in microbial fermentation processes. This function can also influence the populations of microbial species that regulate methane production (Teoh et al., 2019; Schmidt et al., 2019).

1.4. Functions for Soil, Environment, and Animal Health

Traditionally, the most common use of biochar is for soil improvement (Gül, 2021). When applied to soil, it increases water retention capacity, aeration, and nutrient holding ability, while also positively affecting the soil microbiota (Zhu et al., 2017; Osman et al., 2022). Its adsorption capacity also allows it to be used for the immobilization of pesticides, heavy metals, and other pollutants. This characteristic creates a safer environment, especially for microorganisms active in biological conversion processes. In livestock farming, studies on the use of biochar as a feed additive are increasing. It has been shown to improve animal health through its ability to bind mycotoxins, inhibit pathogenic microorganisms, and reduce gas and odor emissions (Schmidt et al., 2019; Graves et al., 2022). Additionally, data suggests that biochar can participate in enteric fermentation processes, modulate the rumen microbiota, and reduce methane production (Rodrigues et al., 2022; Lind et al., 2024). In conclusion, biochar is not just a soil conditioner but also a multifaceted material with functions as an eco-friendly feed additive, an emission-reducing agent, and a supporter of the circular economy (Table 1). However, the optimal expression of these effects is closely related to the source, production method, and application dosage of the biochar used (Schmidt et al., 2019; Osman et al., 2022).

Table 1. Properties and Functions of Biochar

Category	Properties / Description	Sources
Raw Materials	Woody waste (pine shavings, palm fronds), agricultural residues (rice husks, miscanthus), animal organic materials	Cabeza et al., 2018; Keba et al., 2023; Lind et al., 2024

2. BIOCHAR USE IN ANIMAL NUTRITION: A SMALL RUMINANT PERSPECTIVE

The use of alternative feed additives in animal nutrition is becoming increasingly important for both animal health and the reduction of environmental impacts. In this context, the use of biochar has emerged as a notable approach for small ruminant livestock in recent years. Researchers are investigating the effects of adding low doses of biochar to farm animals' rations on digestive efficiency, methane production, immune function, and performance parameters (Schmidt et al., 2019; Graves et al., 2022; Lind et al., 2024).

2.1. Use in Sheep and Goat Nutrition

There are numerous studies in the literature on adding biochar to sheep rations at varying rates, from 0.5% to 4%. For example, Lind et al. (2024) evaluated the effects of different doses of pine and spruce-based biochar on feed intake, live weight gain, and methane emissions in sheep, both in vitro and in vivo. The study found that adding low and medium levels of biochar increased feed intake but did not create a significant change in growth rate or methane emissions. Similarly, McAvoy et al. (2020) reported that the digestibility of the ration increased in lambs fed a diet with 2% biochar derived from lodgepole pine and aspen, but there was no significant difference in live weight gain or feed conversion ratio. In another study on Naeemi sheep by Burezq and Khalil (2025), a diet containing 1% date palm-based biochar was reported to reduce methane emissions by 77.63% and significantly improve live weight and body condition scores. These findings demonstrate that the effect of biochar depends not only on the species and dosage but also on the pyrolysis temperature and the raw material used.

2.2. Effects on the Digestive System

Thanks to its high porosity and surface area, biochar can facilitate the binding of toxins in the digestive system, positively influence microbial balance, and increase the activity of digestive enzymes (Schmidt et al., 2019; Teoh et al., 2019). As a result of these mechanisms, an increase in the production of volatile fatty acids (VFAs) and a change in the acetate-to-propionate ratio have been observed (Lind et al., 2024). Regarding its effects on the rumen microbiota, studies have shown that biochar particles can reduce the populations of methane-producing microorganisms (methanogens) and support methane-consuming species (Rodrigues et al., 2022). However, in some studies, these effects on the microbiota were not significant (Teoh et al., 2019). These differences may be due to the heterogeneity of the physicochemical properties of the biochar used (Table 2). Additionally, it has been reported that biochar supplementation contributes positively to rumen pH balance, especially by increasing the concentrations of acetic and propionic acids, thereby supporting the fermentation process (McAvoy et al., 2020). Biochar is considered not just an additive that increases digestive efficiency and reduces methane emissions but also a component that can affect the gut health, immune status, and microbial balance of animals (Table 2). A study by Pereira et al. (2024) evaluated the use of a commercial biochar in dairy cows. The effects of the biochar supplement on fecal pH and microbial composition were specifically examined. The results showed that biochar stabilized fecal pH, promoting the growth of more acidophilic microbial species in the gut. An increase in probiotic species like Lactobacillus was also observed, while Enterobacteria levels decreased. These findings suggest that biochar can function as a beneficial gut modulator, potentially reducing the pathogen load in ruminants. The same study also assessed secondary indicators of animal welfare, such as fecal consistency, tear pH, and licking behaviors, and noted that biochar supplementation led to improvements in these parameters. These effects were attributed to the biochar's microbial toxin-binding capacity and the indirect strengthening of the gut barrier function. Meanwhile, another advanced experimental study by Duan et al. (2023) compared the effects of biochar variants produced at different pyrolysis temperatures (300°C, 500°C, 700°C) on rumen microecology and methane formation. A key finding of this study was that biochar produced at higher temperatures led to greater methane reduction, but this effect was accompanied by the suppression of some beneficial microbial species. For example, the 700°C biochar resulted in up to a 27% reduction in methane production, but a decrease was also found in cellulolytic species in the rumen microbiota, such as Butyrivibrio fibrisolvens and Ruminococcus. Another notable aspect of this study was the finding that biochar also affects the VFA profile by altering the microbial balance, specifically increasing the proportion of propionate and reducing the acetate-to-propionate ratio. This change indicates a more energy-efficient fermentation pattern. Both studies show that biochar has a complex profile of effects, including not only physiological but also microbiological and behavioral interactions. It was also reconfirmed that parameters such as pyrolysis conditions, particle size, and dosage are decisive for the effects on animal health and the microbial ecosystem (Table 2).

Table 2. Physicochemical Properties and Effects of Biochar in Animal Nutrition

Physicochemical Property	Definition / Description	Animal Effect / Functional Outcome	Sources
Surface Area (400–1200 m²/g)	Large microporous structure; high surface adsorption capacity	Binds mycotoxins, eliminates toxins, maintains microbial balance	Schmidt et al., 2019; Zhu et al., 2017
Porosity (micro-macro)	Microstructure suitable for the absorption of organic substances	Buffers fermentation intermediates, maintains rumen pH balance	Teoh et al., 2019; Lind et al., 2024
pH (generally alkaline)	Varies depending on pyrolysis temperature	Stabilizes rumen and fecal pH balance, supports the development of acidophilic flora	Pereira et al., 2024
Cation Exchange Capacity (CEC)	The ability to hold ions with functional groups on the surface	Contributes to mineral balance and microbial fermentation balance	Graves et al., 2022
Redox Potential	Structure suitable for electron exchange (reductive/oxidizable surfaces)	Regulatory role in methane production, improves microbial energy efficiency	Schmidt et al., 2019; Teoh et al., 2019
Mineral Content from Raw Material	Source-specific elements like Ca, Mg, K, P	Mineral contribution, indirect effect on	Rodrigues et al., 2022; Keba et al., 2023

		immune functions	
Thermal Stability	Biochar produced at high temperatures is more stable	Provides a long-lasting effect due to slow digestion	Duan et al., 2023
Functional Surface Groups (carboxyl, hydroxyl, aromatic rings)	Ability to bind to organic toxins and gases	Reduction of mycotoxins, ammonia, and odor gases	Schmidt et al., 2019; McAvoy et al., 2020
Electrical Conductivity (EC)	A parameter that supports ion transfer	Can play a role in microbial communication and enzymatic processes	Osman et al., 2022
Properties Depending on Pyrolysis Temperature	300°C: rich in organic matter / 700°C: high porosity, low H/C (hydrogen-carbon) ratio	Suppression of methane production; however, may lead to a decrease in beneficial microbial species	Duan et al., 2023

2.3. Effects on Performance, Feed Utilization, and the Immune System

Biochar can have direct effects on performance parameters in sheep; however, these effects vary depending on the dosage used and the age of the animal. Keba et al. (2023) reported that supplementing lambs with maize cob biochar, especially at a dose of 1.5 g/day, significantly improved feed intake, digestion rates, daily live weight gain, and carcass characteristics. The same study also saw marked increases in carcass yield and rib muscle development. Burezq and Khalil (2025) showed that sheep fed a biochar-supplemented diet had a significant increase in body condition score (BCS) and improved feed conversion ratios. These findings suggest that biochar can enhance feed utilization, thereby supporting both energy use efficiency and animal productivity. Although studies directly evaluating its effects on the immune system are limited, some research indicates that biochar can support immune functions by balancing the gut microbiota and contributing to the suppression of pathogenic microorganisms (e.g., Campylobacter, Proteobacteria) (Graves et al., 2022; Schmidt et al., 2019).

2.4. Methane Emissions and Environmental Impacts

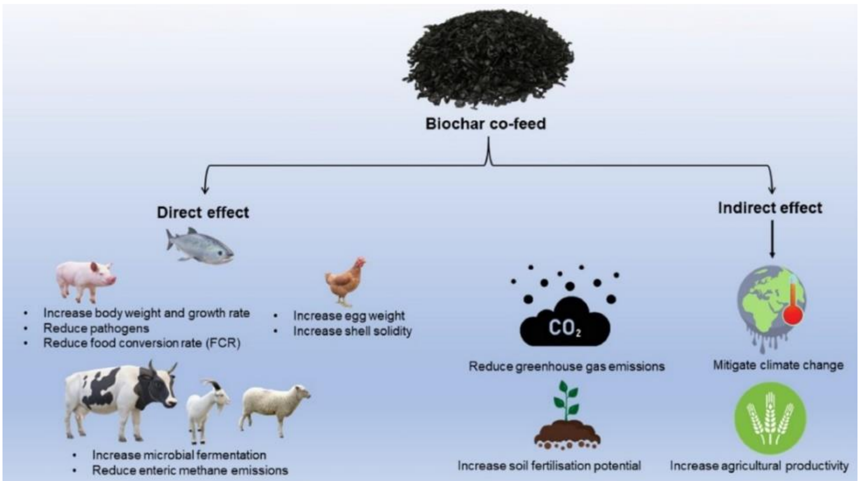

Figure 2. Biochar and its effects in agriculture (Osman et al., 2022)

The environmental impacts of biochar, particularly in the context of methane emissions, are notable. A meta-analysis by Pepeta et al. (2024) revealed that biochar reduced enteric methane production by an average of 21% and could suppress methane production by altering the acetate/propionate ratio of rumen fermentation products. The growing body of literature on biochar's use in animal nutrition demonstrates that this material is not merely a physical additive but has multifaceted effects on microbial metabolism, digestive processes, and environmental emissions (Figure 2). Recent studies involving meta-analyses and advanced biochemical characterization provide deeper insights into biochar's effects on enteric methane formation, microbial composition, and digestive parameters in ruminants. A study by Tahery et al. (2025) developed an activated biochar-mineral supplement with a high surface area (34 m^2/g), oxygen-containing functional groups, and free radical content, which reduced methane production by up to 29%. Activating this supplement with peracetic and propionic acids created a unique microbial-suppressing effect in the mechanism of methane oxidation. Similarly, a study by Nair et al. (2023) stated that biochar improved the feed conversion ratio, helped bind mycotoxins and heavy metals, and positively affected gut health. Promising effects were observed for pathogen control, especially in reducing Clostridium botulinum toxins. An in vitro study by Qomariyah et al. (2021), which used biochar derived from cocoa pods in combination with liquid smoke, observed that the biochar increased acetate production but negatively affected dry matter digestibility at high doses. These findings highlight the sensitivity to dosage and suggest that a reduction in the protozoa population could suppress methane production. A broader meta-analytic evaluation on methane production was conducted by Qomariyah et al. (2023). This study, which analyzed 51 other studies, showed that biochar supplementation increased gas production in vitro while reducing methane emissions. Significant improvements in fiber digestibility and feed conversion ratios were also reported. The suppressive effect of biochars with a low pH on methanogenic bacteria was particularly noteworthy. Biochar's potential to reshape the rumen microbiota has also been demonstrated in experimental studies by Terry et al. (2019) and Martinez-Fernandez et al. (2024). Terry et al. (2019) reported that supplementing with a pine-based "enhanced biochar" did not reduce enteric methane but significantly changed rumen microbial diversity, specifically decreasing Fibrobacter and increasing groups like Spirochaetae. The long-term effects of these changes on production efficiency are not yet clear. On the other hand, a controlled feeding trial by Martinez-Fernandez et al. (2024) showed that specially formulated biochar types could reduce methane by 12.9%. However, the same study reported that this effect was lost under grazing conditions, clearly demonstrating the influence of environmental factors in field applications. Biochar's effects on microbial colonization and nitrogen metabolism in the digestive system were evaluated by Mirheidari et al. (2020). In their study on male lambs using biochars from different sources, a walnut shell-derived biochar significantly increased feed digestion, microbial protein synthesis, and feed utilization. Another finding regarding microbial modulation came from Reggi et al. (2025). This study showed that biochar highly adsorbed Escherichia coli strains while promoting the growth of probiotics like Lactobacillus plantarum. The continued post-digestion effects suggest that biochar can be considered a functional feed additive with antimicrobial selectivity. However, some studies also report that biochar can be ineffective. For example, experiments by Benchaar et al. (2023) observed no significant effect of different biochar types on methane production. This indicates that the raw material, pyrolysis temperature, and chemical properties are key determinants of the effects. A comprehensive evaluation by Kammann et al. (2017) revealed that biochar can play a suppressive role on both CH_4 and N_2O emissions through microbial mechanisms, but these effects can vary depending on soil type, environmental conditions, and application method. Terler et al. (2023) reported in their study on dairy cows that adding 200 g/day of biochar had no significant effect on feed intake or milk yield, and no change was observed in methane production. These conflicting results show that the methane-reducing effect of biochar varies depending on the animal species, ration composition, microbial communities, and the characteristics of the biochar itself (Cabeza et al., 2018; Rodrigues et al., 2022).

Overall, the use of biochar in small ruminant livestock stands out as a supplement that supports both animal performance and environmental sustainability (Figure 2). However, more in vivo studies with standardized protocols are needed to optimize this potential.

3. SMART FARMING TECHNOLOGIES: APPLICATIONS IN SMALL RUMINANT LIVESTOCK

The digitalization of the livestock sector has enabled a transition from traditional management methods to a data-driven and automation-focused production paradigm. This transformation, accelerated by the widespread adoption of "Agriculture 4.0" and "Precision Livestock Farming (PLF)," has begun to show its effects in small ruminant livestock systems as well (Babar and Akan, 2024; Caja et al., 2020). Smart farming technologies aim to provide more efficient and sustainable management by monitoring animals' behavioral, physiological, and environmental data in real time through decision support systems (Terence et al., 2024).

3.1. Wearable Sensors and IoT-Based Monitoring Systems

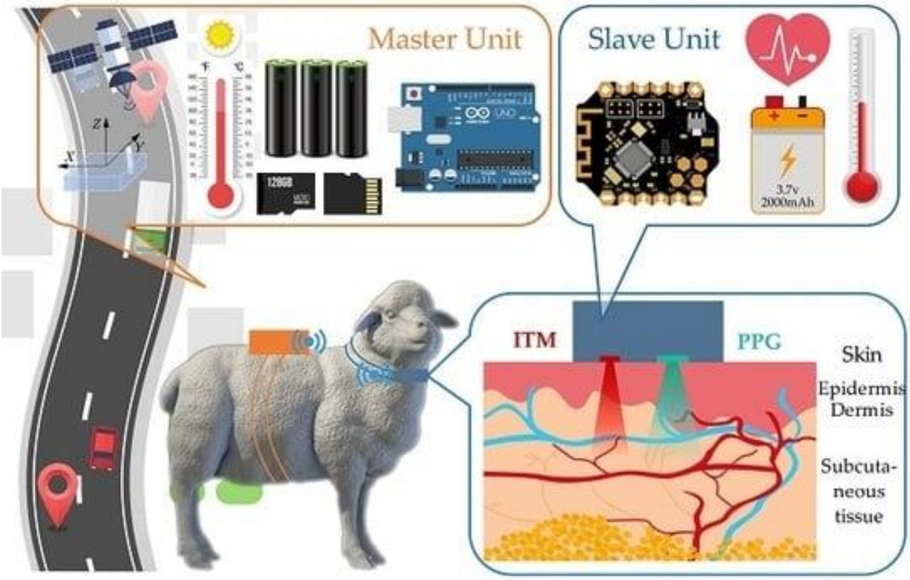

Figure 3. Use of smart technologies for small ruminants (Cui et al., 2019)

The Internet of Things (IoT) makes it possible to automatically collect and analyze animal-based data in small ruminant farms (Figure 3). Wearable sensors (ear tags, collars, accelerometers, rumen boluses), environmental sensors, and data transfer modules allow for the monitoring of animal health, location, temperature, heart rate, and movement (Caja et al., 2020; Gonçalves et al., 2024). One of the greatest advantages of IoT systems in this context is their ability to enable individual animal tracking. This allows for the development of a more precise management approach based on individual animal behavior and welfare rather than on a flock-based approach (Babar and Akan, 2024). For example, sensors placed inside the ear can simultaneously monitor body temperature, activity levels, and stress indicators, enabling the early detection of diseases (Caja et al., 2020; Terence et al., 2024).

3.2. Rumen pH Sensors, GPS, and Behavior Monitoring Technologies

Rumen pH is a critical parameter for the metabolic health of ruminant animals. Sensors in the form of a rumen bolus, ingested by the animal, can record data such as pH, temperature, and rumen activity, allowing for the early detection of conditions like acidosis and ruminal stress (Caja et al., 2020). The widespread use of these systems makes significant contributions to optimizing feeding strategies and increasing feed utilization rates. Furthermore, GPS-based monitoring systems enable the mapping of animals' grazing behavior and movement patterns. This allows for easy identification of herd direction, the effectiveness of grazing areas, and individual deviations (e.g., a sick or calving animal separating from the flock) (Gonçalves et al., 2024). Image processing, machine learning, and deep learning-based models are used to recognize animal behavior. In their systematic review, Rohan et al. (2024) showed that models like Convolutional Neural Networks (CNNs), YOLOv8, and ResNet50 can successfully classify a wide range of behaviors, including feeding, lying/standing frequency, lameness, and mating. Monitoring these behavior patterns is crucial for both welfare and productivity.

3.3. Opportunities for Monitoring Productivity and Welfare

Smart systems allow for the continuous and objective assessment of animal welfare and productivity indicators. The monitoring of pre- and post-calving behavioral changes using accelerometer sensors can predict births hours in advance, preventing lamb losses (Gonçalves et al., 2024). A model developed by Kim et al. (2024) was able to predict births with 82.4% accuracy an average of 90 minutes in advance. Furthermore, anomaly detection algorithms can identify animals in the herd that show physiological or behavioral deviations from the norm. This enables faster decisions regarding early disease detection, treatment, and isolation (Terence et al., 2024). The use of solar panels, low-power communication protocols (LoRaWAN, Zigbee), and embedded systems increases the applicability of these technologies in rural areas (Sadowski and Spachos, 2020). For instance, LoRaWAN-based sensor systems minimize energy consumption, offering long-term monitoring even in rural areas without electricity infrastructure.

3.4. Application Challenges and Infrastructure Requirements

The implementation of these technologies in small ruminant systems can be limited by certain technical and socioeconomic barriers. Low production scales, the cost of technological equipment, a lack of infrastructure in rural areas (electricity, internet), and farmers' digital literacy levels make it difficult to scale these systems (Caja et al., 2020; Babar and Akan, 2024). Additionally, the lack of standardized datasets and behavior definitions reduces the generalizability of algorithms, and there are significant variations in sensor placement and data collection frequency (Gonçalves et al., 2024). Despite these challenges, applications such as mandatory electronic identification (e-ID) systems in Europe provide a strong foundation for the integration of these technologies (Caja et al., 2020). In developing countries, the development of cost-effective, scalable, and user-friendly solutions is critical for the adoption of these technologies.

4. INTEGRATION OF BIOCHAR APPLICATIONS AND SMART FARMING TECHNOLOGIES

In small ruminant livestock, both biochar applications and smart farming technologies are promising tools for achieving sustainable production goals. However, the integrative use of these two approaches has the potential to offer much stronger and more systematic solutions for both reducing environmental impact and managing individual animals. The real-time tracking of the biological effects of biochar as a feed additive using sensor systems and digital monitoring tools holds high added value, not only scientifically but also for practical field applications (Caja et al., 2020; Graves et al., 2022; Gonçalves et al., 2024).

4.1. Monitoring Biochar Application with Real-Time Data

Monitoring the digestive, metabolic, and behavioral changes that may occur with the addition of biochar to a feed ration is made possible by the data infrastructure provided by smart sensor systems. Rumen bolus sensors, in particular, can record parameters such as pH, temperature, and ruminal activity in real-time, offering the opportunity to directly evaluate the effect of biochar supplementation on fermentative processes (Caja et al., 2020). Furthermore, behavioral indicators like rumination time and standing/lying time can be tracked with accelerometer sensors, allowing for the analysis of physiological responses to biochar application (Gonçalves et al., 2024; Terence et al., 2024). Studies by Lind et al. (2024) monitored the effects of biochar supplementation on feed intake and methane emissions at an individual level, revealing varying response patterns among animals. This demonstrates that digital farming tools can be used as support technologies to optimize environmentally friendly initiatives like biochar at the individual level.

4.2. Feeding Optimization and Individual Monitoring

To balance the variations that may occur when including biochar in rations, it's possible to develop feeding strategies based on individual animal monitoring. For example, feeding animals with high digestive sensitivity a low dose of biochar can prevent the disruption of their microbial balance. Similarly, the biochar dosage can be increased for animals with higher methane emissions to reduce enteric emissions in a targeted manner (Pepeta et al., 2024; Schmidt et al., 2019). This approach is an adaptation of the "Precision Feeding" paradigm to small ruminant livestock. IoT-based feeding systems can define specific rations for each animal, and this process can be monitored automatically with sensor data. For instance, Radio-Frequency Identification (RFID) technology can identify an animal and apply a customized feed formulation (Caja et al., 2020).

4.3. Case Studies or Model Proposals

The literature contains a limited number of examples of the integrated use of biochar and sensor technologies. However, by synthesizing existing research, applicable field models can be created. For example, a digitally integrated feeding model could include:

Monitoring an animal's rumen pH and temperature with bolus sensors.

Simultaneously measuring feed consumption from RFID-supported feeders.

Tracking movement and rumination behavior with accelerometers.

Analyzing physiological and behavioral responses to biochar supplementation.

Transferring the collected data to AI-supported decision-making systems.

This model enables not only the optimization of feeding strategies but also the data-driven management of decision-making processes focused on sustainability and animal welfare. This approach can also provide an effective monitoring infrastructure for farm-level carbon footprint calculations (Graves et al., 2022; Osman et al., 2022). To make such systems viable, it is critical to promote collaborations between universities, farmers, and industry, to increase technological literacy, and to provide infrastructure support. For developing countries like Türkiye, developing cost-effective, low-power sensor systems and encouraging local biochar production are strategically important for the widespread adoption of this integration (Babar and Akan, 2024).

5. EVALUATION FROM THE PERSPECTIVES OF SUSTAINABILITY, CIRCULAR ECONOMY, AND CARBON FOOTPRINT

As global agricultural production systems begin to exceed environmental limits, the principle of sustainability has become not just an eco-friendly choice but a mandatory production model. This is particularly evident in sectors with high carbon footprints, like livestock farming. Small ruminant livestock contributes to greenhouse gas emissions through many processes, including direct methane emissions from grazing-based systems, manure management, and feed production and transportation. It also puts pressure on biodiversity, soil health, and water resources (Rodrigues et al., 2022; Graves et al., 2022).

5.1. The Environmental Cost of Livestock Farming

Enteric fermentation from ruminants is the largest source of methane emissions from the global agricultural sector. Methane has a warming potential 84 times greater than CO_2 in the short term (over a 20-year period), dramatically increasing the impact of animal production systems on climate change (Pepeta et al., 2024). Additionally, agricultural inputs used for feed production (fertilizers, irrigation, pesticides), overgrazing, and waste management further increase the environmental burden of livestock activities (Osman et al., 2022). In this context, developing low-emission production methods, establishing systems based on a circular resource management approach, and integrating carbon-balancing practices should be prioritized, especially in sheep farming.

5.2. The Carbon Sequestration Cycle of Biochar

Biochar is a material that prevents the release of carbon from biomass into the atmosphere by converting it into a stable form during production and provides long-term carbon storage in soil and biological systems. For this reason, it is defined as both a negative emissions technology and a tool for the circular economy (Zhu et al., 2017; Osman et al., 2022). Biochar obtained from the pyrolysis process does not undergo rapid decomposition and can remain in the soil for up to 1,000 years, thereby serving as a long-term sink in the carbon cycle (Cabeza et al., 2018). Its production from agricultural and industrial waste also provides a significant opportunity for waste recovery. For example, biochar produced from materials like palm tree waste, corn cobs, and rice husks not only adds value to waste but also reduces the need for imported feed additives (Burezq and Khalil, 2025; Keba et al., 2023). The use of biochar in animal production is not limited to carbon sequestration; it also plays a role in reducing methane production from feed. This dual effect offers a strategic potential for reducing enteric fermentation emissions and the overall carbon footprint of the system (Lind et al., 2024; Pepeta et al., 2024).

5.3. Contribution of Smart Systems to Sustainability

Smart farming technologies offer critical advantages for achieving sustainability goals, including not just increased productivity but also the optimization of efficiency and resource use. Real-time data flow enables the need-based and minimal use of resources (feed, water, medicine), and monitoring animal welfare prevents production losses (Caja et al., 2020; Gonçalves et al., 2024). This both reduces the environmental burden and supports economic sustainability. Furthermore, data collected with smart systems can be integrated into carbon footprint calculation models to measure environmental performance at the farm level. This makes it possible to objectively monitor not only greenhouse gas emissions but also other environmental indicators like water footprint and energy consumption (Graves et al., 2022). In this respect, smart systems are a critical component that brings together environmental sustainability and digital transformation. The widespread adoption of smart systems in small ruminant farming is also important for the adaptation of technological innovations in rural areas. Thanks to low-power, wireless data-transfer IoT-based sensor networks, sustainable production practices can spread regardless of farm scale (Sadowski and Spachos, 2020; Babar and Akan, 2024).

6. CHALLENGES, LIMITATIONS, AND FUTURE PERSPECTIVES

Despite their environmental and productive potential, the integration of biochar applications and smart farming technologies in small ruminant livestock faces various technical, economic, and socio-cultural limitations. These limitations stem from multidimensional factors such as application scale, access to technology, farmer profiles, and a lack of research. However, developing strategic solutions for these problems is critical for a sustainable and data-driven future for sheep farming.

6.1. Limitations in Application

The most fundamental challenge for biochar applications is the infrastructure requirement related to the production process. Factors like the cost of pyrolysis equipment, energy supply, raw material sourcing, and quality standardization limit applicability in rural and low-capacity production units (Osman et al., 2022; Cabeza et al., 2018). Furthermore, the safety profiles of biochar types produced from different raw materials have not yet been clearly established, and standardized protocols for issues like toxic effects, heavy metal accumulation, and microbial interactions have not been developed (Zhu et al., 2017; Schmidt et al., 2019). As for smart farming systems, high initial investment costs, a lack of digital infrastructure in rural areas (internet, energy, data transfer networks), and farmer literacy and user experience are significant obstacles (Caja et al., 2020; Babar and Akan, 2024). The safe placement of sensors on animals, data security, maintenance needs, and software integration problems can also cause technical issues during the implementation process. Additionally, the lack of successful commercial-scale examples of these technologies used together and the absence of guidance systems for farmers make the adoption of integrated systems difficult (Gonçalves et al., 2024; Graves et al., 2022).

6.2. Gaps in Education, Awareness, and Policy

A large portion of producers lack sufficient knowledge about the advantages of both biochar and smart systems. It is particularly difficult for rural producers with lower levels of education to understand, adopt, and manage these systems. The lack of technical staff also weakens the long-term sustainability of electronic systems that require maintenance (Caja et al., 2020). At the policy level, there are regulatory gaps in areas like the definition of biochar as a feed additive, the determination of usage limits, and the development of incentive systems. For example, while legal frameworks for biochar production and application have been established in the European Union and some developed countries, regulations in countries like Türkiye are very limited (Osman et al., 2022). Similarly, insufficient public support for smart farming technologies means that these systems are limited to large-scale operations, leaving small and medium-sized farmers outside the system. This deepens the technology gap and increases agricultural inequality (Babar and Akan, 2024).

6.3. Research Gaps and Scientific Uncertainties

The literature on the interactive use of biochar and smart farming technologies is still limited. In particular, long-term, controlled field experiments specifically for small ruminants are lacking. The effects of biochar in different ration formulations, performance changes according to age groups, rumen microbial dynamics, and long-term effects on environmental emissions have not yet been clarified (Lind et al., 2024; Pepeta et al., 2024). Furthermore, the integrated use of smart sensor systems in such research has not yet been systematized. Although the potential of data analytics, machine learning, and AI integration in small ruminant systems is high, most of the algorithms in this area have been developed based on data from large ruminants (Rohan et al., 2024). It is necessary to create species-specific datasets for small ruminants' behavioral identifiers and to adapt and test the accuracy of the models in the field.

6.4. Strategic Recommendations for the Future

Despite these challenges, it is possible to establish sustainable small ruminant livestock systems by integrating biochar and digital technologies. The following strategic recommendations can be developed in this direction:

Standardization: Determine the maximum dose, particle size, and safety criteria for biochar types that can be used as feed additives.

Education and Extension: Develop practical training modules, remote guidance applications, and simplified interfaces for sensor use for farmers.

Policy Incentives: Promote the widespread use of smart farming investments and local biochar production through public support, pilot farm applications, and demonstration projects.

Multidisciplinary Research: Support long-term monitoring and evaluation projects where disciplines like animal science, environmental engineering, data science, and veterinary medicine work together.

7. CONCLUSION AND RECOMMENDATIONS

The increasing global environmental problems necessitate the restructuring of agricultural production systems within the framework of sustainability principles. The small ruminant livestock sector, in particular, holds a strategic position in terms of ensuring food security and supporting rural development. However, the climatic and environmental pressures faced by this sector require innovative and holistic approaches. The two fundamental strategies evaluated in this study—biochar-supported feeding and the integration of smart farming technologies—constitute the building blocks of an eco-friendly, sustainable, and high-efficiency production model in sheep farming. Biochar can have positive effects on many physiological parameters, including digestive system functions, feed utilization, the reduction of methane emissions, and the immune system. At the same time, its waste-based production supports the circular economy and makes it an important tool in the fight against climate change. On the other hand, smart farming technologies enable the real-time and objective monitoring of animal behavior, health status, and environmental interactions. These technologies not only increase production efficiency but also offer gains such as optimized resource use, early disease detection, and improved animal welfare. The integration of these two approaches creates a multidimensional opportunity for the future of sheep farming. This way, both productivity and sustainability goals can be achieved simultaneously. However, to successfully implement this integration, various structural, technical, and political barriers must be overcome. Defining biochar as a feed additive in a legal framework, increasing farmer education and digital literacy, providing infrastructure support, and conducting multidisciplinary field research are the key dynamics of this process.

In conclusion, the combined use of biochar and smart farming technologies has great potential not only for reducing environmental pressures but also for modernizing production systems and establishing resilient agricultural structures. The widespread adoption of these two innovative approaches through collaboration between the public, private sectors, and academia is a critical requirement for the sustainable transformation of the small ruminant livestock sector.

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CHAPTER 5

CLIMATE CHANGE AND POTATO

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INTRODUCTION

Climate change is governed by a complex system that encompasses interacting atmospheric and oceanic processes. In agricultural production, these processes include the depletion of beneficial stratospheric ozone (O_3) and the increasing concentrations of carbon dioxide (CO_2), methane (CH_4), and nitrogen and sulfur oxides (NO_x, SO_x). These gases exert both direct and indirect effects, with CO_2 being the most significant and the primary contributor to global warming.

Climate change, with its impacts and increasingly evident consequences, has become a major global issue. In recent years, natural disasters such as floods, wildfires, and droughts have occurred on a global scale, threatening ecosystems and human life. The frequency, intensity, and duration of such events have markedly increased in recent decades. Climate change is no longer merely an environmental concern but a profound challenge to the sustainability of human life. Excessive increases in atmospheric temperature cause global warming, which results from the greenhouse effect induced by greenhouse gases emitted through unsustainable human activities.

Globally, energy consumption remains the largest source of anthropogenic greenhouse gas emissions, accounting for approximately 73% of the total. Other major sources outside the energy sector include agricultural activities (12%), land use, land-use change, and forestry (6.5%), industrial processes such as chemical and cement production (5.6%), and waste-related activities such as solid waste disposal and wastewater management (3.2%) (Anonymous, 2021).

Climate change constitutes an inevitable and predominantly irreversible process with profound implications for all aspects of human existence, especially food security. Its direct impacts include rising temperatures, drought -particularly in arid and semi-arid regions irregular rainfall patterns, and unpredictable heavy precipitation events (Trenberth, 2008; Andjelkovic, 2018). In 2016, the global average temperature was 0.99°C higher than in the mid-20th century (NASA, 2018). By the end of the 21st century, global mean surface temperature is projected to increase by 1-3.7°C relative to the late 20th century (IPCC, 2014).

According to projections, the annual mean precipitation is anticipated to rise across high-latitude and equatorial Pacific regions, as well as in some humid mid-latitude areas, whereas a decrease is expected in many arid zones of the mid-latitudes and subtropics by the century's end (IPCC, 2014).

Plants experience abiotic stress when exposed to adverse environmental conditions that reduce growth and yield. Such conditions include high or low temperatures, drought, metal toxicity, and salinity stress. Under climate change, high temperature (heat stress), drought, and salinity have emerged as the most severe abiotic stresses. Rising global temperatures have increased the frequency of heat stress events, while the decline in annual precipitation in some mid-latitude and subtropical regions has raised serious concerns regarding water scarcity (IPCC, 2014). Low precipitation, high surface evaporation, rock weathering, seawater intrusion, and improper agricultural practices collectively exacerbate soil salinity (Shrivastava and Kumar, 2015; Duan, 2016).

A complex and interdependent relationship exists between agriculture and climate. Variability in weather patterns causes fluctuations in crop production, thereby increasing uncertainty in agricultural outputs. The changes observed in the global climate are largely attributable to human activities. Since the onset of the Industrial Revolution, fossil fuel consumption and cement production have risen to meet the needs of a growing population, while new lands have been cultivated for crop and livestock production (Özer and Özer, 2003).

Climate change poses a substantial threat to both animal and plant productivity, thereby jeopardizing global food security (Mosupiemang et al., 2022). Reductions in precipitation and increases in temperature are expected in many regions. In the future, particularly in arid and semi-arid zones, the severity and duration of droughts will inevitably increase due to intensified evaporation. In these areas, drought stress represents a major constraint on plant production (Lobell et al., 2008). The decline in agricultural productivity caused by climate change and drought has become a critical concern for agricultural engineers and plant breeders (Bahrami et al., 2014). This has prompted researchers and practitioners to develop drought-tolerant genotypes and explore agronomic practices aimed at mitigating drought effects and improving yield.

Today, one of the key goals of agricultural production is to utilize plant species and cultivars adapted to changing climatic conditions. In this context, diversification of crop types according to climatic challenges has become essential (Acevedo et al., 2020; Hufnagel et al., 2020). Plants have evolved various physiological, morphological, and biochemical mechanisms to survive under drought stress (Claeys and Inzé, 2013). While some plants naturally possess such mechanisms, others lack them (Seki et al., 2007). Consequently, significant differences exist among genotypes in terms of drought tolerance. Moreover, the response of genotypes to water stress depends on the intensity and duration of the stress as well as the developmental stage of the plant. It should be emphasized that the duration of stress is often more critical than its intensity (Nargeseh et al., 2020).

Among environmental factors, air temperature is one of the most influential parameters determining plant growth and development (Delavega and Hall, 2002). A practical application of temperature in agriculture is the estimation of crop development stages through accumulated temperature or Growing Degree Days (GDD). The GDD concept is based on the principle that plants require a specific amount of heat units to complete each growth stage (Yasari et al., 2014).

Disruptions in the global food system caused by climate change threaten human well-being and social stability. Although there is broad scientific agreement that climate change affects agricultural systems, consensus regarding the magnitude and direction of these impacts remains limited. It is well established that shifts in climate alter weather distribution patterns worldwide and that agricultural biophysical processes respond accordingly (Porter et al., 2014; Rosenzweig et al., 2014). However, the extent to which farmers and societies can effectively adapt to these changes remains uncertain (Challinor et al., 2014; Thornton, 2018). Additionally, the adaptive capacity of producers to overcome the challenges imposed by climate change has yet to be fully established (Lobell et al., 2008).

Potato is considered a staple crop that can contribute significantly to food security owing to its high nutritional value, affordability, and broad accessibility (Mbow et al., 2019; FAO, 2022). Within the global food system, the potato plays a crucial role not only in nutrition but also in supply stability and food security (Devaux et al., 2020). In light of increasing climate pressures and population growth, the potato has been proposed as a strategic crop for sustaining global food security (Devaux et al., 2020; Villa, 2021).

As a plant-based source of protein, the potato serves as a nutritious alternative to animal protein. It is more tolerant of adverse weather conditions than many other crops. Potato cultivation provides both income and employment, and several countries have designated specific potato varieties as part of their national agricultural heritage. Furthermore, potato production has a relatively low carbon footprint and requires less water than many other staple crops (Devaux et al., 2020).

Although potatoes are generally consumed fresh, they are also considered an important raw material for food processing, such as chips and French fries, as well as for industrial applications, including starch and ethanol production (Birch et al., 2012; Watanabe, 2015). Due to their high carbohydrate content, low fat, and balanced vitamin–mineral composition, potatoes are a valuable crop for human nutrition and food security (White et al., 2009; Birch et al., 2012).

A fundamental concept in plant breeding, the genotype–environment interaction, refers to the dependence of a plant's life cycle on environmental conditions. Adverse environmental conditions reduce growth and yield, resulting in abiotic stress (Cramer et al., 2011). Although potatoes are cultivated under diverse climates and seasons globally, most cultivated varieties originate from the cool, short-day highlands of the Andes in South America (Hawkes, 1994). Currently, potatoes are grown between latitudes 47°N and 65°S, with about 90% of total production concentrated in the narrow belt between 22°S and 59°N (Hijmans, 2001).

Although potato can be cultivated in subtropical and tropical regions, water stress, high temperature, and ion toxicity are the main abiotic stress factors limiting their production (Bohnert, 2007). In particular, high temperatures, drought, and salinity have severe impacts on yield. Combined stresses -such as concurrent heat waves and drought- can exacerbate agricultural losses (Mittler, 2006). For instance, in 2016, potato yields in Ontario decreased by 35–50% due to heat and drought stress (Banks and VanOostrum, 2016).

This section aims to evaluate the effects of climate change and the increasing atmospheric CO_2 concentration on potato yields in current and potential future production regions.

1. AGRICULTURE UNDER CLIMATE CHANGE

For crops to grow healthily, adequate soil, water, sunlight, and temperature are essential. Climate, which exerts a decisive influence over all these factors, is a highly dynamic and complex component of agricultural systems. Consequently, its variability introduces significant uncertainty and risk for the agricultural sector. As one of the main factors directly affecting agricultural production, climate change causes considerable shifts in productivity and cropping patterns. Today, the impacts and consequences of climate change have become evident in almost every aspect of life. These effects manifest in various forms, including drought, erosion, desertification, increased prevalence of infectious diseases, shifts in climatic zones, more frequent extreme weather events, rising sea levels, disruption of natural ecosystems, harm to wildlife, and adverse effects on human health.

The agricultural sector is both a contributor to and a victim of climate change. Therefore, understanding how agricultural production systems respond to changing climatic conditions is of paramount importance. Developing new, climate-resilient agricultural practices and technologies is critical to sustaining productivity (Anonymous, 2021).

Observed climate change -reflected in rising temperatures, altered precipitation patterns, and more frequent extreme weather events- directly threatens food security. Studies isolating the specific impacts of climate change from other yield-determining factors have demonstrated that in many higher-latitude regions, yields of certain crops such as maize, wheat, and sugar beet have increased in recent years. In contrast, in many lower-latitude regions, yields of major crops -particularly maize and wheat- have declined due to observed climatic shifts.

In tropical and subtropical regions, crop yield and suitability are expected to decline under elevated temperature regimes. Heat stress reduces fruit set, accelerates the development of annual vegetables, and consequently results in yield losses, quality deterioration, and greater food loss and waste. Although extended growing seasons may permit multiple cropping and thus increase annual yields, some fruit and vegetable species require a period of chilling to ensure proper fruiting; warmer winters therefore pose a risk in this regard (Mbow, 2019).

Agricultural production worldwide is fundamentally dependent on climatic conditions. Changes in temperature and precipitation regimes adversely affect both crop and livestock production. Variations in temperature, atmospheric carbon dioxide (CO_2) concentration, and precipitation frequency and intensity can have profound impacts on crop yield. For instance, while elevated CO_2 levels may enhance plant growth, if temperatures exceed the optimal range or if water and nutrient availability are limited, yield reductions may occur. Moreover, higher CO_2 concentrations can lower the protein and nitrogen content of forage crops such as alfalfa and soybean, leading to declines in feed quality. Consequently, reduced grain and forage quality adversely affects the nutritional intake of grazing livestock (Türkeş, 2006).

2. CLIMATE CHANGE AND POTATO

Potato (*Solanum tuberosum* L.) ranks as the fourth most important food crop globally, following rice, wheat, and maize. In 2021, global potato production reached 376 million tons (FAO, 2022), and due to the growing world population, demand is expected to increase further (Tian et al., 2021). Under temperate climatic conditions, the potato growing period ranges from three to five months, requiring approximately 350–500 mm of rainfall to achieve satisfactory yields (Khurana, 2003; Xie et al., 2012; Tang et al., 2018). Rainfall plays a critical role during the tuber bulking and maturation stages, as it supports tuber development (Djaman et al., 2021). Furthermore, rainfall between planting and tuber initiation determines the number of tubers formed per stem; higher rainfall during this period generally increases tuber number (Ewing and Struik, 1992). To prevent photosynthetic inhibition and temperature stress, an air temperature between 16-30°C, corresponding to an accumulated thermal sum of about 2000 degree-days during the growing season, is optimal (Timlin et al., 2006; Levy and Veilleux, 2007; Struik, 2007; Wang et al., 2015). However, when the average temperature exceeds 19°C, dry matter allocation to tubers decreases (Marinus and Bodlaender, 1975; Kooman et al., 1996; Struik, 2007), which may adversely affect yield.

Soil temperature requirements vary according to the developmental stage of the potato. Optimum soil temperatures are around 15°C for planting, 22°C for tuber initiation, and 15°C for tuber bulking (Struik, 2007). The best growth, in terms of tuber filling rate and final yield, occurs under photoperiods of approximately 11-13 hours (Zhao et al., 2016). Nevertheless, potatoes can continue growing under short-day conditions (4 - 6 hours) (Zhao et al., 2016) and may even be cultivated under long-day conditions in regions above the Arctic Circle (Merzlaya et al., 2008). This demonstrates that the potato is a flexible species capable of adapting to a wide range of light conditions.

The realization of the genetic yield potential of the potato is closely related to environmental variables such as temperature, photoperiod, and solar radiation (Sood et al., 2022). Final yield varies across years depending on biotic stresses (Dupuis et al., 2019) and agronomic practices, including soil management (Ochuodho et al., 2014; Abrougui et al., 2019) and soil fertility (Prasad et al., 2015). Interannual and regional variability in climatic factors enhances the influence of environmental conditions on yield. Therefore, genotype × environment interaction plays a critical role in assessing the sustainability of potato production under the combined pressures of climate change and global population growth (Cooper et al., 2021).

The effects of climate change on potato production manifest through several abiotic factors such as rising air temperatures, prolonged droughts, altered precipitation patterns, and elevated atmospheric CO_2 concentrations (Adekanmbi et al., 2024).

The impacts of climate change on potato production are multifaceted. Elevated temperatures accelerate developmental rates and increase respiration, which may lead to lower yields depending on the intensity and duration of heat stress. Conversely, while higher atmospheric CO_2 contributes to global warming, it can also enhance potato yields (Haverkort and Verhagen, 2008). However, elevated CO_2 levels have been reported to modify the nutritional composition of potato tubers by increasing soluble starch and sugar contents while decreasing protein and zinc concentrations (Kumari et al., 2013; Dong et al., 2018).

For a given planting date, higher temperatures shorten the growth duration of potato plants, resulting in lower final yields (Muthoni and Kabira, 2015). Nonetheless, in some regions, rising temperatures may extend frost-free periods, enabling earlier planting and a potentially longer growing season.

Potato plants are exposed to abiotic constraints such as water stress, temperature extremes, and ion toxicity (salinity and heavy metals) in their growing environments (Bohnert, 2007). The combination of drought and heat waves can result in severe yield losses (Mittler, 2006). Although the potato is an efficient water user that produces more food per unit of water than many other staple crops (Vos and Haverkort, 2007), its shallow and low-density root system makes it highly sensitive to water scarcity (Yamaguchi and Tanaka, 1990; Wishart et al., 2014;). Potatoes generally require 400-800 mm of rainfall for full development, depending on climate, soil type, and cultivation conditions (Ekanayake, 1989). Reduced rainfall in mid-latitude and subtropical arid regions due to climate change leads to drought stress, negatively affecting plant growth, tuber yield, and quality (Mackerron and Jefferies, 1988; Soltys-Kalina et al., 2016; Aliche et al., 2018).

Although the potato performs best in sandy soils with low water-holding capacity, its shallow root system (Iwama, 2008; Djaman et al., 2021) makes it vulnerable to prolonged drought especially in rainfed systems which can severely limit growth (Handayani et al., 2019; Ontario Ministry of Agriculture, Food and Agribusiness, 2022), particularly during the late growth stages (Jiang et al., 2024). Water stress affects tuber weight more than tuber number, producing smaller tubers (Badr et al., 2012). Conversely, excess water also harms potato plants (Jiang et al., 2021 and 2024). Restricted soil oxygen exchange reduces respiration and increases the risk of physiological disorders (Adekanmbi et al., 2024; Scheufele, 2022). In temperate and humid regions, irrigation has become essential; however, if mismanaged, it may cause waterlogging and favor diseases such as late blight, thereby reducing yield (Bélanger et al., 2000; Jiang et al., 2021).

Under drought conditions, the starch content of potato tubers tends to decrease. Nevertheless, since water loss during drought often exceeds the limitation of starch biosynthesis, the relative starch concentration per fresh weight may actually increase (Bach et al., 2013). Starch content is a critical quality parameter determining the processing and nutritional properties of harvested potatoes.

Climate change threatens potato production by triggering heat stress, drought, and salinity. Potatoes require a specific amount and quality of water for optimal growth. In contrast, lower temperatures generally contribute to more stable yields. Various cultivation techniques are being developed to mitigate the adverse effects of stresses such as drought, heat, and salinity. Developing new cultivars tolerant to abiotic stresses is essential to ensure sustainable production under suboptimal environmental conditions. The susceptibility of commercial varieties to stress and their limited genetic diversity make it difficult to improve tolerance levels. However, local varieties and wild relatives offer valuable genetic resources for breeding and improvement programs.

The complex polysomic and heterozygous genetic structure of the potato complicates phenotypic evaluation and the transfer of tolerance traits under stress conditions, making stress-resistance breeding more challenging than breeding for disease or pest resistance. Currently, potatoes face increasing levels of abiotic stress in the field. Therefore, achieving high yields requires the adoption of appropriate cultivation techniques, precision agriculture technologies, and stress-tolerant varieties developed through advanced breeding programs (Handayani et al., 2019).

3. POTATO YIELD UNDER CLIMATE CHANGE

Seed quality is a critical determinant in every agricultural production system, and in potatoes, the tuber serves as the seed, playing a central role in the establishment of new plants. The health and physiological status of seed tubers significantly influence overall yield (Kwambai et al., 2023). Among environmental factors, drought, salinity, and especially temperature exert profound effects on potato growth and productivity (Demirel, 2023). For optimal stem elongation and proper development of seed tubers, temperatures between 6°C and 18°C are required (Kumar et al., 2022).

Temperature, water availability, atmospheric CO_2 concentration, pest pressure, and plant diseases are among the main determinants of potato yield under changing climatic conditions. In general, climate change accelerates potato development but often leads to a reduction in total yield. In addition to these abiotic stressors, biotic factors such as pathogens, weeds, insects, and nematodes also play a major role in yield variability (Sanabria and Lhomme, 2013; Adavi et al., 2018; Handayani et al., 2019).

Climate change represents a decisive factor influencing potato yield worldwide (Hijmans, 2003; Haverkort and Verhagen, 2008). Although potatoes can partially adapt to drought, they are highly sensitive to high humidity and temperature fluctuations. The crop performs best during a well-defined, frost-free growing period, whereas elevated temperatures negatively affect tuber formation and yield (Haverkort and Verhagen, 2008). Potato yield varies according to climatic variables such as temperature, solar radiation, and day length; extended photoperiods and moderate temperatures generally enhance yield, whereas high temperatures during tuber development significantly reduce it (Saxena and Mathur, 2013).

Temperatures above the optimum threshold and heat stress reduce leaf area and canopy light interception, thereby lowering photosynthetic efficiency and ultimately leading to yield losses (Timlin et al., 2006; Fleisher et al., 2006; Tang et al., 2018). However, elevated atmospheric CO_2 concentrations can enhance the rate of photosynthesis, improve water and nitrogen use efficiency, and partially offset the negative effects of heat stress, potentially contributing to yield stability (Leakey et al., 2009; Lee et al., 2020; Yubi et al., 2021).

In northern regions, where average temperatures remain below the optimum range, concurrent increases in temperature and CO_2 concentration are expected to exert a synergistic positive effect on tuber yield. Conversely, in regions where temperatures are already near or at the optimum level, the beneficial impacts of CO_2 enrichment may not fully counteract the detrimental effects of further warming. Moreover, such combined effects tend to be more pronounced during early growth stages and diminish during later developmental phases as photosynthetic activity declines (Lee et al., 2020; Yubi et al., 2021).

Potato exhibits strong sensitivity to high temperatures (Levy and Veilleux, 2007), which restricts its cultivation in tropical and subtropical regions. Exposure to high temperatures during early developmental stages can delay tuber initiation, shorten the overall growth period, and reduce the rate of carbon assimilation, all of which contribute to yield loss (Aien et al., 2016).

Although the potato is considered a relatively water efficient crop, it remains highly susceptible to water deficits. It has been reported that for every 10% reduction in precipitation, rainfed tuber yields decline by approximately 2% (Fleisher et al., 2017). In the Netherlands, a 1 mm water deficit caused a loss of about 117 kg ha^{-1}, leading to smaller tubers (Vos and Groenwold, 1987). Furthermore, climate change is projected to reduce rainfed potato production areas in England and Wales by 74-95% by the 2050s (Daccache et al., 2012).

The impacts of climate change on potato production have been investigated at both global (Fleisher et al., 2017; Raymundo et al., 2018;

Adekanmbi et al., 2024) and regional scales, including Iran (Adavi et al., 2018), South Korea (Kim and Webber, 2024), and Egypt (Rabia et al., 2018). The projections from these studies show considerable variability, primarily due to differences in regions, climate models, and assumed CO_2 concentrations (Jégo et al., 2024).

Raymundo et al. (2018) projected that, excluding Western Europe, potato yields in temperate regions of the Northern Hemisphere could decline by 2055. They also highlighted that yield variability and climate-induced uncertainties are likely to be more pronounced in North America than in other temperate regions.

Adavi et al. (2018) reported that under future climatic conditions in Iran, increased temperatures are expected to reduce maximum leaf area index (LAI), vegetation duration, and tuber yield. Conversely, Huang et al. (2022) found that despite rising temperatures and declining precipitation between 1961 and 2018 in Inner Mongolia, yield improvements occurred due to adaptive management practices such as fertilization and irrigation. Their results also indicated that potato yield is more sensitive to temperature than to precipitation, with high temperature and low rainfall leading to significant yield declines.

Jennings et al. (2020) suggested that modifications in cultivar selection and planting schedules could increase global potato yields by 9-20% between 2040 and 2060, primarily due to extended growing seasons and the positive influence of elevated CO_2 concentrations. Similarly, Hijmans (2003) predicted that adjusting the growing season and utilizing varieties of different maturity groups could increase potential potato yield in Canada by about 5%, while the absence of adaptation could result in a yield reduction exceeding 15% between 2040 and 2059. Adekanmbi et al. (2023) further estimated that potato yields may decline by 2-19% between 2045 and 2055, and by 6-80% between 2080 and 2095, depending on the region and adaptive capacity.

CONCLUSION

Climate change is recognized as one of the most critical environmental threats to the sustainability of global agricultural production. Variability in agricultural output is largely influenced by fluctuations in climatic factors, which often result in substantial yield losses particularly in crops sensitive to environmental stress. Despite its strategic importance for global food security due to its high nutritional value, the potato crop is directly affected by climate change because of its susceptibility to adverse environmental conditions. Worldwide, climate change has emerged as a dominant factor reshaping agricultural production systems. Rising temperatures, irregular precipitation patterns, and extreme weather events have created considerable uncertainty in cropping systems, leading to declines in both yield and quality especially in water-sensitive species. Owing to its short growing period and high yield potential, the potato is considered a strategic crop for ensuring food security. However, its shallow root system and vulnerability to heat and drought make it particularly sensitive to changing climatic conditions.

Evidence indicates that high temperatures restrict the photosynthetic activity of potato plants, thereby adversely affecting tuber development, while drought stress reduces marketable yield primarily by decreasing tuber weight rather than tuber number. Conversely, elevated atmospheric CO_2 concentrations may partially mitigate these adverse effects by enhancing photosynthesis and improving water-use efficiency. Nevertheless, this compensatory effect remains insufficient under conditions of prolonged and severe heat or water scarcity.

A major challenge in potato production under climate change is the high variability arising from genotype × environment interactions. Differences in temperature, photoperiod, and soil moisture across ecological zones result in substantial yield variation even among identical cultivars. This highlights the importance of selecting genotypes that are well adapted to local climatic conditions and developing new cultivars with enhanced tolerance to drought, heat, and salinity.

In conclusion, maintaining sustainable potato production under the pressures of climate change will depend on the integration of climate-resilient breeding strategies, adaptive agronomic practices, and region-specific management approaches. Such measures are essential to minimize yield losses, strengthen food security, and enhance the resilience of global potato production systems in an era of rapidly changing climate dynamics.

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CHAPTER 6

MILK PROTEIN POLYMORPHISM STUDIES IN DAIRY CATTLE

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INTRODUCTION

Milk, an essential food throughout all stages of human life, is known as an excellent source of macro- and micronutrients, except for vitamin C and iron. It holds particular importance during childhood, pregnancy, lactation, and old age due to its nutritional value and contribution to bone health. Milk and dairy products are among the most valuable animal-derived foods, providing vital minerals such as calcium and phosphorus, B-group vitamins (especially riboflavin), and high-quality proteins that play a crucial role in growth and health, particularly for infants (Özek, 2015).

The main components of milk are water, carbohydrates, proteins, fats, lactose, and minerals, with an approximate composition of 88.32% water, 4.52% carbohydrates, 3.22% protein, 3.25% fat, and 0.69% ash (USDA-ARS, 2004). Numerous factors influence the composition of milk (Schwendel et al., 2015). These factors can broadly be categorized as genetic (breed) and non-genetic (nutritional and environmental) (Snowdon, 1991; Schroeder, 2012). The milk yield and composition of cattle breeds vary considerably, primarily due to differences in gene expression and heritability levels associated with these traits. As heritability increases, the genetic contribution to phenotypic expression becomes more pronounced. Therefore, determining the heritability levels of milk yield and composition both across and within mammalian species is essential. When comparing the composition of milk from cows, sheep, and goats, the average dry matter and protein contents are reported to be 12.6% and 3.4% in cow milk, 19.3% and 5.5% in sheep milk, and 13.2% and 3.2% in goat milk, respectively (Gürsoy, 2017).

Milk proteins in dairy cattle can be broadly classified into caseins and whey proteins**.** The composition of milk in mammals has been studied extensively, not only because casein and whey protein polymorphisms are closely linked to milk quality but also because they directly affect the quality of dairy products such as cheese, yogurt, and ice cream. Caseins, which constitute about 80% of total milk protein, are essential for the nutritional value of milk and its coagulation properties during cheese production. The major caseins αS1-casein, αS2-casein, β-casein, and κ-casein play distinct roles, with κ-casein and β-casein particularly influencing cheese yield and milk-clotting properties. Variations in these caseins have been shown to affect milk-processing efficiency, making them primary targets in polymorphism research.

Whey proteins, including β-lactoglobulin and α-lactalbumin, account for the remaining protein content in milk. Among these, β-lactoglobulin has attracted attention due to its influence on milk composition, yield, and fat content (Aschaffenburg & Drewry, 1955; Heck et al., 2009).

The concept of genetic polymorphism is defined as the occurrence of two or more allelic variants of a gene within a population at frequencies that cannot be maintained solely by recurrent mutation. In other words, it refers to the presence of multiple alleles at a single locus within a population. Genotypic traits often exhibit polymorphic characteristics, forming homozygous or heterozygous combinations of alleles at a given locus. Since these alleles often show codominance, the phenotypic expression directly reflects the underlying genotype. This fundamental principle has revolutionized livestock breeding by enabling **indirect selection** methods in genetic improvement programs. By identifying associations between polymorphic genetic markers and various performance traits, breeders can perform early selection for desirable characteristics.

Advancements in biotechnology, particularly DNA-based techniques such as Polymerase Chain Reaction (PCR) and Restriction Fragment Length Polymorphism (RFLP) analysis, have made it possible to determine genotypes at very early ages, regardless of sex. These molecular tools facilitate the early identification of high-yielding animals and the estimation of breeding values for production and growth traits. Studies on milk protein polymorphism aim to understand the chemical evolution of milk proteins, identify similarities with other proteins, elucidate relationships among species and breeds, explain variations observed across populations and environments, and determine the biological significance of genetic variants (Özdemir, 2000).

Recent research has made extensive use of molecular genetic techniques to determine the genetic basis of milk protein systems (Formaggioni et al., 1999). Many studies have focused on the casein complex**,** given its strong association with milk quality, composition, and technological properties. Since caseins make up about 80% of total milk protein, research has concentrated heavily on this group, particularly on κ-casein (CSN3)**.** Numerous studies have established significant associations between genetic variation at milk protein loci and milk yield and composition (Martin et al., 2002).

Polymorphisms in genes encoding milk proteins often alter their structure and function. These variants are typically inherited **co-**dominantly, meaning that heterozygous cows express both alleles in their milk protein profiles. Understanding these genetic variations and their relationship with desirable traits allows dairy breeders to make more informed selection decisions, ultimately optimizing both milk production efficiency and product quality**.**

The foundation of milk protein polymorphism studies was laid in the 1960s and 1970s with the introduction of electrophoretic techniques, which enabled the identification of distinct protein variants based on migration patterns. Early findings revealed that specific protein such as the A and B alleles of β-casein and κ-casein were associated with variations in milk yield and coagulation properties (Kamiński et al., 2006). In a pioneering study, Aschaffenburg and Drewry (1955) used electrophoresis to distinguish between the A and B variants of β-lactoglobulin, laying the groundwork for future research on polymorphisms and their influence on milk traits.

Many genetic studies have since demonstrated that milk proteins encoded by specific genes are linked to economically important traits in dairy cattle. As physiological and molecular research advanced, a range of methods including recombinant protein production, immunological assays, and molecular biology techniques have revealed intricate relationships between gene expression and protein function. Numerous studies have suggested that genetic information may influence milk protein function and that these proteins exhibit polymorphisms affecting milk yield, composition, and nutritional properties. Such variations arise from differences in nucleotide sequences or gene expression patterns and have been associated with disease resistance and physiological traits relevant to national breeding programs.

Some researchers have examined milk protein polymorphisms to estimate allele frequencies, identify breed-specific genetic diversity, and construct phylogenetic relationships among breeds. Others have used milk protein markers to define breed characteristics, assist in the production of breed-specific dairy products, and prioritize conservation strategies within genetic improvement programs. Knowledge of genetic variation and breed interactions enhances the efficiency of selection and contributes to breed conservation and genetic improvement efforts (Haenlein et al., 1987; Özbeyaz et al., 1991).

If a relationship is established between economic traits and polymorphic systems, the genes determining these polymorphic characteristics may be considered as marker genes, allowing their use in marker-assisted selection (MAS). This approach enables early selection in breeding programs, particularly for male sires that do not express milk production traits and for heifers at the beginning of their first lactation. In other words, indirect selection through marker genes becomes possible. Since milk protein variants are controlled by a relatively small number of genes, changes in gene and genotype frequencies over time can be easily monitored, allowing the analysis of the population structure with respect to these loci. Consequently, this facilitates both the development of population genetics theory and the optimization of breeding systems toward specific production goals (Haenlein et al., 1987; Özbeyaz et al., 1991).

Overall, the study of milk protein polymorphisms in dairy cattle represents a vital intersection of genetics, animal science, and dairy technology. This section reviews the main research methodologies, findings, and applications from early electrophoretic studies to the most recent genomic approaches. By analyzing key milk proteins caseins (αS1, αS2, β, and κ) and whey proteins (β-lactoglobulin and α-lactalbumin) this review explores how genetic variation influences milk production traits, processing characteristics, and industrial applications. Since the first identification of milk protein variants in the 1950s, research has increasingly employed advanced molecular techniques to uncover genetic variations associated with economically valuable milk properties. The most recent studies compare various methodologies to evaluate their contributions to understanding and applying milk protein genetics in dairy production systems.

Developments in Research Methodologies and Related Studies

In recent years, molecular genetic techniques such as PCR-RFLP, SNP genotyping panels, and targeted sequencing methods have enabled more accurate, sensitive, and comprehensive analyses at the genotypic level (Chessa et al., 2007). In the early stages of milk protein polymorphism studies, classical protein separation techniques such as electrophoresis, PAGE, and isoelectric focusing were used to distinguish protein variants based on phenotypic band profiles. Since these methods directly analyzed the proteins, they were practical and cost-effective for initial studies; however, their resolution capacity and ability to reveal molecular sequence variations were limited, particularly in detecting minor changes (Caroli et al., 2009; Mayer et al., 2021).

The PCR-SSCP method was also preferred for rapid screening. Csikós et al. (2016) reported that the SSCP technique provided high sensitivity in detecting polymorphisms in milk protein genes. At a more advanced level, Vigolo et al. (2022) compared PCR-RFLP, AS-PCR, and sequencing methods for identifying A1/A2 β-casein variants, reporting that AS-PCR was more advantageous in terms of time and cost. Additionally, Sebastiani et al. (2020) analyzed genotype frequencies of β-casein polymorphisms in different cattle populations using SNP genotyping panels. The PCR-RFLP technique has been widely employed in detecting milk protein gene variants in different cattle breeds. Ünal and Kopuzlu (2022) analyzed κ-casein variants using the HinfI enzyme and reported that the B allele was associated with milk coagulation properties. Similarly, Boushaba and Tabet-Aoul (2024) applied PCR-RFLP using HaeIII on the β-lactoglobulin gene, indicating that the identified variants were related to milk composition.

In a study conducted to determine DGAT1 alleles in Holstein, East Anatolian Red, and Native Black cattle breeds, a primer set was used with the following sequences: forward 5′–GCACCATCCTCTTCCTCAAG–3′ and reverse 5′–GGAAGCGCTTTCGGATG–3′. The 411 bp PCR products obtained were digested with the CfrI restriction endonuclease. As a result, individuals with the KK genotype exhibited a single 411 bp band; KA genotypes showed three bands of 411, 208, and 203 bp; and AA genotypes showed two bands of 208 and 203 bp. In Holstein cattle, the A allele of the DGAT1 gene was reported to be associated with lower milk fat and higher protein content, higher milk yield, and lower intramuscular fat deposition. Conversely, the lysine variant (K allele) was linked to increased milk fat yield but decreased milk and protein yield, whereas the alanine variant (A allele) was associated with increased milk and protein yield but reduced fat yield (Bal and Akyüz, 2014).

In another study on Holstein cattle, PCR was performed for all genes examined. The primer pairs used were as follows: for the FABP4 gene, F: 5′–ATTATCCCCACAGAGCATCG–3′ and R: 5′–ACAAGACTTGGCCTCAAGGA–3′; for the NR1H3 gene, F: 5′–

GCGTGGCGTATGAGAGCTAC–3′ and R: 5′–TAGACGTGGTCTTGCTGTGG–3′; and for the SCD gene, F: 5′–CCCGGTGTCCTGTTGTTGTG–3′ and R: 5′–TAGACGTGGTCTTGCTGTGG–3′. Enzymatic digestion was carried out with 5 U of Hin1II**,** HpyCH4IV, and Fnu4HI**,** respectively, as recommended by the manufacturer.

For the FABP4-Hin1II polymorphism, PCR amplification yielded a 399 bp product, and digestion revealed two alleles (A and G) and three genotypes (AA, AG, and GG). Individuals with the GG genotype showed a single 399 bp band; AG genotypes displayed three bands of 399, 302, and 97 bp; and AA genotypes showed two bands of 302 and 97 bp. For the NR1H3-HpyCH4IV polymorphism**,** digestion of the 436 bp PCR product was expected to yield two alleles (A and G) and three genotypes (AA, AG, and GG). The AA genotype produced two bands of 251 and 185 bp; GA genotypes showed four bands of 251, 185, 95, and 90 bp; and GG genotypes exhibited three bands of 251, 95, and 90 bp. However, the 95 and 90 bp bands were so close in size that they could not be clearly separated by agarose gel electrophoresis. Among the Holstein cattle analyzed, the GG genotype showed the highest frequency (96.4%), while AG genotypes were not detected.

For the SCD-Fnu4HI polymorphism, PCR amplification produced a 256 bp product. Enzyme digestion revealed two alleles (C and T) and three genotypes (CC, CT, and TT). Individuals with the CC genotype exhibited two bands of 143 and 75 bp; CT genotypes showed three bands of 143, 113, and 75 bp; and TT genotypes displayed two bands of 143 and 113 bp (Arslan et al., 2019).

Restriction endonucleases used in PCR-RFLP analyses play a critical role in differentiating genetic variants. In this method, the amplified gene region is digested by specific restriction endonucleases, allowing the distinction of different genotypes based on fragment patterns. For the **κ-**casein (CSN3**)** gene, the enzyme HinfI is most commonly used to distinguish between the A and B variants, producing characteristic banding patterns from an amplicon of approximately 453 bp (Ünal and Kopuzlu, 2022). In the β-casein (CSN2) gene, differentiation between the A1 and A2 variants has been achieved using various restriction endonucleases, while the allele-specific PCR (AS-PCR) method has also been frequently employed (Vigolo et al., 2022). Furthermore, some studies have found DdeI and TaqI enzymes to be effective for A1/A2 discrimination, with variation in enzyme selection depending on laboratory conditions (Farrell et al., 2004).

The targeted regions and amplicon sizes used to identify genetic polymorphisms constitute an important part of the applied methodologies. Although the primers employed in various studies differ depending on the target regions, the literature generally reports similar amplicon sizes. For CSN3, amplicons of approximately 450-460 bp have been obtained; for β-lactoglobulin (LGB), around 247 bp; and for β-casein (CSN2) particularly concerning the A1/A2 variant amplicons ranging between 200 and 400 bp have been reported (Sebastiani et al., 2020; Vigolo et al., 2022).

Ünal and Kopuzlu (2022) reported that a 453 bp amplicon was digested with the HinfI enzyme for the detection of κ-casein variants. Similarly, Boushaba and Tabet-Aoul (2024) reported that a 247 bp amplicon was analyzed with the HaeIII enzyme to identify β-lactoglobulin variants. In earlier studies, Chessa et al. (2007) developed a SNP genotyping microarray platform that systematically defined primer regions for milk protein genes and demonstrated that target amplicons of approximately 300 bp could be used, particularly for the A1/A2 variant in exon 7 of the β-casein gene. Kučerová et al. (2006) reported amplicon sizes ranging from 200 to 500 bp in genotyping analyses of milk protein genes (CSN1S1, CSN2, CSN3, and LGB) using PCR-RFLP in Fleckvieh cattle, and examined the associations between different gene regions and milk composition.

Polymorphism studies have been carried out on both sheep and goat breeds. In these studies, particular emphasis was placed on the CAST, DGAT1, and IGF-1 genes in Akkaraman sheep. It was reported that the PCR products for the CAST gene (622 bp) were digested with 5 U of the appropriate restriction enzyme, while the PCR products for the IGF-1 gene (294 bp) were digested with 5 U of the suitable restriction enzyme, and those for the DGAT1 gene were digested using the AluI restriction enzyme (Bayram et al., 2019). In another study conducted using blood samples from Imroz and Chios (Sakız) sheep breeds, the lysine (K) and alanine (A) alleles of the DGAT1 gene were identified through PCR amplification and digestion with the AluI (EURx) endonuclease enzyme. In this study, for each primer pair, the reaction mixture contained 12.5 µL of 2X PCR master mix and 0.5 µM of each primer (forward primer: 5′-GCATGTTCCGCCCTCTGG-3′, reverse primer: 5′-GGAGTCCAACACCCCTGA-3′) (Cerit and Demir, 2015).

In the study conducted on goats, the DGAT1 gene was investigated. Based on the DGAT1 gene sequence, three pairs of primers were designed to amplify the regions covering intron 6, exon 7, intron 7, exon 8, intron 8, as well as exon 15, intron 15, exon 16, intron 16, exon 17, and partially the 3′ untranslated region (UTR) of the DGAT1 gene. The PCR products obtained in this study were separated by electrophoresis on 2% agarose gels in parallel with a 100 bp DNA marker. For genotyping, 20 µl of PCR product was digested overnight at 37°C with 10 U of EaeI, NlaIII, and AluI enzymes for exons 8, 16, and 17, respectively. The digested PCR products were resolved by electrophoresis on 4% agarose gels stained with ethidium bromide. PCR products showing different band patterns on the RFLP gel were selected for sequencing (Özmen and Kul, 2014).

The studies reviewed clearly demonstrate that genetic polymorphisms in milk protein genes particularly those encoding caseins (αS1-, αS2-, β-, and κ-caseins) and whey proteins (β-lactoglobulin and α-lactalbumin) play a crucial role in determining milk yield, composition, and processing characteristics. Advances in molecular techniques such as PCR-RFLP, SNP genotyping, and sequencing have significantly enhanced the precision of genotype identification, enabling early selection of superior animals and contributing to more efficient breeding programs. These findings highlight the importance of integrating milk protein polymorphism data into genetic improvement strategies, not only to optimize milk production and quality but also to support the conservation of valuable genetic diversity within and across cattle breeds.

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CHAPTER 7

THE EFFECTS OF GLOBAL WARMING ON CLIMATE CHANGE

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INTRODUCTION

Global warming refers to the increase in temperatures on the Earth's surface due to heat-trapping gases accumulating in the Earth's atmosphere. It is generally caused by greenhouse gases accumulating in the atmosphere as a result of human activities, disrupting the natural balance (Figure 1). Since the early 1900s, rapid industrialization has occurred as a result of population growth and human needs. With the industrial revolution, fossil fuel consumption began to increase significantly. At the same time, many changes occurred rapidly, such as the increase in industrial activities, the establishment of large industrial facilities, and the restriction of agricultural activities due to the conversion of agricultural land into urban areas. As a result of all these processes, more heat-trapping gases are being released into the atmosphere than necessary. The number, density, and concentration of heat-trapping gas molecules, primarily carbon dioxide (CO_2), nitrous oxide (N_2O), water vapor, and methane (CH_4), have also increased (Table 1; Figure 1). Thus, global warming has accelerated at a faster rate than expected (Morice et al., 2021; IPCC, 2021). These heat-trapping gases are increasing day by day and enveloping the world. They trap both the rays coming from the sun and the rays reflected from the Earth's surface into space, further strengthening the greenhouse effect (Forster et al., 2020). Over the last 150 to 200 years, human activities (anthropogenic effects) have increased very rapidly, especially with the industrial revolution. This has increased the atmospheric CO_2 level from 280 ppm to 420 ppm. This situation has manifested itself at a rate of change that is well above the natural change process of the last 2 million years of Earth's life (Huang et al., 2023). An example of this situation is the fact that the years 2015-2023 were the eight hottest years on a global scale (World Health Organization: WMO, 2023). This situation shows that global warming is not just a future problem, but a serious environmental threat that is clearly visible today.

On the other hand, it would be incorrect to examine Global Warming solely from an atmospheric perspective. In addition, changes in the volume of glaciers, the continuity of the hydrological cycle, the warming of ocean and sea waters, and extreme weather events must also be directly examined. Research has shown that approximately 90% of the oceans have warmed with additional heat over the last 50 years. This increase in heat has been accompanied by a rise in sea levels. Furthermore, this situation has also led to thermal heat increases in ecosystems (Morice et al., 2021; Rahmstorf et al., 2023). For these reasons, it is clear that global warming is not merely an atmospheric or environmental problem. It is also seen as a multi-layered crisis that affects countries' economies, health sectors, and political and social lives (Table 1).

Table 1: Causes and effects of global warming (IPCC, 2021; WMO, 2023)

Causes of Global Warming	Major Effects of Global Warming
Increase in atmospheric CO_2, CH_4, and N_2O levels due to fossil fuel use (coal, oil, natural gas)	Rise in global temperatures and more frequent extreme heatwaves
Industrial emissions and energy production	Increase in extreme weather events (floods, droughts, storms, heavy precipitation)
Land-use changes (deforestation, agricultural expansion)	Rapid melting of glaciers and rising sea levels
High carbon footprint from industry and transportation sectors	Ecosystem degradation, species loss, and habitat changes
Methane emissions from agriculture and livestock	Decline in water resources and intensified regional droughts
Rapid urbanization – urban heat island effect	Increased heat-stress–related mortality and health issues
—	Food security risks (yield reduction, crop diseases)
—	Ocean acidification and coral reef loss

Global warming is one of the greatest threats humanity may face in this century. Global warming is a process that can profoundly affect both the natural balance and all socio-economic structures (Diffenbaugh and Burke, 2020; Morice et al., 2021). With the industrial revolution, greenhouse gases released into the atmosphere from various sources have increased rapidly. This has affected the existing energy balances on Earth, causing a noticeable increase in global temperatures. According to the IPCC's 6th assessment report, the temperature on the Earth's surface has increased by 1.4°C over the last century (Forster et al., 2020; IPCC, 2021). This increase has resulted in climate change and, subsequently, the effects of climate change (Figure 2). Furthermore, research shows that extreme events in the Earth's atmosphere have intensified as a result of global warming. These atmospheric events include droughts, extreme heat waves, heavy rainfall, storms, flash floods, and forest fires. At the same time, the frequency and destructive effects of these atmospheric events have also increased significantly (Liv d., 2022; Türkeş et al., 2022; WMO, 2023). Regions such as Turkey, the Middle East, and the Mediterranean region, in particular, have become areas that are fully experiencing climate change, especially in terms of the hydrological cycle. Extreme weather events in these regions have seriously affected agriculture and livestock farming, causing a decline in production (FAO, 2022).

The effects of global warming are not limited to physical destruction caused by weather events. It also seriously impacts countries' economies. It has been observed that low-income countries are particularly affected by rising temperatures (Diffenbaugh and Burke, 2020). Furthermore, global warming has significantly impacted the health sector. It has been determined that countries with large elderly populations have experienced a significant increase in mortality rates (Ballester et al., 2023; WHO, 2022). On the other hand, global warming has also seriously affected ecosystems. The melting rate of polar ice caps has increased in recent years. The warming of the oceans has also led to undesirable situations such as coral bleaching. Furthermore, research has revealed that approximately 25% of species on Earth will become extinct due to global warming (IPBES, 2022). At the same time, it has been explained that events such as an increase in forest fires, glacier melting, and ocean acidification have led to a significant increase in CO^2 emissions into the atmosphere (Ciais et al., 2023). As a result of these studies, it has been shown that global warming no longer only affects the human environment, but also significantly affects ecosystems, socio-economies, and political structures. The increasing climate change has also made water scarcity, migration, energy, and food security more fragile. For these reasons, Global Warming should not be viewed as a single or scientific study. It should also be addressed as a holistic problem and believed to be an issue that affects the security of all countries in the world. From this perspective, the effects, causes, precautions, and measures of Global Warming, along with all future risks, need to be examined in detail. Thus, policies related to climate change must be developed and implemented quickly. While carrying out this work, Global Warming must first be thoroughly understood. Then, efforts must be made to reduce the effects of Global Warming. In addition, adaptation strategies for Global Warming must be developed, and sustainable goals must be prepared urgently (Xu et al., 2020).

This section of the book comprehensively addresses the causes of global warming, its fundamental issues, and its potential multidimensional effects, taking into account recent literature studies. It also explains the effects of global warming in Turkey and the country's current status regarding these issues. Furthermore, global warming and its effects are evaluated in detail from every angle, and the results of this evaluation are presented below under different headings:

2. STUDY AREA

2.1. Global Warming and Its Effects

Global Warming, when viewed broadly, consists of a series of multidimensional processes (Table 1). Therefore, limiting it solely to increases in atmospheric temperature is insufficient. Global Warming is a complex system that broadly encompasses all climate factors and triggers them all. Particularly after the issue of temperature increase, many other meteorological factors such as precipitation, winds, humidity, and pressure should also be considered and examined. These factors affect both their interrelationship cycle and have a holistic impact on the ecosystem. Climate change and its effects as a result of global warming can have irreversible consequences by seriously affecting water resources, the hydrological cycle, ecosystems, public health, agricultural areas, energy systems, and socio-economic structures. A review of current literature reveals that global warming is not a concept of the future but is already seriously affecting all of humanity and its external environment to a significant degree (Diffenbaugh and Burke, 2020; Gutierrez et al., 2021; IPCC, 2021; WMO, 2023). If the effects of Global Warming are examined in all their dimensions, it is believed that they can be better understood under the headings presented below (Figure 1):

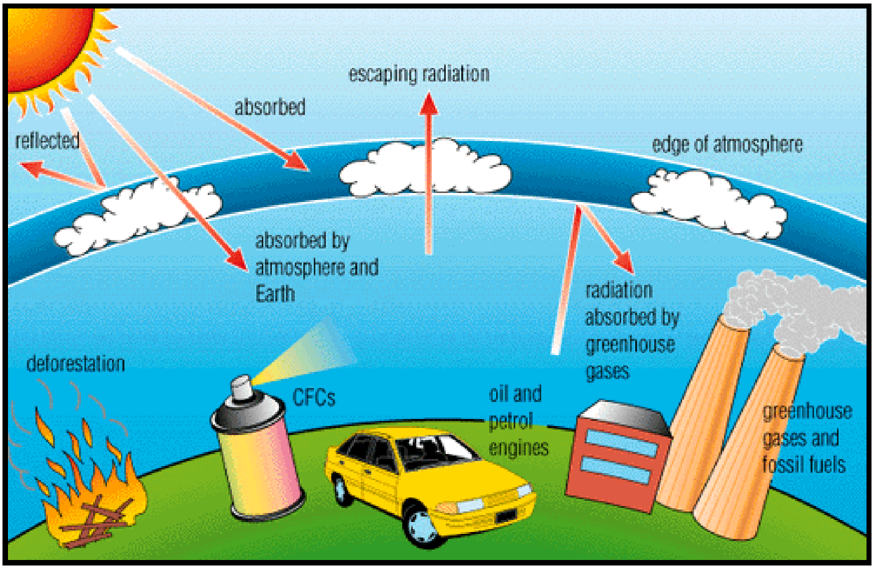

Figure 1: Global Warming (URL-1)

2.1.1. Extreme Weather Events and Atmospheric Temperature Increase

Global warming inevitably leads to increases in atmospheric temperatures, which can intensify the severity, frequency, and speed of extreme weather events on the Earth's surface. The term "heat waves," which emerged in the literature after 2020, has gained significant prominence. As a result, the deaths of sixty thousand people in European countries after 2023 have been linked to this situation. These deaths have revealed the serious effects of heat waves caused by high temperatures on human health (Ballester et al., 2023). After the specified heat waves, the damage caused by different climatic effects is also becoming increasingly apparent. To list a few of these: heavy rainfall and flash floods caused by the effects of this rainfall. Prolonged droughts resulting from excessive increases in temperature. The strengthening of cyclones observed in tropical areas. An increase in forest fires, again due to excessive temperature increases. In addition, the increased intensity of short-term climate events such as storms and hail are direct consequences of global warming (Figure 2) (Li et al., 2022; Huang et al., 2023). The extreme weather events observed in our century are most prominent in the Mediterranean basin and the Middle East in today's world.

2.1.2. The Hydrological Cycle and Its Effects on Water Resources

Global warming significantly affects the cycle and functioning of natural water resources on Earth. Thus, it causes both water scarcity and excessive rainfall worldwide. Global warming increases temperatures and ultimately affects the water cycle. As temperatures rise, evaporation accelerates. At the same time, water levels in dams and lakes decrease. Snow cover thickness is reduced. It changes the timing of snowmelt, such as snow falling late and melting early. It causes fluctuations in the flow rates of streams and rivers. Observations show that snowfall in places with high snow cover, such as the Alps, the Himalayas, and Eastern Anatolia, is lower than in previous years. This means that water resources are decreasing for more than two billion people. On the other hand, parallel to rising temperatures, increased evaporation and droughts are increasing the need for irrigation in agricultural areas every day. As a result of these developments, it is seen that this will affect food security and become dangerous (Türkeş et al., 2022; FAO, 2022).

2.1.3. Events Occurring in the Oceans (Warming, Acidification, and Rising Sea Levels)

Global warming has caused oceans to store approximately 90% more heat over the past 50 years. As a result, sea water temperatures have risen. White coloration in corals has increased. Marine ecosystems have been destroyed. This has led to changes in fish migration routes and quantities. It has also led to an increase in the intensity of storms at sea (Pörtner et al., 2022). On the other hand, with the increase in temperatures, a number of situations have changed as a result of the oceans absorbing carbon dioxide. First and foremost among these is a decrease in pH value. Deterioration has begun in the outer shells and skeletal systems of marine life. There have even been collapses at the lower levels of the food chain. Furthermore, rising sea levels have increased erosion in coastal areas. This has put settlements in coastal regions at risk of flooding. Thus, it directly threatens 700 million people living in coastal areas (Rahmstorf et al., 2023).

2.1.4. Biodiversity and Losses in Ecosystems

Global warming is directly affecting ecosystems around the world, leading to losses in biological diversity. This situation has been rapidly increasing over the past 50 years. According to studies (IPBES, 2022), approximately 25% of all living species are at risk of extinction. It has also been reported that nearly 70% of coral reefs will be completely lost if the temperature reaches 1.5°C. At the same time, it has been reported that natural habitats will be lost as a result of the rapid melting of polar ice caps. Furthermore, as a result of increasing forest fires and droughts, the carbon sink capacity will decrease in regions with critical ecosystems (such as the Amazon and Siberia). The weakening of ecosystems will also create positive feedback loops that will accelerate global warming by altering the global carbon cycle (Ciais et al., 2023).

2.1.5. Effects on Agriculture and Food Safety

Global warming has seriously affected agricultural activities. This situation is seen in different ways in different regions of the world. Thus, differences have also occurred in food production. The effects of global warming on agriculture, along with the resulting increase in temperatures, can be listed as follows: It increases the irrigation needs of agricultural land. It affects yield losses in crops. It changes plant structure. It gradually reduces soil moisture. Finally, it also increases the number of harmful insects. According to the FAO (2022), with climate change, global agricultural production and products will experience losses of up to 10% over an average of 50 years. This will create serious supply problems for the most consumed crops: wheat, corn, and rice.

2.1.6. Effects on Human Health

The potential effects of global warming on human health include: Heat-related deaths due to rising temperatures. An increase in heart and vascular diseases. Increased risks associated with air pollution. The spread of climate-related diseases (dengue fever, malaria, etc.). An increase in psychological anxiety among humans. Risks such as premature birth in pregnant women (Table 2). Furthermore, according to some studies, global warming and the resulting climate change have led to an increase in serious mortality rates, particularly among the elderly population (WHO, 2022). In addition, between 2021 and 2023, mortality rates due to extreme heat in Europe increased by 30% (Zhong et al., 2024).

Table 2: Effects of global warming on human health and diseases it will cause (Zhong et al., 2024; WHO, 2022)

Impact Category	Direct Health Effect	Explanation
Heat Stress and Heatwaves	Heat stroke, heat exhaustion, increased cardiovascular and respiratory stress	Body thermoregulation becomes impaired; elderly individuals, children, and those with chronic illnesses are at highest risk.
Respiratory Problems	Asthma attacks, COPD exacerbations, acute respiratory distress caused by particulate matter	Rising temperatures increase ozone formation; wildfires further elevate $PM_{2.5}$ concentrations.
Increase in Infectious Diseases	Higher risk of malaria, dengue fever, West Nile Virus, and Lyme disease	Mosquito and tick populations expand into wider regions as temperatures rise.
Food Security and Nutrition Issues	Malnutrition, vitamin and mineral deficiencies	Droughts and extreme events reduce agricultural yields and increase food prices.
Waterborne Diseases	Diarrhea, cholera, norovirus infections	Heat reduces water quality; floods may cause sewage overflow and contamination.
Mental Health Effects	Anxiety, depression, post-traumatic stress disorder (PTSD)	Climate-related disasters (wildfires, floods, droughts) increase psychological trauma.
Pregnancy and Child Health Risks	Low birth weight, preterm birth, increased infant mortality	Extreme heat and air pollution negatively affect fetal development.

2.1.7. Economic and Social Impacts

Global warming has caused economic difficulties that have most affected low- and middle-income regions around the world. The primary impact is damage to infrastructure. Other impacts include increased energy demand and reduced work capacity and productivity (Diffenbaugh and Burke, 2020). On the other hand, losses in agricultural products are also observed. There is an increase in human migration. Parallel to this, rising water and food prices seriously threaten global economic goals. Furthermore, global warming has exacerbated the economic crises of many countries, reducing per capita income by up to 20%.

2.2. Causes of Global Warming

Global warming is an environmental process that seriously disrupts the balance of the atmosphere. The main cause of this situation is the increase in the number of heat-trapping gas molecules, such as greenhouse gases, resulting from human activities (Table 1). While the natural greenhouse effect does not pose any threat, the effects of artificial greenhouse gases created by human activities and industrial growth are seriously threatening all areas (Forster et al., 2020; IPCC, 2021). It has been determined that all of these effects have increased the Earth's temperature by 1.1°C compared to its temperature before the global warming process began. On the other hand, the main causes of global warming can be listed under four main headings (Figure 2):

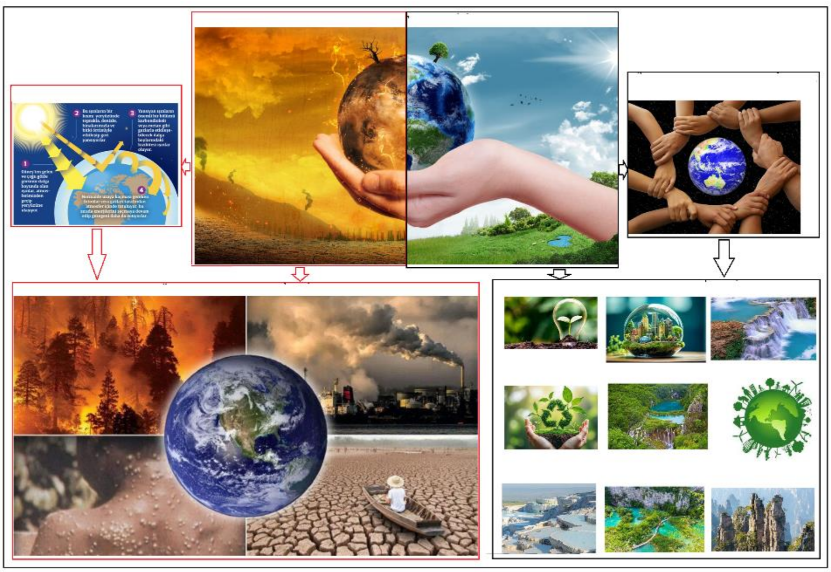

Figure 2. Results of actions taken or not taken to combat global warming (URL-2)

2.2.1. Fossil Fuel Use and Combustion

With the increased energy demand brought about by the industrial revolution, the combustion of fossil fuels such as coal, oil, and natural gas has also increased significantly in the transportation sector. Billions of tons of CO_2 are released into the atmosphere each year as a result of this combustion. As of 2023, more than 75% of CO_2 emissions will come from fossil fuel combustion (Forster et al., 2020). The continued and predominant use of fossil fuels in domestic, industrial, and commercial heat energy production is one of the most significant factors contributing to global warming.

2.2.2. Industrial Production and Industrial Activities

As a result of high temperature requirements in the industrial and manufacturing sectors, significant amounts of greenhouse gases such as CO_2, water vapor, and N_2O are released into the atmosphere. In our era, CO_2 emissions from cement factories alone account for approximately 7% of total CO_2 emissions (Huang et al., 2023). Furthermore, chlorofluorocarbon refrigerants (HFCs) used in industry have the potential to trigger global warming thousands of times more than CO_2.

2.2.3. Changes in Land Use and Agricultural Activities

Agricultural activities account for approximately 20% of global warming (FAO, 2022). The main causes of Global Warming from agricultural activities are methane (CH4) gases (from rice paddies, decomposition of agricultural organic matter, and large-scale livestock farming). Another is nitrous oxide (N_2O) gases, which result from the excessive use of nitrogen fertilizers. Furthermore, changes in land use (the loss of forests and the conversion of agricultural land, resulting in a decrease in carbon sink capacity) can be cited as fundamental causes. Particularly in Southeast Asia and the Amazon regions, the destruction and loss of forests has partially contributed to the increase in atmospheric CO_2 levels (Pörtner et al., 2022).

2.2.4. Anthropogenic Factors, Waste Management, and Transportation Factors

Since there are regular landfill sites where household waste is stored, and due to the oxygen-depleted environments that form in these areas, large amounts of methane gas (CH_4) are produced. In global warming, methane gas, the most potent greenhouse gas, accounts for approximately 28 times that of CO_2. Additionally, CO_2 generated through land, air, and sea transportation accounts for 28% of the total CO2 associated with global warming (Forster et al., 2020; WMO, 2023). In addition to these reasons, energy inefficiency and the misuse of heating and cooling systems in buildings are also among the main causes. Furthermore, fugitive emissions from industry and the weakening of soil carbon sinks are among the other factors accelerating global warming (Ciais et al., 2023).

3. MATERIALS AND METHODS

3.1. Measures that can be Taken Against Global Warming

The main measures that can be taken against global warming include the adoption of joint and simultaneous measures and transitional measures in industry, energy, transportation, agriculture, and land use. According to scientific research, in order to limit global warming to a 1.5°C increase, greenhouse gas emissions must be reduced by at least 45% by 2030. It has also been stated that net zero emissions must be achieved by 2050 at the latest (IPCC, 2021). In this context, the most effective measures to be taken are considered to be emission reduction (mitigation) and adaptation strategies. The measures that can be taken in this context are presented below:

3.1.1. Transformation of Energy Systems

In this context, fundamental changes must be made in energy production. In particular, the burning of fossil fuels must be gradually reduced. Instead, the transition to renewable energy sources must be accelerated. This will make global emission reduction inevitable. All countries worldwide must transition to other renewable energy systems (wind energy systems, hydroelectric energy systems, etc.), primarily solar energy systems, for energy production. A full transition to renewable energy systems will both reduce carbon emission intensity and ensure energy security (IEA, 2023). In addition, building insulation, the use of high-capacity devices, the creation of smart grids, and energy efficiency applications are among the most important factors in reducing emissions.

3.1.2. Taking Carbon Neutrality Measures in Transportation

In this day and age, there has been a rapid increase in transportation vehicles and devices for air, land, and sea transportation. In this situation, the share of CO_2 emissions in the transportation sector has increased considerably. Different alternatives can be created for carbon-free transportation. First and foremost, the development and number of electric vehicles should be increased. Public transportation methods should be expanded and made more active.

Bicycle and pedestrian transportation routes should be expanded and their numbers increased. Furthermore, carbon footprints can be reduced by taking serious measures, particularly in the heavy transport and aviation sectors, thereby significantly reducing carbon dioxide emissions. The use of alternative energy sources such as biofuels and green hydrogen should be increased in this area (WMO, 2023).

3.1.3. Carbon Reduction in Industry and Production

In the transition to low-carbon technologies in the industrial sector, serious measures must be taken to reduce emissions, particularly in the iron and steel, cement, aluminum, and chemical industries. One such method is the CCUS system, which requires the enhancement of carbon capture, utilization, and storage technologies (Ciais et al., 2023). Furthermore, waste reduction, material efficiency, and circular economy models should also be utilized to reduce carbon emissions from industrial sources.

3.1.4. Sustainability in Agriculture and Land Use

Agricultural practices should be developed, particularly livestock farming methods that reduce methane emissions. Fertilizer use must be further optimized. At the same time, new agricultural techniques that increase soil carbon, such as drip irrigation, should be developed (FAO, 2022). Furthermore, deforestation policies must be halted to protect forests, which are among the most important carbon sinks. It is also crucial to take the necessary steps to restore degraded ecosystems. At the same time, new forest areas must be created. This will both increase carbon sink capacity and further strengthen the resilience of ecosystems. Protecting tropical forests is also one of the most important measures to be taken in terms of the global carbon budget (Pörtner et al., 2022).

3.1.5. Climate-Friendly Planning in Cities

In the industrial era we live in, rapid population growth is accompanied by urbanization and, consequently, an increase in the rate of global emissions. At the forefront of climate-friendly city or urban planning models is the need to increase the volume and number of green spaces and parks. Methods to completely reduce the effects of urban heat islands should be expanded. The number of energy-efficient buildings should also be increased. Waste management should be taken seriously and recycling programs should be implemented. In addition, sustainable practices in water management must be implemented quickly. Thanks to these practices, cities will be more resilient to global warming and its effects (Huang et al., 2023).

3.1.6. Adaptation Strategies:

There has been almost no reversal of the harmful effects caused by global warming. However, adaptation measures to minimize the impact of these effects now and in the future are as important as carbon emission reduction. When examining possible adaptation strategies: Early warning systems must be established and activated quickly. Methods that enable the integrated use of water resources must be developed. The transition to infrastructure that can withstand extreme weather events must be accelerated. Along with global warming, climate change and climate change-resilient agricultural models must be developed. In addition, health systems need to be further strengthened against climate change (WHO, 2022).

In conclusion, the above-mentioned measures or technological transformations will not be sufficient against global warming. Along with these changes and transformations, strong political policies, social solidarity, and adherence to sustainable development goals are also required. According to literature studies, if adaptation strategies are not implemented alongside carbon emission reduction, global temperature increase is projected to reach approximately 3°C by the end of this century (IPCC, 2021). For these reasons, measures and precautions against global warming should not be taken individually. On the contrary, they require multidisciplinary and long-term strategic planning. Furthermore, the measures and precautions that can be taken against global warming are summarized in Table 3 below:

Table 3: Key Measures That Can Be Taken Against Global Warming (Forster et al., 2020; IPCC, 2021)

Category of Measure	Possible Actions	Explanation
Energy Transition	Increasing the use of renewable energy (solar, wind, hydroelectric)	Reduces CO_2 emissions from fossil fuels and accelerates the shift toward low-carbon energy systems.
Transportation Sector Measures	Adoption of electric vehicles, expansion of public transportation	Significantly reduces greenhouse gas emissions from the transportation sector.
Building and Urban Planning	Energy-efficient buildings, thermal insulation, green roof applications	Reduces the urban heat island effect and lowers overall energy consumption.
Industry and Production Technologies	Clean production technologies, carbon capture and storage (CCS)	Decreases industrial emissions and strengthens the circular economy approach.
Agriculture and Land Management	Sustainable agriculture, optimized nitrogen fertilization, increasing soil carbon storage capacity	Reduces methane and nitrous oxide emissions; supports soil health.
Reducing Deforestation and Reforestation	Forest conservation, rehabilitation of degraded forests, afforestation programs	Strengthens carbon sinks and enhances ecosystem biodiversity.
Waste Management	Recycling, separation of organic waste, biogas production	Reduces methane emissions and improves resource efficiency.
Water Management	Water conservation, rainwater harvesting, sustainable watershed management	Provides adaptation to water stress associated with climate change.
Individual Measures	Energy saving, conscious consumption, low-carbon dietary choices	Contributes individually to the reduction of the global carbon footprint.
Policy and International Cooperation	Compliance with Paris Agreement targets, emission trading systems	Ensures greenhouse gas emissions are regulated at national and international levels.

3.2. Effects of Global Warming on Climate Change

Global warming is one of the fundamental irreversible factors affecting climate change. Global warming, which triggers global temperature increases, also initiates processes that affect the climate, leading to various climate change effects that are difficult to reverse. Numerous studies have shown that the temperature increase from the Earth's creation to the industrial revolution has risen by 1.1°C in the short period following the industrial revolution (IPCC, 2021). This value is recorded as the fastest heat increase in the last two thousand years of recent Earth history. This warming process is significantly affecting both the short-term variability and long-term persistence of naturally occurring climate factors (Gutierrez et al., 2021) (Figure 3).

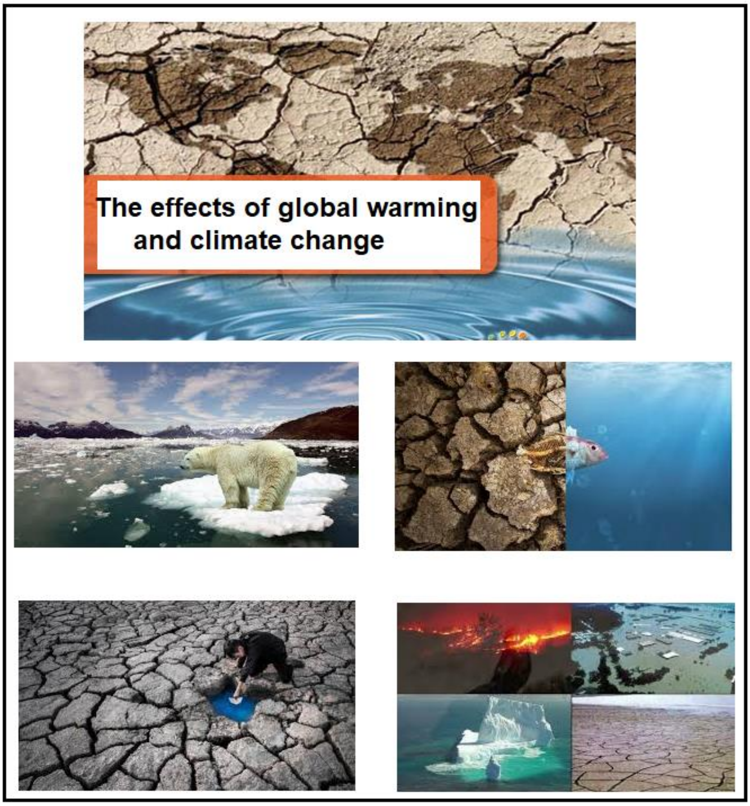

Figure 3: Effects of global warming on climate change (URL-3)

Global warming has the greatest impact on climate events occurring around the world by significantly increasing the frequency and intensity of atmospheric phenomena. Global warming causes an increase in temperature, which leads to more clouds and moisture being retained in the atmosphere. This increase in moisture causes tropical storms at the equator to become even more powerful. It also causes sudden floods and heavy rainfall (Li et al., 2022). At the same time, the duration and destructiveness of heat waves are increasing along with the rising temperatures. The clearest example of this is the record-breaking temperatures experienced in Asia and Europe during the summers of 2022-2023, reaching levels never before seen on thermometers (WMO, 2023; Ballester et al. 2023). These events are no longer future scenarios but are clearly visible today as destructive weather events. Furthermore, from the perspective of the hydrological cycle, one of the world's most important systems, global warming is seriously affecting these systems. Along with rising temperatures, it increases the rate of evaporation, which primarily affects these systems. This, in turn, causes irregularities in river flows. Ultimately, it also affects snowfall, reducing the duration of the snow cover. As a result of these significant effects of global warming on the hydrological cycle, it seriously impacts and alters ecosystem balance, drinking water quality, and agricultural activities. At the same time, even with an increase of approximately 1.5°C, serious water shortages are observed, especially in arid areas (IPCC, 2021). On the other hand, another area affected by global warming is the oceans. As a result of the increase in heat, more heat is retained in the depths of the oceans. This causes sea levels to rise. This also causes weakening in ocean currents. Ultimately, this has led to disruptions in many marine ecosystems (Rahmstorf et al., 2023). Furthermore, global warming affects the climate system in every way. The most visible aspect of climate change is the increase in droughts. It is also causing changes in the seasonal cycle experienced around the world. At the same time, it is causing irregularities in the monsoon systems. For example, with global warming, the regions where rainfall has decreased the most as a result of temperature increases are North Africa, the Middle East, and the Mediterranean Basin (Huang et al., 2023). These consequences, combined with the socio-economic disruptions brought about by climate change, are becoming more devastating in the regions.

Overall, global warming is the main source of the processes that are changing the climate. It is seriously affecting and changing all of the world's systems. In other words, it is affecting everything from atmospheric weather events to ocean systems. At the same time, it can affect all systems in many ways, from the hydrological cycle to biospheric processes. The significant increase in these effects highlights the urgent need for countries around the world to immediately accelerate scientific, technological, green energy initiatives, and political interventions.

4. RESULTS AND DISCUSSIONS

4.1. The Effects of Global Warming in Turkey and Turkey's Current Situation

Turkey is a country located within the Mediterranean basin and is one of the countries most significantly affected by global warming. As mentioned in the IPCC (2021) report, Turkey is identified as one of the hottest spots globally in terms of climate change. Global warming, as in many regions of the world, seriously affects the hydrological cycle, temperature patterns, ecosystems, agricultural activities, and water resources in Turkey. Thus, it increases quite serious risks in terms of both the environment and socioeconomics throughout the country.

Average temperatures in Turkey have risen, particularly in the last 50 years since the industrial revolution. According to statistics, temperatures have increased more rapidly since 1998. It has also been determined that Turkey's temperature over the last 10 years has exceeded the long-term average of 13.2°C (MGM, 2023). Furthermore, it has been stated that the Mediterranean basin, which covers Turkey, has exceeded the world's average warming rate by 20% (WMO, 2023). This indicates that heat waves will increase in intensity and duration, meaning that summer months will be longer and more oppressive for living beings in terms of temperature. Furthermore, global warming also threatens water resources in Turkey. Sudden natural disasters (floods, storms, hailstorms, forest fires, etc.) occurring in Turkey between 2020 and 2023 have increased significantly compared to data from the previous 30 years. At the same time, the large forest fires that occurred in the Aegean and Mediterranean regions demonstrate how much global warming affects these fires (Turkish Forestry Directorate, 2022). This situation has also prolonged fires and droughts, increasing their spread.

Another sector affected by global warming in Turkey is agriculture. Rising temperatures and irregular rainfall directly affect water resources. Consequently, agricultural production in Turkey, which is dependent on water resources, is also significantly affected. According to recent analyses, Turkey is at greater risk than other countries in the Mediterranean basin in terms of agricultural production losses due to climate change (FAO, 2022). Cereals such as corn, wheat, cotton, and barley are the most affected agricultural products. In addition, losses have begun in the high levels of biological diversity found in the Eastern Anatolia, Black Sea, and Taurus regions. Some species have been observed to migrate towards higher altitude regions (Demircan et al., 2022). Furthermore, increases in sea temperatures have both increased invasive species and caused fish migrations in the Mediterranean.

Overall, Turkey, like other similar countries, is one of the countries most affected by global warming. For these reasons, the measures taken must be expanded as soon as possible and the implementation policies must be updated. In this regard, climate adaptation policies in Turkey must be strengthened. Water management must be re-evaluated. New solution models must be developed against fires and the risks they may pose. Furthermore, the rapid transition to climate-friendly agricultural practices is of critical importance.

5. CONCLUSION

Global warming is a complex process that must be addressed on many levels. These include rising atmospheric temperatures, climate change, and its effects on human life. Starting with the industrial revolution, the increase in greenhouse gases and, consequently, the greenhouse effect has rapidly accelerated. Thus, with rising temperatures, global warming has enveloped the entire world. Along with the rising heat, the natural climate cycle is also being disrupted. As the climate cycle is disrupted, it triggers unusual weather events, causing many negative effects. It is known that these changes alter the physical and chemical structure of oceans and seas. At the same time, they threaten the entire structure of ecosystems, affecting both living and non-living environments. Furthermore, it is clear that if serious measures are not taken against the countless risky factors of global warming, the entire world will face situations that will destroy all living things and the socio-economy.

On the other hand, when Turkey is examined in terms of its geographical structure, it is a country located in the Mediterranean Basin. When examined in terms of this location, global temperature increases are greater in these regions compared to other regions. In this case, Turkey is facing climate change effects on a serious scale. The foremost of these effects include drought, forest fires, depletion of water resources, increased flooding, more severe storms, irregular hail and rainfall, and decreased agricultural production. At the same time, systems such as the hydrological cycle, carbon cycle, nitrogen cycle, and energy production systems, which are fundamental to the world, further increase the risk ratio in Turkey. Based on these possible scenarios, climate change not only affects environmental structures but also poses a social and economic threat. For these reasons, a number of measures and precautions are presented below with the aim of increasing climate resilience by combating global warming. Compliance with these recommendations is critically important:

5.1. Mitigation of Greenhouse Gases

- In mitigating greenhouse gases, priority should be given to low-carbon technologies, which are among the key technologies required to increase energy production from fossil fuels. In addition, energy efficiency measures should be promoted in industry, transportation, and buildings.
- Current economic models must be changed. In particular, circular economy models must be activated.
- Waste production must be reduced worldwide.
- Carbon conversion processes must be accelerated.
- Modern practices must be adopted to reduce N_2O, an important greenhouse gas emitted mainly from agricultural activities.
- More sensitive processes should be adopted in agriculture, and new technologies that produce low emissions should be used in animal husbandry.

5.2. Strengthening Adaptation Strategies for Turkey

- Water management, one of the most important issues for Turkey, should be reorganized with its holistic aspects. Basin-based planning should be implemented. Rainwater and surface water efficiency should be reorganized. Modern and state-of-the-art irrigation systems should be developed. Along with these, groundwater protection measures should also be developed.
- Early warning systems for forest fires, which are the most successful in carbon reduction, should be developed. At the same time, risk maps should be drawn up for forests as a priority. Furthermore, fire-resistant mechanisms should be developed and ecosystem protection plans should be strengthened.
- In agricultural activities, seeds that are highly resistant to hot climates should be developed. Product types should be changed to obtain resistant products. To support all of this, advanced techniques that increase water efficiency should be developed. In addition, adaptation policies should be developed to enable farmers to comply with this process.
- With rising temperatures, infrastructure must be redesigned to withstand the risks of floods and flash floods caused by extreme rainfall. At the same time, permeable surfaces that can absorb water should be increased. While

doing so, projects should be designed using nature-based solutions that do not harm the environment.

5.3. Scientific studies and capacity building

- As with all studies, scientific studies should be conducted collectively with scientists. For example, national climate models can be developed. Studies can be conducted to prepare for potentially risky scenarios from a regional perspective. Microclimate or macroclimate analyses can be developed on a city basis.

- From a scientific perspective for Turkey, climate and weather observation networks can be expanded. The number of stations necessary for atmospheric measurements can be increased. In addition, ecosystem monitoring systems can be developed in these areas.

- Collective work should be carried out with all institutions in the country from a scientific perspective. In this joint effort, the integrity of scientific data analysis should be ensured by increasing collective solidarity among universities, central research laboratories, and public institutions and organizations for these purposes.

5.4. Enhancing institutional capacity in environmental activities

- Turkey's targets in global warming efforts (National Determined Contribution: NDC) in recent years should be further developed. This development should be supported by feasible policies to ensure it is not hindered by any political or social obstacles.

- Efforts should be divided at the country level into provinces, at the provincial level into cities, and at the city level into districts. Municipalities and local governments should be given the most active role and authority in these divisions. Thus, an improved climate action plan should be prepared. The implementation of the plans to be made within this framework should also be monitored.

- Furthermore, all countries around the world should increase the number of climate finance instruments to be used, particularly in the field of climate change, and facilitate their access. At the same time, they should establish carbon markets and increase their number. They should also facilitate access to green fund support.

- The number and volume of renewable energy sources, which are alternatives, should be increased. During this transition process, dependence on fossil fuels should be gradually reduced.

- According to scientific analyses, global warming will continue to accelerate over the next 10 years. For this reason, everyone must quickly fulfill their responsibilities at the country level. First and foremost, emission reduction efforts must be expanded. At the same time, while reducing greenhouse gas emissions and other harmful emissions, adaptation strategies must also be prepared and implemented simultaneously. In fact, in this technological age we live in, the necessary capacity and scientific knowledge to stop climate change are available in all developed countries. Any shortcomings will be addressed through urgent policy decisions and rapid implementation by countries.

As explained throughout this book chapter, environmental policies alone are not sufficient to combat global warming. There are certain essential areas that must be addressed in order to combat it at full capacity. First and foremost among these are agriculture, energy, health, economy, security, and urbanization, which must be addressed collectively and at full capacity. If these conditions are met, global warming can be combated under any circumstances. Furthermore, concrete evidence obtained from scientific studies has shown that it is possible to mitigate the effects of global warming. However, it is also vitally important that steps to be taken globally in these areas are implemented without delay.

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CHAPTER 8

ENVIRONMENTAL JOURNEY OF HEAVY METALS: PHYSICAL TRANSPORT MECHANISMS AND INTERACTIONS

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INTRODUCTION

The growing global population and the ever-expanding demands of modern life are leading to a rapid proliferation of production-focused activities and a sharp acceleration of industrialization. These growing needs, across a wide range of areas, from energy demand and food production to technological advancements and infrastructure investments, are significantly increasing the pressure on natural resources. The uncontrolled progress of industrialization paves the way for the emergence of various problems that threaten the environmental balance (Angon et al., 2024). Chief among these problems is heavy metal pollution from industrial facilities, agricultural practices, household waste, and fossil fuel use. Heavy metals tend to accumulate in soil, water, and the atmosphere, disrupting ecosystems, negatively impacting plant growth and development, and posing serious risks to human health through the food chain (Vardhan et al., 2019).

Heavy metals, which can be found in the environment at certain concentrations due to natural processes, rise to toxic levels under the influence of anthropogenic activities, posing a risk to both agricultural production and human and animal health. Therefore, heavy metal accumulation is a priority topic in modern environmental sciences and sustainable agriculture research. Today, heavy metal pollution is recognized as one of the most significant environmental problems for ecosystems and human health. The high toxicity of these metals and their long-term persistence in nature make them among the primary sources of soil pollution. Factors such as increasing industrialization, the intensive use of chemical inputs in agricultural activities, urban waste, and atmospheric transport are the main factors accelerating heavy metal accumulation in soils (Das et al., 2023).

Many agricultural lands worldwide are affected by pollution from various heavy metals, such as ^{33}As, ^{48}Cd, ^{80}Hg and ^{82}Pb (Liu et al., 2018). International health organizations report that these metals enter the food chain and pose serious threats to human health. Studies reveal that heavy metal residues are found in cereals, vegetables, fruits, and seafood, which are among the staple foodstuffs (Ahmed et al., 2019). These contaminants, detected even in drinking water, pose a global problem that must be addressed urgently to protect environmental health and ensure food safety.

Anthropogenic factors such as industrial activities, mining, energy production processes, municipal waste, domestic sewage, transportation emissions, and intensive fertilizer and pesticide use play a major role in the introduction of heavy metals into agricultural and environmental environments. Uncontrolled waste discharged into the environment from industrial facilities, process waters released from sectors such as metal plating, paint, textile, and chemical industries, and residues generated during the processing of metal ores are among the most significant sources of heavy metal pollution in soil and water ecosystems. Similarly, increasing amounts of solid waste and sewage, in parallel with rapid population growth, can be directly transported to the environment in regions where treatment facilities are inadequate, contributing to heavy metal burdens in soil and water (Alım, 2020).

This book chapter aims to provide a comprehensive assessment of heavy metals in terms of agriculture and the environment by discussing their definition in terms of different disciplines, basic physical properties of heavy metals, main sources of heavy metal accumulation in agricultural and environmental environments, physical transport mechanisms and interactions of heavy metals.

5. HEAVY METALS AND THEIR PHYSICAL PROPERTIES

Heavy metals comprise a highly heterogeneous group of elements, both essential and non-essential, that vary widely in their chemical properties, availability, and biological functions, and can be toxic to organisms depending on their concentration levels. They can be defined differently for different disciplines (Alım, 2020). Physically, the heavy metals are qualified as metals with bulk density greater than 5 g/cm^3 and high atomic weight. In medicine, this term refers to all metals and metal-like elements that exhibit toxic effects in living organisms, regardless of the element's atomic weight; therefore, the potential for biological harm is central to the definition (Özbolat and Tuli 2016). In plant science, the term "heavy metal" should be defined based on the system of elements in the periodic table. In agriculture, the heavy metal term encompasses metal ions that can be naturally absorbed by plants but that, when exceeded by certain thresholds, cause metabolic disruptions, physiological stress, and growth retardation. Therefore, each discipline defines the term "heavy metal" according to different criteria, tailored to the needs of its field of study. If we were to define heavy metals by bringing all disciplines together, heavy metals can be defined as chemical species that are not easily degraded in environmental environment, have toxic effects, are resistant to biochemical transformation processes, and have long half-lives. Figure 1 shows the grouping of heavy metals in agriculture and plant science. In this grouping, the metals defined in physics as transition metals other than lanthanides and actinides, and framed in red, represent the 1st subgroup heavy metals; the metals defined in physics as rare earth metals, namely lanthanides (heavy metals with atomic numbers between 57 and 71) and actinides (heavy metals with atomic numbers between 89 and 103), and framed in black, represent the 2nd subgroup heavy metals; and the semimetals, called metalloids in physics, and framed in blue, represent the 3rd subgroup heavy metals. The term "Lead (Pb) Group" is used for this group (Appenroth, 2010).

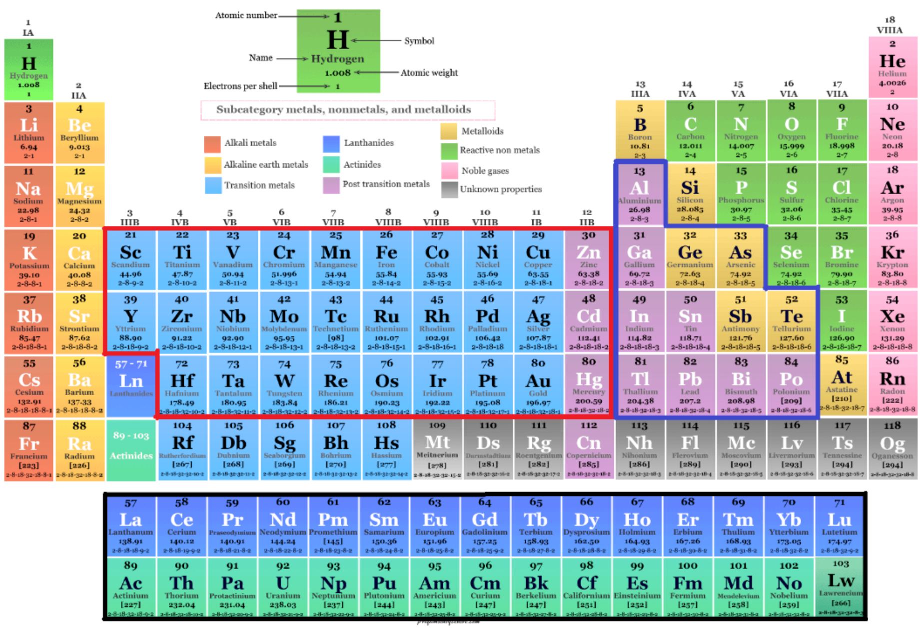

Figure 1. Heavy metal classification according to plant science (Red frame: classified as 1st subgroup heavy metals, black frame: 2nd subgroup heavy metals and blue frame: 3rd subgroup heavy metals).

While heavy metals are indispensable for plant enlargement and development and are used by plants as nutrients, there are also toxic heavy metals that negatively impact their development. Among the heavy metals presented in Figure 1, many of the heavy metals in subgroup 1 are essential for plant growth, while those in subgroup 3 are toxic to plants. Excessive doses of these essential heavy metals can also negatively impact plant physiology and become toxic. Some of the physical properties of some important heavy metals selected from the aforementioned classifications, which are essential for the agricultural environment, are presented in Table 1.

Table 1. Basic physical properties of selected heavy metals (PubChem, 2025; NIST Database, 2025)

Heavy Metal	Atomic Number (Z)	Atomic Weight (g/mol)	Density (g/cm^3)	Atomic Radius (pm)	Melting Point (K)	Specific Heat Capacity (J/kg·K)	Electrical conductivity ($S/m \times 10^6$)
Pb	82	207.2	11.34	202	600.61	127	4.8
Hg	80	200.6	13.53	209	234.32	139.5	1
Cd	48	112.4	8.69	158	594.22	230	14
Cr	24	51.9	7.15	189	2180	448	7.9
Cu	29	63.5	8.93	140	1357.77	384.4	59
Zn	30	65.4	7.13	139	692.68	388	17
Ni	28	58.7	8.91	163	1728	445	14
Co	27	58.9	8.86	192	1768	421	17
Mn	25	54.9	7.26	197	1519	479	0.62

The general physical properties of heavy metals across all disciplines can be listed as follows:

- High atomic weight and density,
- Easily participating in redox reactions,
- High lasting effects in the environment,
- Ability to form complexes,
- Low electrical resistance and good electrical conductivity,
- High capacity for heat conduction,
- Stability in crystalline lattice structures,
- High affinity for biological systems,
- Very high toxic effects,

- Possessing a critical risk for agriculture and the environment.

In addition to these properties, heavy metals can transition between different oxidation states in the environment and biological systems. This is the primary factor determining their ability to participate in redox reactions, their complexation tendency, their solubility, and their degree of toxicity. Furthermore, heavy metals can alter their mobility and bioavailability by forming complexes with hydroxide, sulfur, phosphate, and organic matter in water and soil environments. Heavy metals possess thermodynamic characteristics that conform to specific equilibrium reactions in environmental environment. Therefore, a decrease in soil pH or an increase in oxidative conditions in agricultural areas can cause the metal to convert into a form available to plants. Because heavy metals are in elemental form, they cannot be chemically destroyed in the environment. This property accelerates processes such as bioaccumulation (accumulation within organisms) and biomagnification (ascension up the food chain). Thus, aquaculture, agricultural products, and the soil itself can become persistent reservoirs of heavy metals (Angon et al., 2024; Alengebawy et al., 2021; Satpathy et al., 2014; Zwolak et al., 2019; Wydro et al., 2021; Riyazuddin et al., 2022).

In the overall assessment, although the heavy metals group includes many elements, the main heavy metals that are decisive for agricultural ecosystems and environmental sustainability are ^{13}Al, ^{24}Cr, ^{25}Mn, ^{26}Fe, ^{27}Co, ^{28}Ni, ^{29}Cu, ^{30}Zn, ^{33}As, ^{46}Pd, ^{47}Ag, ^{48}Cd, ^{51}Sb, ^{80}Hg and ^{82}Pb. These elements are classified as significant environmental pollutants due to their toxicity, bioaccumulation potential, and ecotoxicological risks to plant and animal biota and human health (Alım, 2020).

6. HEAVY METAL RESOURCES IN AGRICULTURE AND THE ENVIRONMENT

Population growth, coupled with the ever-increasing industrialization that has become widespread and consistent with the demands of the modern age, leads not only to environmental pollution but also to soil pollution, including heavy metals in water and agricultural land. Heavy metal pollution in agriculture and the environment stems from industrial and agricultural activities, as well as natural processes such as volcanic activity, geological weathering, and soil erosion. The sources of heavy metals found in our environment, soil, water, and air are innumerable. However, when the main source categories of these pollutants are evaluated, they can be grouped as follows:

- Industry
- Agriculture
- Urban problems and energy needs
- Natural processes
- Other.

Some specific sources and the main heavy metal pollutants within these main categories are listed in Table 2 (Özyürek, 2016).

Tablo 2. Sources of Heavy Metal Pollution and Pollutant Distribution

Main Source Category	Spesific Sources	Major Pollutants
Industrial	Mining waste	Pb, Cd, Hg, Cr, As, Cu, Zn
	Metal industry	
	Battery and accumulator waste	
	Oil refineries, etc.	
Agriculturel	Pesticies	Cd, As, Pb, Cu, Zn, Ni
	Chemical fertilizers	
	Animal waste	
	Wastewater sludge, etc.	
Urban	Wastewater discharge	Pb, Zn, Cu, Cd, Cr, Ni
	Solid waste landfills	
	Trafic emissions, etc.	
Naturel	Geological weathering	As, Cr, Ni, Zn, Cu
	Volcanic activity	
	Forest fires, etc.	
Other	Fossil fuel consumption	Hg, Pb, Cd, As, Cr
	Waste incinerators	
	Military activities, etc.	

This pollution is a complex and borderless problem that concerns not only agricultural sciences but also many disciplines, including physics, chemistry, biology, environmental engineering, toxicology, and medicine. Solving the problem is only possible through multidisciplinary approaches and interdisciplinary collaborations. Indeed, the heavy metal sources presented in Table 2 clearly demonstrate that numerous human activities and natural processes, from mining and energy production to waste management and modern agricultural practices, contribute to this pollution. This complexity necessitates the development of integrated and sustainable management strategies, as the problem cannot be solved by the efforts of a single discipline or sector.

7. IMPACT OF HEAVY METALS ON THE ENVIRONMENT AND AGRICULTURE

Anthropogenic activities such as industrialization, mining, intensive agricultural activities, wastewater discharges, and the use of chemical fertilizers and pesticides cause heavy metals (especially ^{33}As, ^{48}Cd, ^{80}Hg and ^{82}Pb) to enter soil, water, and plant environments. Because these metals cannot be dissolved by natural processes, they cause long-term, persistent pollution in their environments (Yadav et al., 2025) and accumulate in soil, plants, humans, and other living organisms. This occurs through bioaccumulation, the accumulation of naturally occurring heavy metals in organisms over time, and biomagnification, the exponential accumulation from the smallest to the largest organisms in the food chain. Therefore, heavy metals are of great importance to all living organisms, including plants, animals, and humans, both because they play a role in carrying out vital activities and because their deficiencies or excessive doses directly affect general health in terms of the continuity and quality of life (Özyürek, 2016). As a matter of fact, it is also known that the intake of many heavy metals into the body through consumption of foods has long-term harmful effects on human health as a result of the accumulation of these metals by binding to lipid metabolism or proteins in the body (Rajeswari and Sailaja, 2014).

Heavy metals exist in two primary forms in the aquatic and soil environments that are of critical ecotoxicological importance: dissolved species and particulate-bound species. Dissolved heavy metal ions are particularly notable for their high toxicity potential across a wide range of biological species, including vertebrates. Metals bound in particulate form occur adsorbed to sediment surfaces, in suspended solids or colloidal systems, in interstitial complexes, or integrated into organic matter-carbonate phases via Fe/Mn hydroxide networks. In this context, heavy metal accumulation levels are significantly higher in urban and industrial settlements compared to natural ecosystems, thus emphasizing the dominant determinant of heavy metal dynamics by anthropogenic influences (Rawat et al., 2003; Marcovecchio, 2004; Breward, 2003). Therefore, heavy metals may enter drinking water, agricultural land, irrigation channels, or trophic networks in urban or industrial areas, potentially leading to harmful effects on human populations (Jha, 2004; Obbard, 2001; Quinn et al., 2003).

Heavy metals can negatively affect the functional integrity of essential biomolecules such as nucleic acids, enzymes and intracellular structural proteins, and by binding to them. Furthermore, heavy metals can sometimes act as detrimental elements in the body, even interfering with metabolic processes at certain times (Jaishankar et al., 2014). In general, chronic exposure to heavy metals can cause carcinogenic risks, as well as functional damage to the central and peripheral nervous systems and various health problems related to the circulatory system. Heavy metals can penetrate plant, animal, and human tissues through respiration, ingestion, or direct contact. Motor vehicle emissions are one of the primary pathways that transport metals such as As, Cd, Co, Ni, Pb, Sb, V, Zn, Pt, Pd, and Rh into the atmosphere. Furthermore, runoff from industrial and urban wastes and acid rain can remobilize metals trapped in soil, increasing their release into the environment. The general hierarchical order of heavy metal accumulation in the human body is as follows: crops are exposed to heavy metals through water intake, animals consume these plants, and humans directly consume these plants or animal-based foods that have consumed these plants (Rajeswari and Sailaja, 2014). Furthermore, heavy metals are naturally present at certain limits in both plants and other living organisms because they serve various structural functions in living metabolism. Therefore, their deficiencies can lead to structural disorders in living organisms and the development of numerous physiological problems. Furthermore, when heavy metals are consumed in excessive doses or not at all, they can cause reactions that can threaten the survival of living organisms. This situation is generally referred to as heavy metal poisoning or toxicity (Alaoui-Sossé et al., 2004).

Heavy metal accumulation in soil systems negatively affects both soil biological and chemical-physical properties. These effects include suppression of soil microbial communities and enzymatic activities, decreased fertility, and disruption of organic matter and nutrient cycles. This phenomenon demonstrates that heavy metal contamination disrupts healthy soil functions (Yerli et al., 2020). Therefore, the effects of heavy metals on soil physical properties are quite complex and multifaceted. On soil structure, heavy metals significantly reduce aggregate stability, negatively impacting soil durability (Zhang et al., 2024). This leads to structural deterioration in the soil pore system and increases soil surface hardening and crust formation. Their effects on soil porosity and air permeability are also quite pronounced. Heavy metals reduce the macropore ratio, limiting the soil's aeration capacity. This reduces water infiltration rates and impairs soil drainage capacity. These changes in pore structure impede air and water circulation in the soil, negatively impacting plant root development.

The influence of heavy metals on soil-water dynamics are another important issue. Heavy metals cause changes in soil water holding capacity and reduce hydraulic conductivity. This leads to increased surface runoff and increases the risk of soil erosion. Furthermore, the presence of heavy metals can negatively impact surface and groundwater quality. The occurrence of heavy metals in aquatic systems used for soil irrigation not only negatively impacts water quality but also leads to the transport of metals from the soil to plants through irrigation. Thus, waterborne metal contamination directly threatens agricultural production and food security (Yadav et al., 2025). Additionally, heavy metal pollution causes significant changes in soil color and temperature properties. Heavy metal accumulation alters the reflectance capacity of the soil surface and affects thermal conductivity (Trujillo-González et al., 2016). This leads to changes in soil heat capacity and disrupts soil moisture balance by increasing evaporation rates. Their effects on soil density and texture are also noteworthy. Heavy metals increase soil density and alter the distribution of particles. All of these changes in physical properties lead to the deterioration of soil quality and disruption of ecosystem functions. The primary effects of some important heavy metals on soil are listed in Table 3.

While heavy metals are absolutely essential for plant growth and development and are used by plants as nutrients, there are also toxic heavy metals that negatively affect their development. Among the heavy metals shown in Figure 1, many of the heavy metals in subgroup 1 are essential for plant growth, while those in subgroup 3 are toxic to plants. Excessive doses of these essential heavy metals can also negatively affect plant physiology and become toxic (Alım, 2020).

Table 3. Effects of some selected heavy metals on soil (Angon et al., 2024; Yadav et al., 2025; Nagajjoti et al., 2010)

Heavy Metal	Effects on Soil
Pb	It changes the activity of soil enzymes and reduces their productivity
Cd	Disrupts the chemical processes of the soil
Hg	Affects soil microbial metabolism and disrupts organic matter cycling
Cu	Toxic to soil microorganisms at high concentrations and inhibits plant root development
Zn	Affects soil fertility
Ni	Inhibits soil enzyme activities, limits plant growth

Plants can more quickly absorb ions and mobile elements that can be released into the soil through their roots. However, it is very difficult or almost impossible for elements and ions that are strongly bound in the soil to reach the plant. In addition, a condition called "antagonistic effect" can occur in plants. This effect is described as the interchangeable binding of plant nutrients in the soil or irrigation water, preventing or reducing the uptake of the required element (Kafadar and Saygıdeğer, 2010). This negatively affects plant physiological characteristics and growth. Indeed, heavy metals, called trace elements and essential for plants, fulfill various functions for healthy plant growth and development. These functions include fertilization and flawless pollination, the healthy and abundant production of genetic material and seeds, plant resistance to environmental factors and adverse conditions, the performance of various beneficial biochemical and metabolic processes, and fruit formation. Deficiency of some metals described as trace elements (^{24}Cr, ^{25}Mn, ^{26}Fe, ^{27}Co, ^{28}Ni, ^{29}Cu, ^{42}Mo, etc.) manifests itself in the form of chlorosis, various necrosis, leaf deformities, drying, or brownish-yellowish spots in plants. When this occurs, plant growth and development slow down, and yield and quality decrease. This is because plants need to store the necessary amount of trace elements (heavy metals) from the soil through their roots to fully perform their growth and development functions (Özyürek, 2016; Nagajjoti et al., 2010).

Consequently, heavy metal pollution is not merely a local soil problem; it poses a multifaceted threat linked to soil, water, plant, food security, and human health. Therefore, monitoring contamination, identifying the source of the contamination, risk analysis, and, if necessary, implementing remediation methods are essential for the continuity of agricultural production and ecosystem health (Yadav et al., 2025).

8. PHYSICAL TRANSPORT MECHANISMS OF HEAVY METALS

The movement and distribution of heavy metals in environmental mediums occur through a series of physical transport mechanisms. These mechanisms constitute the fundamental processes that determine the distribution, accumulation points, and ultimate fate of metals within ecosystems. These mechanisms include:

- **Atmospheric Transport:** In this transport, dust, ash, aerosols and particles containing heavy metals are transported environmentally by wind currents, gravity, and binding to rain, snow and fog droplets (Liu et al., 2018; Oladimeji et al., 2025).
- **Runoff Transport:** Surface runoff from rain or irrigation transports dissolved or particulate heavy metals in the soil to streams, lakes, and river systems. In this transport, heavy metals are mostly adsorbed onto clay, silt, and organic matter particles (Qiao et al., 2022; Yang et al., 2024).
- **Leaching and Percolation:** Vertical transport occurs through fractured structures, macropores and worm channels as heavy metals leak downwards into the soil profile with rain or irrigation water (Oladimeji et al., 2025; Wijngaard et al., 2017).
- **Diffusion:** Metal ions are transported from high to low concentrations by free molecular movement (Qiao et al., 2023; Rashid et al., 2023). As soil water content increases, the diffusion coefficient increases.

Diffusion rates are lower in fine-textured soils. This type of transport can be physically determined by Fick's laws.

- **Advective Flow:** Heavy metals are transported en masse in the direction of water movement, and as groundwater flow increases, metal transport also increases.
- **Colloidal and Nanoscale Transport:** Transport occurs by binding heavy metals to clay colloids, humic substances and Fe-Mn oxide nanoparticles (Yao et al., 2021; Oladimeji et al., 2025).
- **Physical Transport by Plant Roots (Rhizosphere-Mediated Transport):** Metal ions are transported from the root to the stem as plants absorb water. The concentration gradient created by the root accelerates the diffusive movement of metals towards the root (Oladimeji et al., 2025).
- **Sediment Transport:** Heavy metal-bound sediments on the river and lake bottom are displaced when the flow velocity increases. As the stream accelerates, metal-adsorbed particles remain suspended and are transported. Floods and inundations mix metals accumulated at the bottom back into the water column.
- **Thermal and Physical Mixing (Mixing Processes):** Transport resulting from temperature gradients and density differences. When thermal stratification is broken, heavy metals can redistribute in the water column. Dissolved metal salts can alter water density and cause downward movement of heavy metal-rich layers.
- **Hydrodynamic Transport in Marine and Coastal Ecosystems:** Transport resulting from tidal movement (tidal mixing), wave action, and the mixing of fresh and salt water. It is effective in the transport of metals from the shore to the open sea.

Each of these physical transport mechanisms affects the behavior and fate of heavy metals in environmental systems in different ways and often interacts with the other. Quantitatively understanding and modeling these mechanisms is crucial for predicting the spread of heavy metal pollution, assessing risks, and developing effective control strategies. The relative contribution of each mechanism varies dynamically depending on environmental conditions, seasonal changes, and the specific physical-chemical characteristic of the metal.

9. EFFECTS OF PHYSICAL PROPERTIES ON THE TRANSPORT BEHAVIOR OF HEAVY METALS

The transport behavior of heavy metals in environmental environments is significantly influenced by their fundamental physical properties-particle size, density, and atomic weight. These parameters shape their environmental fate by determining their susceptibility to different transport mechanisms.

Particle Size Effects: Particle size is one of the most decisive physical parameters in the environmental transport of heavy metals. Metals with fine particle sizes (diameter <10 µm) are more susceptible to atmospheric transport by wind erosion and can be transported long distances. These particles exhibit higher reactivity due to increased surface area and move more effectively in colloidal systems. In the diffusion mechanism, ions with small particle sizes diffuse faster, while in advective transport, increasing particle size increases the sedimentation rate and limits transport. Nanoparticle-sized metals (diameter <100 nm) are particularly effective in colloidal transport and have the potential to pass through conventional filtration systems (Huang et al., 2020; Yao et al., 2015; Gunawardana et al., 2014).

Effects of Density: Density is a key parameter that directly affects the sedimentation tendency and sedimentation rate of heavy metals. High-density metals (Mercury (Hg): 13.53 g/cm^3, Lead (Pb): 11.34 g/cm^3) tend to settle rapidly in aquatic environments and are more likely to accumulate in sediments. Therefore, during advective transport, the transport distances of high-density metals may be more limited. In wind erosion transport, density affects the transport threshold of particles; low-density metals can be transported even at lower wind speeds. Density also affects filtration and retention behavior in porous media, reducing the potential for high-density metals to leach deeper into the agglomerate.

Effects of Atomic Weight: Atomic weight indirectly affects transport mechanisms through the chemical reactivity and complex formation capacity of metals. Metals with higher atomic weights (Lead (Pb): 207.2 g/mol, Mercury (Hg): 200.59 g/mol) generally tend to form more stable complexes, which increases their colloidal transport potential. The diffusion coefficient varies inversely with atomic weight, with lighter metals diffusing more rapidly.

Atomic weight is also related to parameters such as ionic radius and hydration energy, thus affecting the adsorption-desorption equilibrium. In electrokinetic transport, ion mobility varies with atomic weight and charge density.

10. CONCLUSION AND EVALUATION

The environmental journey of heavy metals involves a complex dynamic involving physical, chemical, and biological processes. The physical transport mechanisms discussed in this section—diffusion, advection, sedimentation, colloidal transport, atmospheric suspension, and redeposition—are the primary components determining the mobility and persistence of heavy metals in the environment. Physical parameters such as particle size, density, surface area, charge properties, and the hydrodynamic structure of the environment directly influence how long metals remain active in each environmental matrix and the distances they can be transported.

When examining the transition processes between soil, water, and atmospheric systems, it becomes clear that the environmental distribution of heavy metals is not static but follows a constantly changing and often irreversible course. Adsorption and desorption equilibrium in soil, binding behavior to suspended solids in aquatic environments, and transport mechanisms by fine particles in the atmosphere stand out as critical processes determining the environmental destiny of heavy metals. Each of these processes is profoundly influenced by physical-chemical characteristics of the metal species, such as their oxidation state, ionic radius, hydration ability, and interaction strength with carrier particles.

This continuous cycle in environmental systems has significant consequences for agricultural production. The mobility of heavy metal carriers (e.g., fine clay fractions, organo-mineral complexes, or nanoparticles) in the soil profile facilitates metal access to the root zone and increases the risk of plant uptake. Metals transported from aquatic environments to agricultural lands through irrigation can cause irreversible deterioration in the physical and chemical structure of the soil. Atmospheric transport, in turn, allows metal-containing dust to spread over large areas, transforming the pollution landscape from a regional to a global problem.

In this context, understanding the physical mobility of heavy metals in the environment is not only a scientific necessity; it is also critical for sustainable environmental management, risk assessment, pollution prevention strategies, and agricultural safety planning. Extreme meteorological events (heavy rainfall, drought, and increased wind speed), particularly those driven by climate change, have the potential to alter the intensity and direction of heavy metal transport mechanisms. This necessitates the continuous updating of existing knowledge.

In conclusion, a holistic approach to assessing the physical mechanisms related to the environmental transport of heavy metals is a fundamental step toward controlling pollution sources, identifying risky areas, and protecting agro-ecosystem health. Future research focusing on transport models at the micro- and nanoparticle scale, the behavior of metal-organic complexes, transition processes at the atmosphere-soil-water interfaces, and the effects of climate variability on transport will contribute to the development of more effective and scientifically based environmental management strategies.

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CHAPTER 9

ECOTOXICOLOGY OF AIR POLLUTION IN HONEY BEE (*Apis mellifera* L.) HEALTH AND POLLEN INTERACTIONS

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INTRODUCTION

Modern urbanization and rapid industrialization have increased atmospheric pollutant loads beyond the limits that ecosystems can bear and have created irreversible biological pressures on pollinator systems. Air pollution is one of the most significant environmental problems in today's world, profoundly impacting both natural ecosystems and agricultural production systems. Increasing global urbanization, industrialization, fossil fuel use, mining activities, and dense transportation networks have historically increased the atmospheric pollutant load.

Honeybees play a fundamental role in the sustainability of global ecosystems. Approximately 35 percent of global crop production depends on animal pollination, and a significant portion of agricultural production, whose economic value exceeds hundreds of billions of dollars, relies on the pollination services provided by bees (Klein et al., 2007).

Traditional risk factors threatening bee health have long been recognized, including infections with the *Varroa destructor* parasite, *Nosema spp*., pesticide exposure, habitat loss, and nutritional deficiencies.

The effects of air pollutants on bees are generally explained through three primary mechanisms. First, bees are directly exposed to pollutants during flight; the attachment of PM and gaseous pollutants to their antenna and feather surfaces impairs sensory functions.

Honeybees, thanks to their electrostatic body structure, collect atmospheric particles at high speed during flight. While this normally provides an advantage for pollen collection, it facilitates the adhesion of toxic substances such as heavy metals and PAH compounds to the bee's body in polluted environments (Vaknin, Gan-Mor, Bechar, Ronen, & Eisikowitch, 2000). The coating of PM2.5 particles on the antenna surface reduces the function of bees' olfactory receptors, leading to disruptions in flower-finding and hive-return behavior (McFrederick, Kathilankal, & Fuentes, 2008).

Air pollution also has significant consequences for plant ecology. Pollutants such as ozone and NO_x can chemically break down the volatile organic compounds of flowers, reducing bees' ability to perceive floral scents to a few meters (Farré Armengol et al., 2016). This creates a two-way interaction that negatively impacts both bee behavior and plant reproductive success.

Bee products such as pollen and beeswax are also critical materials for the accumulation of environmental pollutants. Pollen adsorbs both plant-derived and atmospheric particles, making it a powerful biomonitor of regional pollution (Bayir & Aygun, 2022).

The primary objective of this book chapter is to comprehensively address the effects of air pollution on honeybees from the ecological, physiological, and practical beekeeping perspectives. Beyond understanding the biological effects of air pollutants, the potential for honeybees to be used as biomonitors, the mechanisms by which pollutants migrate into bee products, and the risks they pose to colonies are presented with a holistic approach.

1- Air Pollutants and Their Main Effect Mechanisms on Bees

Bees are exposed to pollutants through three main mechanisms: (i) particle attachment to antenna and feather surfaces during flight, (ii) systemic exposure via plant-derived pollen and nectar, and (iii) accumulation of pollutants carried to the hive in products such as wax, pollen, and propolis**.**

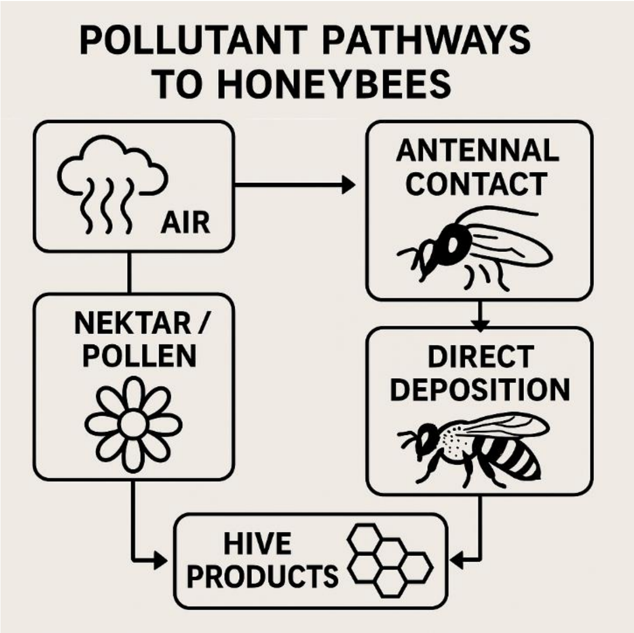

Figure 1. Schematic representation of honey bee exposure pathways to atmospheric pollutants.

Air pollution is a complex environmental stress factor caused by pollutants such as particulate matter, heavy metals, volatile organic compounds, polyaromatic hydrocarbons, ozone, nitrogen oxides, and sulfur dioxide accumulated in the atmosphere. The chemical structures, atmospheric distributions, and biological effects of these pollutants vary greatly. Honeybees are sensitive to these pollutants both because they come into direct contact with atmospheric conditions during their flight activities and because they play an active role in plant-atmosphere interactions.

Particulate matter (PM) is one of the most critical pollutants for bees. Particles in the size range of PM10 and PM2.5 are emitted into the atmosphere from sources such as traffic, industry, road dust, brakes, and tire wear. Because bees naturally acquire electrostatic charges during flight, these particles quickly adhere to their body hairs, antennae, and legs. This accumulation of PM blocks bees' olfactory receptors, reducing their ability to detect floral scents and reducing their foraging efficiency. Furthermore, PM2.5 particles often serve as a carrier phase for heavy metals and PAH compounds. Heavy metals (Pb, Cd, Ni, Cr, Hg, Cu, and Zn) are among the pollutants that pose a risk to bees. These metals are emitted into the atmosphere from sources such as various industrial activities, mining, exhaust gases, and waste incineration plants. Bees are exposed to heavy metals both directly and indirectly. In direct exposure, metal particles adhere to the bees' feather surfaces and are transported to their mouthparts and digestive tract during cleaning behavior.

Metals carried into the hive by bees affect not only adults but also hive products. Beeswax, due to its lipophilic structure, is the bee product with the highest concentration of both metals and PAHs.

Polyaromatic hydrocarbons (PAHs) are lipophilic organic pollutants originating from combustion processes such as diesel exhaust, coal, and biomass combustion, and pose a separate risk to bees. These compounds are carried along with PM2.5 particles and rapidly adsorb onto bees' feather surfaces. They can accumulate to high levels in lipophilic bee products such as beeswax and propolis. Reactive gases such as ozone, nitrogen oxides, and sulfur dioxide are atmospheric pollutants that directly affect both plants and pollinators. Ozone oxidatively degrades the volatile organic compounds produced by flowers, dramatically reducing the range at which bees can detect floral scents. Some studies show that floral scents, normally detected by bees from 10–20 meters away, can only be detected from a few meters away in the presence of ozone.

Volatile organic compounds (VOCs) such as benzene, toluene, and xylene are common pollutants in industrial areas and can affect bees' neurological functions, leading to impaired flight coordination, navigational problems, and memory impairment. In recent years, it has been demonstrated that VOC and SVOC (Semi-Volatile Organic Compounds) accumulation can be detected with high sensitivity using silicone absorbent materials (e.g., silicone bracelets) placed in the hive (Bullock et al., 2020).

A general overview of this section demonstrates that air pollutants have extensive behavioral, physiological, and ecotoxicological effects on bees. Pollutants threaten bee health through mechanisms such as direct adsorption to body surfaces, chemical changes on plants, and migration and accumulation in bee products. Recent scientific studies have demonstrated that both acute and chronic exposures increase biological stress at the colony level, reduce pollination efficiency, and negatively impact beekeeping practices.

Table 1. Major atmospheric pollutants and their primary mechanisms of action on honeybees.

Pollutant	Exposure Route	Individual Effects	Colony-Level Effects	Sources
PM2.5 / PM10	Antenna + body hair adhesion	Olfaction loss, increased ROS	Forager loss, disorientation	McFrederick et al. (2008)
Pb, Cd, Ni, Cr	Pollen – nectar – body	Mitochondrial damage, neurotoxicity	Immune collapse	Conti et al. (2020)
PAHs	Transported with PM2.5	DNA damage, impaired PER response	Larval mortality, CCD	Sari & Esen (2024)
O_3	VOC oxidation	Loss of floral detection	Reduced pollination	Farré-Armengol et al. (2016)
NO_x	VOC degradation	Navigation impairment	Reduced forager efficiency	Fuentes et al. (2016)

Summary of major atmospheric pollutants affecting honeybees, including their exposure routes, individual-level impacts, colony-level consequences, and primary environmental sources. This table highlights how PM, heavy metals, PAHs, and reactive gases impair sensory, physiological, and behavioral functions in bees.
** PM: Particulate Matter; PAH: Polycyclic Aromatic Hydrocarbons; VOC: Volatile Organic Compounds; ROS: Reactive Oxygen Species; CCD: Colony Collapse Disorder*

2-Plant-Pollen-Atmosphere Interactions

Air pollution is an environmental problem that directly affects not only bees but also flowering plants, a key component of the pollination system, and the pollen they produce. Pollen grains produced by plants play a critical role in ecological processes, both as targets for atmospheric pollutants and as biological structures that carry these pollutants on their surfaces. Pollen grains are surrounded by a durable, lipophilic, and high-surface-area outer layer called sporopollenin.

Atmospheric pollutants have a wide range of physicochemical effects on pollen. PM and heavy metals form micro-precipitates on the pollen surface, altering its aerodynamic properties. This not only increases the metal load bees are exposed to during pollen digestion but also reduces the success of pollen adhesion to the plant's stigma.

Reactive gaseous pollutants such as ozone and nitrogen oxides are another factor affecting the bee-plant relationship through pollen. Volatile organic compounds (VOCs), which enable bees to find flowers, are quickly degraded by the oxidative effects of ozone. When the chemical integrity of floral scents such as linalool, geraniol, and benzaldehyde is disrupted, bees' range of detection for flowers decreases dramatically.

Sulfur dioxide (SO_2) affects plant physiology, leading to qualitative changes in the pollen production process. SO_2 causes stomata to close in plant leaves, decreases photosynthesis, and slows carbon metabolism. As a natural consequence, nectar volume decreases, pollen viability decreases, and pollen tube development is impaired.

The transport of pollutants from soil to pollen is also crucial for bee nutrition. Plants absorb metal ions found in polluted soil through their roots and transport them to upper organs via the xylem.

Air pollution also directly affects the nutritional value of pollen. Under ozone stress, some amino acids increase in plants, while essential amino acids decrease. PAH compounds disrupt the lipid profile of pollen, reducing its energy value. As bees return from flowers to the hive, they carry pollen in the pollen baskets on their hind legs, body hairs, and mouthparts. Pollutants are transferred to the hive during this process; PM can migrate from the hairs to hive surfaces, heavy metals from pollen to honey and larvae, PAH compounds to beeswax, and VOCs to propolis. In regions with high air pollution, pollutant accumulation within the hive increases rapidly, resulting in measurable levels of chemical contamination in bee products.

All these characteristics make pollen a unique biological sensor for monitoring environmental pollutants. Pollen is frequently used in biomonitoring studies because it simultaneously reflects both plant- and atmospheric-derived pollutants, is easy to collect, offers high sensitivity for heavy metal and PAH analyses, and is a strong indicator for urban-rural comparisons.

Table 2. Effects of Major Air Pollutants on Pollen Morphology, Chemistry, and Plant Pollinator Interactions

Pollutant	Effect on Pollen	Outcome for Bees	Outcome for Plants
PM2.5	Adherence to the sporopollenin surface	Increased digestive load	Reduced pollination success
Ozone	Degradation of VOCs	Decreased flower-finding distance	Reduced fertilization rate
SO_2	Stomatal closure	Decreased nectar availability	Reduced pollen viability
Heavy metals	Accumulation of metal ions	Intestinal epithelial stress	Reduced flowering quality

Comparative effects of major air pollutants on pollen morphology, biochemical composition, and plant–pollinator interactions. The table summarizes how PM, ozone, SO_2, and heavy metals alter pollen structure, reduce nectar or VOC integrity, and negatively impact bee foraging and plant reproduction.

** VOC: Volatile Organic Compounds. Represents chemical changes influencing plant–bee communication.*

3-Behavioral Effects on Bees

3.1. Olfaction and Flower Perception

The behavioral repertoire of honeybees is based on a sophisticated neural and hormonal regulatory system that responds sensitively to environmental changes. Bees perform many sophisticated behaviors, including orientation, flower recognition, foraging, intra-colony division of labor, communication through dance language, and discrimination of colony individuals.

The olfactory system plays a critical role in bees' environmental perception. Hundreds of sensilla on bee antennae sensitively recognize the volatile organic compounds in flowers and determine which plant the bee will navigate to. However, the adhesion of PM2.5 and PM10 particles to the antenna surface physically blocks these sensillary entrances, significantly reducing olfactory sensitivity. This prolongs the time it takes for bees to find flowers and reduces foraging efficiency.

3.2. Navigation and Direction Finding

Air pollution directly affects bee navigation behavior. Bee navigation relies on numerous environmental cues, such as solar position, polarized light, landforms, magnetic fields, and wind direction. On days when PM concentrations increase, atmospheric visibility decreases and sunlight is scattered more, making it difficult for bees to accurately read the sun's angle.

Learning and memory processes are also negatively affected by pollutants. PER (Proboscis Extension Reflex) experiments have shown that exposure to heavy metals and ozone reduces bees' ability to learn odor-reward associations by 25–55%. PAH compounds such as phenanthrene suppress short-term memory and shorten the time it takes for bees to recall information about food sources.

Air pollution also has a wide spectrum of effects on bee flight behavior. Due to VOC degradation, bees take longer to find flowers, requiring them to expend more energy during flight. PM accumulation causes small weight changes on the thorax and wing surface, impairing flight stability; flight performance decreases further in windy conditions.

3.3. Intra-Colony Social Behavior

Air pollution profoundly affects not only individual behavior but also intra-colony social organization. Bees recognize individuals within a colony by their cuticular hydrocarbon profiles; Exposure to PAHs and VOCs alters these profiles, increasing aggression at colony entrance and leading to inappropriate exclusion behaviors.

All these behavioral mechanisms also weaken the pollination function of bees in crop production. Pollination success rates for plants such as tomatoes and squash have been reported to decrease by 28–60% in agricultural areas exposed to ozone (Langford et al., 2023). These findings demonstrate that air pollution disrupts bee behavior, directly threatening both ecosystem health and agricultural productivity.

Table 3. Behavioral Disorders in Honeybees Caused by Exposure to Air Pollutants.

Pollutant	Mechanism of Action	Behavioral Outcome	Source
PM2.5 / PM10	Antennal obstruction	Loss of olfaction	McFrederick 2008
O_3	VOC degradation	Reduced flower-finding ability	Farré-Armengol 2016
Pb, Cd	Neurotransmitter disruption	Decrease in PER learning	Aldgini 2019
PAHs	DNA and synaptic damage	Disorientation, impaired flight	Sarı 2024

*Behavioral impairments observed in honeybees following exposure to air pollutants. This table categorizes sensory, navigational, memory-related, and flight-related disruptions and associates each with specific pollutant types and their modes of action. * PER: Proboscis Extension Reflex—an assay used to assess learning and memory capacity in honeybees.*

4. Physiological and Genotoxic Effects on Bees

Honeybees (*Apis mellifera*) are sensitive to air pollution. This sensitivity is primarily due to their high metabolic rates despite their small body size, their commitment to a life cycle requiring continuous flight, their delicate and sensitive tracheal respiratory system, and their physiological mechanisms capable of rapid biochemical responses to environmental stressors. Atmospheric pollutants exert pressure on nearly every component of bee physiology, affecting a wide range of factors, from energy metabolism and immune functions to respiratory efficiency, neurological processes, and cellular DNA integrity.

The respiratory system is one of the first physiological structures directly affected by air pollutants. Bees receive oxygen through their tracheal system, which processes it through their stigmas, which are in direct contact with the external environment. Small particles such as PM2.5 limit oxygen diffusion by coating the stigmas and tracheal openings.

Energy metabolism is another physiological area most affected by exposure to pollution. Bee flight muscles have one of the highest aerobic capacity tissues in the animal kingdom and are dependent on continuous ATP production. Heavy metals and PAH compounds disrupt the electron transport chain by causing oxidative damage to the inner mitochondrial membrane. This disruption leads to a decrease in ATP production, disruption of NADH utilization, and the accumulation of ROS (reactive oxygen species).

The effects of air pollutants on the immune system are also striking. Bee immunity consists of both humoral and cellular components. Heavy metals suppress cellular immunity by causing a decrease in hemocyte numbers. Aldgini and other researchers have reported that the number of hemocytes in bee hemolymph can decrease by up to 30% under Pb and Cd exposure.

The neurological system is one of the most sensitive structures to air pollutants. Heavy metals and PAH compounds disrupt synaptic transmission, reduce acetylcholine esterase activity, and cause changes in dopamine and serotonin levels. These neurochemical changes negatively impact bees' coordinated movements, navigational capacity, and foraging motivation.

One of the most severe effects of air pollution occurs during the larval and pupal stages. Larvae are approximately ten times more sensitive to pollutants than adult bees, and consumption of contaminated pollen or honey can lead to decreased growth rate, developmental deformities, and reduced pupal hatching rates in larvae.

Genotoxic effects, on the other hand, are associated with the pollutants' disruption of cellular DNA integrity. PAH compounds, when metabolized, form reactive epoxide derivatives that bind to DNA, leading to DNA adducts and increasing the risk of mutations. Heavy metals, on the other hand, can cause DNA breaks, telomere shortening, and chromosome aberrations through oxidative stress.

The impact of these physiological and genotoxic effects on the colony level is critical. Consequences such as increased forager losses, decreased brood production, shortened bee lifespan, inadequate protein stores, immune collapse, and decreased overwintering success significantly increase the risk of colony collapse syndrome (CCD). When combined with other stressors such as pesticide exposure and Varroa pressure, air pollution becomes a holistic threat that severely weakens the biological resilience of colonies.

5- Pollutant Accumulation in Bee Products

Pollutants carried by honeybees from the environment directly affect not only adult bees but also bee products produced in the hive. Products such as pollen, honey, beeswax, propolis, and royal jelly are of great importance for both bee health and human consumption.

Pollen is one of the most sensitive indicators of heavy metals and PAH compounds in the environment. The sporopollenin layer of pollen grains readily retains heavy metal ions and organic pollutants on its surface. Therefore, pollen very quickly reflects the accumulation of both plant-derived and atmospheric metals.

Despite being a nectar-based product, honey can exhibit some levels of contamination through indirect contaminant transfer. Metal accumulation in honey tends to be lower than in pollen; this is due to honey's lower surface area and limited adsorption capacity for metal ions. However, metals such as Pb, Cd, Ni, and Zn have been detected in honey during urban beekeeping practices. The accumulation of PAH compounds in honey is more limited, but the high PAH content in beeswax may indirectly transfer to the honey through contact. Among bee products, beeswax is the material with the highest concentration of pollutants. Its highly lipophilic structure allows it to store organic pollutants and PAH compounds for extended periods. As beeswax combs remain in the hive for years, the accumulated PAH load increases over time, effectively becoming a pollution archive. Large-scale studies in Europe have found PAH concentrations in beeswax to range from 900–2600 μg/kg, with phenanthrene, anthracene, pyrene, and benzo[a]pyrene being among the most commonly detected species.

Because propolis is derived from plant resins, it reflects environmental pollutants with high sensitivity. PAH and heavy metal loads accumulated on the surfaces of trees and shrubs in urban areas can be directly transported to propolis. The lipophilic matrix of propolis is suitable for PAH accumulation, and these compounds can be stored in propolis for extended periods without deterioration.

Royal jelly is the material least exposed to pollutants compared to other bee products. This is primarily due to the fact that royal jelly is produced in a more isolated area within the hive, and due to its high-water content, it adsorbs metal and organic pollutants to a lower level than other products. However, there is evidence that lower amounts of Pb and Cd are detected in royal jelly in heavily polluted areas.

Contaminants in bee products constitute an important consideration not only for bee health but also for human health. Heavy metals and PAH compounds pose a risk to children, pregnant women, and immunocompromised individuals.

Overall, the accumulation of pollutants in bee products is an important indicator both in the biological monitoring of environmental pollution and in assessing the safety of beekeeping products. The rise in heavy metal and PAH concentrations in bee products in regions with increasing air pollution indicates that beekeeping activities should be supported with management strategies appropriate to these conditions.

Table 4. Comparative Accumulation of Heavy Metals and PAHs in Hive Products and Their Biological Implications.

Bee Product	Heavy Metal Accumulation	PAH Accumulation	Biological Implication	Human Health Risk
Beeswax	Very high	Very high	Impaired larval development	Moderate–high
Propolis	Moderate–high	High	Reduced antioxidant capacity	Moderate
Pollen	Most sensitive	Moderate	Gut stress, decreased protein content	Moderate
Honey	Low–moderate	Low	Low risk for the colony	Low

Comparison of heavy metal and PAH accumulation levels across hive products and their biological implications for colony health and human exposure. Beeswax, propolis, pollen, and honey are evaluated in terms of their pollutant retention capacity and associated risks.

** PAH: Polycyclic Aromatic Hydrocarbons. "Low–moderate–high" indicate relative accumulation intensities.*

6- The Use of Bees as Biomonitors

Honeybees (*Apis mellifera*) have become one of the most widely used biomonitor organisms worldwide for monitoring environmental pollutants. This is primarily due to their constant contact with the environment, their wide flight range, their ability to collect samples simultaneously from different habitats, and the bee products they produce providing ideal biological materials for chemical analyses.

One of the most important characteristics that makes bees effective as biomonitors is their wide flight radius. A forager bee can scan an area of 3–5 km in a single day and collect thousands of microsamples from different locations.

Because thousands of forager bees fly within bee colonies over weeks, bees act as a natural passive sampling mechanism. These flights, conducted at different times of day, under varying meteorological conditions, and over different plant species, create a multi-layered pollutant collection process.

Bee products used in biomonitoring applications offer distinct advantages for different types of pollutants. Pollen is one of the most powerful short-term indicators because it carries both atmospheric particles and heavy metals absorbed from the plant. Samples obtained using pollen traps accurately reflect the distribution of metals and PAHs in urban and rural areas.

Biomonitoring methods can be categorized into three main categories: direct analysis of bee bodies, chemical examination of bee products, and the use of synthetic samplers placed in the hive. Particles deposited on the bees' feathers, antennae, and leg surfaces can be imaged using microscopic techniques such as SEM-EDX to determine both the type of pollutant and its morphological characteristics.

The chemical profiles of bee products can also reveal the sources of pollutants. Heavy metal profiles can indicate the accumulation of Pb, Zn, and Cu from traffic, while PAH profiles can be used to distinguish combustion processes from exhaust, heating, and industrial sources. Multivariate statistical analysis (Principal Component Analysis (PCA), Hierarchical Cluster Analysis (HCA), and Linear Discriminant Analysis (LDA)) models are effective tools for determining the sources of pollutants.

The use of bees as biomonitors has become a systematic practice in many countries worldwide. Heavy metal mapping is conducted using bee products in many cities in Italy, particularly in Milan; national bee biomonitoring programs are implemented in France; and bees are actively used in VOC and PAH monitoring projects in Canada and the US. These examples clearly demonstrate that bees provide a reliable, economical, and high-resolution environmental monitoring system in urban and industrial areas.

Turkey is a suitable country for the implementation of bee-biomonitoring programs, both in terms of its beekeeping capacity and its floristic diversity.

Due to the presence of dense traffic networks, industrial zones, thermal power plants, and mining sites, the creation of regional pollution maps is a strategic necessity.

Table 5. Analytical Methods and Target Pollutants Used in Bee-Based Biomonitoring Studies.

Sample	Analytical Method	Target Contaminant	Advantage
Pollen	ICP-MS	Pb, Cd, Ni	High sensitivity
Beeswax	GC-MS/MS	PAHs	Long-term contamination record
Propolis	ICP-OES + GC-MS	Metals + VOC/PAH	Comprehensive chemical profile
Bee Body	SEM-EDX	PM, metal particles	Source identification
Silicone Wristband	GC-TOF-MS	VOC	Real-time exposure assessment

Analytical methods commonly used in bee-based biomonitoring studies and the target pollutants each technique can detect. The table also highlights the analytical advantages of ICP-MS, GC-MS/MS, SEM-EDX, and related methods when analyzing bees, pollen, wax, and hive matrices.

** ICP-MS: Inductively Coupled Plasma Mass Spectrometry; ICP-OES: Optical Emission Spectrometry; GC-MS/MS: Gas Chromatography–Tandem Mass Spectrometry; SEM-EDX: Scanning Electron Microscopy–Energy Dispersive X-ray.*

7-Risk Management and Recommendations in Beekeeping

Air pollution is a powerful source of environmental stress, affecting many processes in honeybees, from their physiology and behavior to their immune systems and the chemical integrity of bee products. The effects of pollutants on bee health not only reduce the biological resilience of colonies but also reduce the economic efficiency of beekeeping operations.

Locating hives is a fundamental step in risk management in beekeeping. It is known that bees rapidly accumulate Pb, Cd, Zn, PAH compounds, and particulate matter from exhaust gases in high-traffic areas. Therefore, locating hives away from gas stations, urban roads, and major transportation routes is critical for bee health.

The vegetation surrounding the hive directly impacts the transport of pollutants and the nutritional quality of bees. Gaseous pollutants such as ozone, SO_2, and NO_x reduce nectar volume, degrade VOC compounds, and make flowers difficult for bees to detect.

Colony management also requires special measures in polluted areas. Because bee products are biological indicators of environmental pollution, regular analysis of pollen, honey, and beeswax is critical for both monitoring colony health and assessing safety for human consumption. Pollen is a sensitive indicator of heavy metal and PAH accumulation, while beeswax reflects long-term PAH storage.

Queen replacement practices should also be performed more frequently in highly polluted areas. Heavy metal and organic pollutant loads can impair queen bees' egg-laying capacity, lifespan, and pheromone production, disrupting the social cohesion of the colony.

Urban beekeeping requires special precautions. In urban environments where hives are placed on rooftops, wind direction, traffic density, and regional PM loads should be carefully evaluated.

Beekeeping management is not just about practices; education and awareness are also crucial for colony protection. Understanding the sources of pollutants, the effects of pollutants on bee health, the types of pollutants that can accumulate in bee products, and biomonitoring methods facilitates risk management. In this regard, it is important for universities, beekeeping associations, and local governments to organize information sharing and training programs for beekeepers. Regional and national policy development is also a long-term necessity. A monitoring system that evaluates bee losses and air quality indices together can be an important tool in identifying both pollution sources and the true causes of bee mortality. Supporting clean production zones for beekeeping, limiting beekeeping in industrial areas, providing economic support for heavy metal and PAH analysis of bee products, and establishing bee-friendly green belts in urban areas are among the holistic policy recommendations that protect bee health.

Overall, air pollution is a significant source of stress affecting the beekeeping sector both biologically and economically. Therefore, regional and national management strategies, in addition to individual beekeepers' practices, must be tailored to address this problem.

8. Conclusion and General Assessment

Air pollution is a global environmental problem that profoundly impacts not only human health but also the holistic functioning of ecosystems, the maintenance of biodiversity, and agricultural production systems. One of the most vulnerable targets of this problem is honeybees (*Apis mellifera*), which are central to ecosystem functions.

PM2.5 and PM10 particles, heavy metals (Pb, Cd, Ni, Cr), polyaromatic hydrocarbons (PAHs), ozone (O_3), nitrogen oxides (NO_x), and sulfur dioxide (SO_2) emitted into the atmosphere directly disrupt bees' sensory, behavioral, and physiological systems. VOC degradation impairs flower-bee communication; particles attached to the antenna surface block olfactory receptors, suppressing the sense of smell and causing serious losses in orientation behavior (Farré Armengol et al., 2016; Fuentes, Chamecki, Roulston, Chen, & Pratt, 2016).

From a physiological perspective, pollutants are known to cause hypoxia, mitochondrial dysfunction, and increased oxidative stress in flight muscles. Heavy metals and PAHs suppress energy metabolism, reducing ATP production; they also cause a decrease in hemocyte count in the immune system, weaken antimicrobial peptide production, and make colonies more susceptible to pathogens.

Bee products are powerful biological recorders reflecting the environmental spread of pollutants. Pollen carries heavy metal and PAH accumulations from both plant and atmospheric sources with high sensitivity, while beeswax, thanks to its lipophilic structure, stores PAH and pesticide residues for long periods, revealing the annual accumulation profile of environmental pollution. Propolis stands out as a bee product with high metal and organic pollutant accumulation due to the chemical structure of plant resins. Honey, on the other hand, is a more limited indicator of pollutant transport to the hive but provides valuable information for assessing metal accumulation in urban beekeeping. Bees are not only victims of pollutants but also powerful biomonitoring organisms for monitoring air quality. Their wide flight radius, electrostatic body structure, and the ability to collect samples simultaneously from different sources allow them to reflect regional pollutants with high sensitivity.

A multi-layered management strategy is necessary to mitigate the impacts of air pollution on the beekeeping sector. Locating hives away from pollutant sources, diversifying vegetation, optimizing colony feeding practices, increasing queen replacement frequency, and analyzing bee products at regular intervals are key measures beekeepers can implement.

At the national level, establishing comprehensive databases that can monitor bee health and air quality indicators together, encouraging beekeeping in clean production areas, limiting beekeeping in industrial areas, and financially supporting heavy metal and PAH analyses of bee products are important components of long-term environmental policies. Such an approach will both protect the beekeeping sector and contribute to the implementation of sustainable environmental management models that strengthen ecosystem health. Therefore, the inclusion of air pollution indicators as mandatory parameters in national bee health monitoring programs has become a critical requirement for identifying the true causes of colony losses.

Consequently, air pollution creates a powerful environmental pressure that threatens bee health, pollination services, beekeeping productivity, and ecosystem sustainability. Honeybees are both one of the most vulnerable to this pressure and one of the most effective biological tools for pollution monitoring. Accurately understanding the impacts of air pollution on bees goes far beyond strengthening the beekeeping sector; it is also crucial for food security, ecosystem stability, and the development of sustainable environmental policies.

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BÖLÜM 10

HELPFUL OR HARMFUL? A PRELIMINARY LOCAL INVESTIGATION OF ROOK (*Corvus frugilegus*): THE CASE OF BAYBURT (TÜRKİYE)

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1. INTRODUCTION

Humanity has undergone changes in many areas over time. Chief among these changes are innovations in agriculture. As the need to expand agricultural lands increases daily, growing and preserving agricultural products has also become increasingly challenging. Crops grown on vast agricultural lands sometimes possess invasive qualities due to their foreign origin. Furthermore, the prepared foods in these agricultural areas also attract certain animal species. The economic damage caused by animal meat on agricultural products is reaching significant levels.

As the human population grows, globalization and construction accelerate the spread and rate of spread of non-native (alien) and invasive species that threaten global biodiversity (Rai and Singh 2020). Invasive species are organisms that are introduced outside their native ranges, whether intentionally or unintentionally, as a result of anthropogenic activities, establish sustainable populations, spread to new environments, and cause significant ecological, economic, or social damage. Not all introduced or introduced species become invasive; a species is considered invasive only when it has successfully established itself and produces negative impacts, such as reducing local biodiversity, altering ecosystem processes, or disrupting agricultural and human health systems (Simberloff, 2013). In this context, whether a species is invasive or not is related to the damage it causes. Considering an invasive species harmful means that it interferes with any ecological functioning in the area in which it is introduced. Internationally adopted definitions, such as the Convention on Biological Diversity, emphasize that the introduction or spread of invasive species threatens biodiversity (Convention on Biological Diversity, 2024).

Ecologically, invasion is viewed as a multistage process in which only a subset of introduced species become invasive (Richardson et al., 2000). These species may not simply compete with or replace native species but rather introduce new pathogens, disrupt habitats, or alter nutrient cycles (Mack et al., 2000). These invasive species, not native to a region, will undoubtedly negatively impact the region's ecological order. The region's food chain or food web will ultimately be manipulated by a different species. Crucially, this will result in a threat to biodiversity. The biodiversity of an area is referred to as its biodiversity. In this context, biodiversity loss is of particular concern to naturalists. Some researchers predict that biodiversity loss will negatively impact environmental quality, ecosystem costs, and ultimately, human well-being and the costs of combating invasive species within the next 50 years (Rai and Singh, 2020; Pyšek et al., 2020). Many factors contribute to the transfer of an invasive species to different areas. Among these, the most common form of transport involves animals. For example, the transfer of invasive plant species to new habitats occurs primarily through zoochory. Within zoochory, there is also ornithochory, or bird transport (Green et al. 2019). Crows are among the most frequently encountered birds in agricultural areas. These birds are omnivorous, feeding on small invertebrates, fruits, and a wide variety of seeds (Kitowski et al. 2017; Sørensen et al. 2023).

When it comes to birds, farmers need to protect their crops. In many parts of the world, increasing flocks of birds are invading agricultural lands. They can feed on these lands, reducing yields. For example, sparrows (Emberizidae, Passeridae), doves (Colombidae), and crows (Corvidae) cause the most damage in Europe, while budgerigars and parrots have become more damaging in the Indian subcontinent (De Grazio 1989). Crows are known to damage agricultural lands worldwide. Türkiye has 10 species belonging to the crow family. In our country, Eurasian Jay (*Garrulus glandarius*), Northern Raven (*Corvus corax*), Brown-necked Raven (*Corvus ruficollis*), Hooded Crow (*Corvus cornix*), Rook (*Corvus frugilegus*), Western Jackdaw (*Coloeus monedula*), Red-billed Chough (*Pyrrhocorax pyrrhocorax*), Alpine Chough (*Pyrrhocorax graculus*), Spotted Nutcracker (*Nucifraga caryocatactes*), Eurasian Magpie (*Pica pica*), and Fan-tailed Raven (*Corvus rhipidurus*) belong to the Corvidae family (TRAKUS, 2025).

This book chapter provides a preliminary study on the relationship between the invasive species *Corvus frugilegus*, or rook, and agricultural lands in Bayburt. It also compiles information on the species' harmful, beneficial, and agricultural conservation measures and offers recommendations for Bayburt.

2. RESEARCH AREA and ROOK

2.1. Geographical Structure of Bayburt Province

Bayburt province is located in northeastern Türkiye, between 40°37′ north latitude and 40°45′ east longitude, and 39°52′ south latitude and 39°37′ west longitude. It is bordered by Erzurum to the east, Gümüşhane to the west, Trabzon and Rize to the north, and Erzincan to the south. Located on the banks of the Çoruh River at an elevation of 1,550 meters above sea level, Bayburt has a surface area of 3,652 km² (Ministry of Culture and Tourism of Türkiye, 2025).

Its geographical structure encompasses high-altitude plains, mountains, and plateaus suitable for the rook's habitat. The plains, where the bird is frequently seen, cover an area of approximately 900 km². This large plain formation can be examined in four sections within Bayburt. These can be summarized as follows:

- Keçevi Plain: Located between 1600 and 1750 meters.
- Mormuş Plain: Located between 1550 and 1600 meters.
- Aydıntepe Plain: Located between 1450 and 1550 meters (Figure 1).
- Düzeker Plain: Located north of Bayburt.

Figure 1. View of the Aydıntepe Plain and sparse poplar groves

The key factor that makes these plains important is the presence of poplar trees (*Populus nigra* L.), the rook's most common nesting site (Figure 2). Poplar trees are typically found in moist meadows along the Çoruh River or on tributaries that feed it. Rooks nest primarily in lowlands, hollows, and upland areas (Luniak, 1972). They nest in agricultural lands lined with tree groves, hedgerows, or small forests (Brebchley, 2009). A study by Porhajašová et al. (2015) also found that rooks prefer *Populus nigra* for nesting. While tree species is not a determining factor, tree height and branching are important (Kasprzykowski, 2008).

Figure 2. Poplar units (*Populus nigra*) as nesting trees for rooks within the area

The Çoruh River, flowing from high mountains, shapes the landscape. It originates in Mescit Mountain, a region bordering Erzurum near the south of the province. It flows through the city center and merges with the Büyük Çayı in the Aydıntepe plain to form a true river.

2.2. Bird species of Bayburt

Bayburt has a rich diversity in terms of biodiversity. This diversity is reflected in its bird species. According to the National Biodiversity Strategy and Action Plan (2007), there are 466 bird species in Türkiye, nearly half of which, approximately 210, have been identified in Bayburt province alone. The presence of the Çoruh River and Bayburt's location on migration routes undoubtedly play a significant role in this diversity (Figure 3).

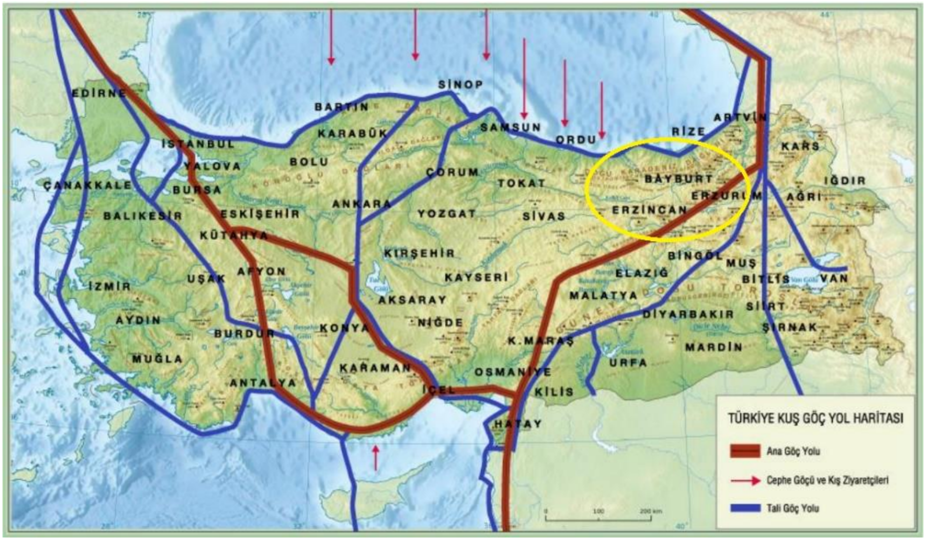

Figure 3. Türkiye bird migration routes (Turan, 2009: cited in Özkan, 2019), Bayburt province is shown with a yellow ring and follows the Bayburt line, which is one of the two main migration routes coming to our country from the north.

The crow species observed in Bayburt province are the Eurasian Jay (*Garrulus glandarius*), Northern Raven (*Corvus corax*), Hooded Crow (*Corvus cornix*), Rook (*Corvus frugilegus*), Western Jackdaw (*Coloeus monedula*), Red-billed Chough (*Pyrrhocorax pyrrhocorax*), Alpine Chough (*Pyrrhocorax graculus*), and Eurasian Magpie (*Pica pica*) (based on research observations). Among these, the Hooded Crow (*Corvus cornix*), Rook (*Corvus frugilegus*), Western Jackdaw (*Coloeus monedula*), and Eurasian Magpie (*Pica pica*) are the most frequently observed species in city centers and agricultural areas. In agricultural areas, parks, and gardens, the Rook (*Corvus frugilegus*) is the most frequently seen species, traveling in flocks.

2.3. Rook (*Corvus frugilegus*)

The rook, scientifically known as *Corvus frugilegus*, can be described as a fruit-gathering raven (Frux: fruit; Legere: gathering). *"Corvus"* means "raven" in Latin, while "frugilegus" means "fruit-gatherer" or "gatherer" (Jobling James, 2010). The rook is black and is characterized by the featherless whitish area around its beak (Figure 4). This crow species is a passerine bird and is classified within the Corvidae family (Seed et al., 2006). The species' biological classification is as follows.

Kingdom:	Animalia
Phylum:	Chordata
Class:	Aves
Order:	Passeriformes
Family:	Corvidae
Species:	*Corvus*
Kingdom:	*Corvus frugilegus* Linnaeus, 1758

Figure 4. Rook (*Corvus frugilegus*) side of the Çoruh River

According to DateZone (2025) data, the following situations have been identified regarding the worldwide distribution of the species. This species occupies a very broad geographical area; therefore, it does not meet the criteria for Vulnerable status based on range size (an extent of occurrence below 20,000 km² together with ongoing or fluctuating declines in range, habitat, or population, and limited locations or severe fragmentation). Its population is also very large, falling well above the threshold for Vulnerable under population size (fewer than 10,000 mature individuals with an expected decline of over 10% within ten years or three generations, or particular population structure requirements). Although its numbers show a downward tendency, the rate of decrease is not considered fast enough to reach the population-trend threshold for Vulnerable (a reduction of more than 30% over ten years or three generations). Consequently, the species is classified as Least Concern.

Although *Corvus frugilegus* has a wide ecological tolerance, it is most concentrated in areas dominated by open agricultural fields, pastures, meadow ecosystems, and wooded coastlines. The species is particularly abundant in areas adjacent to productive agricultural lands due to high nutrient availability and utilizes both natural and human-shaped habitats effectively (Cramp & Perrins, 1994). Gimona and Brewer (2006), analyzing and modeling atlas data, determined that the species occurs in areas with high soil quality and adequate grazing land.

The rook is typically a colonial nesting species, often building its nests in groves of tall, leafy trees or in clusters of large and small trees around settlements. Therefore, the continuity of forested areas is a critical factor for the species' reproductive success (BirdLife International, 2023). The species is highly flexible in its feeding ecology, adapting to changes in environmental conditions by utilizing a wide range of foods, including soil invertebrates, insects, seeds, grains, and agricultural waste. Forming large flocks, particularly in winter, increases the species' dependence on open spaces and agricultural mosaics for energy needs. *Corvus frugilegus* can also thrive in areas with intense human activity, exhibiting a high degree of flexibility in habitat selection, exploiting the resources offered by anthropogenic environments such as agriculture, urban green spaces, and roadside woodlands (Cramp & Perrins, 1994).

Studies that have considered the rook invasive have shown this bird to be of low threat (Global Invasive Species Database 2025). More than 10 million pairs have been recorded in Europe (Burfield & Bommel, 2004). *Corvus frugilegus* is found in the Palearctic region, across much of Europe and Asia (Brenchley, 2009) (Figure 5).

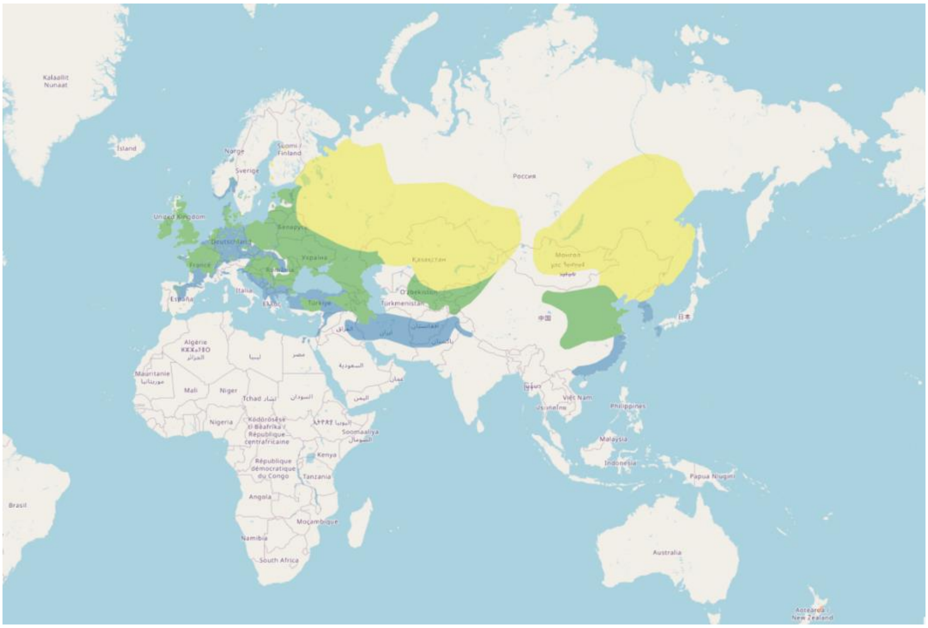

Figure 5. The global distribution of the rook, according to DataZone (2025). Yellow: Breeding, Green: Resident, Blue: Non-breeding

Bayburt, the subject of the study, has ideal geography and temperature values for rooks (Figure 6). Rooks prefer relatively cool and cold locations. Zbyryt et al. (2022) observed these birds nesting in the coldest region of Poland. Their study revealed that the birds are affected by day length.

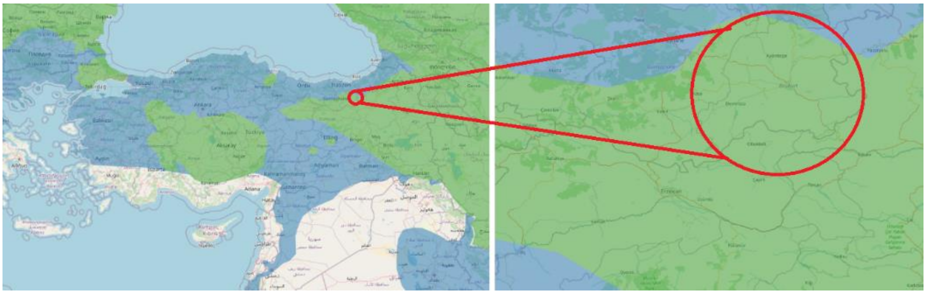

Figure 6. Distribution of the Rook in Türkiye and Bayburt, according to DataZone (2025) data (Green: Resident, Blue: Non-breeding)

2.4. Agricultural Activities in Bayburt

Data on agricultural activities in Bayburt (Table 1-2) were obtained from the website of the Ministry of Agriculture and Forestry, Bayburt Provincial Directorate of Agriculture and Forestry (2025). Currently, only 30% of Bayburt's land area is used for agriculture. Almost half of the province consists of meadows and pastures. Forests and shrublands constitute only a small portion, around 8%.

Table 1. Land percentages and location of agricultural land in Bayburt

Type and Usage	Bayburt (Amount)	Bayburt %	Türkiye (Amount)	Türkiye %	Ratio %
Agricultural Land	114.526	30,6	24.002.092	31,3	0,48
Meadows and Pastures	171.470	45,8	14.617.000	19,1	1,17
Forests and Shrubs	29.793	8	23.245.000	30,3	0,13
Uncultivated and Other	58.908	15,8	14.829.908	19,3	0,4
Total	374.697	100	76.694.000	100	0,49

In agricultural areas, field land is the primary target, followed by vineyards and orchards, and finally greenhouses. The presence of fields is considered attractive to rooks because they consume the seeds and young shoots of crops such as wheat, barley, corn, and sunflower, causing crop losses (Feare, 1969). Feare, Dunnet, and Patterson (1974) found that crows can damage crops during periods of food scarcity or when their daily food requirements increase (during breeding season). Because these birds travel in flocks, they cause significant losses in the fields they visit. Rooks are known to cause significant crop losses in cornfields (Holyoak, 1970). This damage is particularly pronounced in areas with large colonies (Figure 7).

Table 2. Agricultural products grown in Bayburt

Agricultural Areas	Bayburt (decare)	Türkiye (decare)	Ratio%
Field Crops	1.034.908	183.454.042	0,56
Fruit Crops	1.970	38.009.802	0,005
Vegetable Crops	2.971	8.035.874	0,036
Ornamental Plants Area	0	59.192	0,000
Fallow Area	105.411	10.462.008	0,998
Total	**1.145.260**	**240.020.918**	**0,471**

Bayburt is a region where crops such as potatoes and oats are cultivated. Crops that undergo stem metamorphosis, such as potatoes, are preferred by crows during the hottest periods of summer. Feare, Dunnet, and Patterson (1974) observed that crows feed on potatoes and stock fodder during dry summer weather when food is scarce. Similarly, crows are known to prefer hay accumulated by oat cultivation in the area during winter. A similar observation was made by Feare, Dunnet, and Patterson (1974) that oat stacks constitute the main feeding grounds for rooks during periods of deep snowfall. Because oats are particularly suitable for crows during winter, their spring planting can represent a loss for farmers. Feare (1974) clarifies this point as follows: While losses caused by crows in oat stacks may not be significant, they can be significant on small farms. Similarly, losses to planted and abandoned grain due to crow attacks will be relatively greater on small farms than on large farms, and crop protection methods must be inexpensive to benefit all farmers.

Figure 7. *Corvus frugilegus* and *Coloeus monedula* moving in flocks in the Aydıntepe Plain, Bayburt.

The damage caused to grain by rooks in agriculture can be said to vary depending on the number of crows, their feeding rate, the length of the feeding day, the proximity of the field to the nests, and the planting date (Feare, 1974). This statement by Feare (1974) can also be considered valid for Bayburt. The negative relationship between rooks and agriculture can be illustrated in Figure 8.

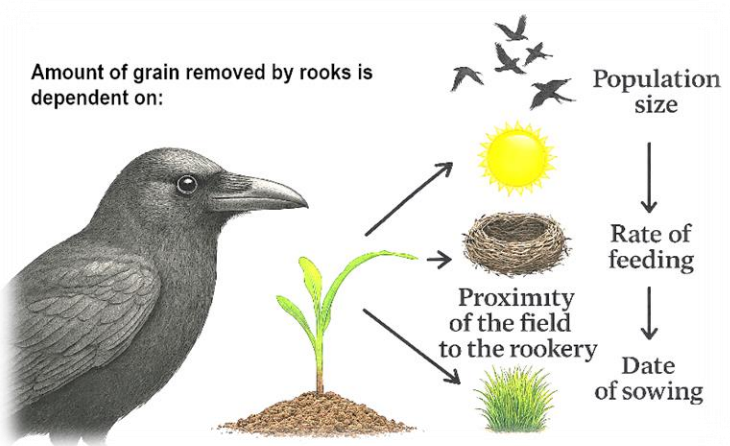

Figure 8. Grain damage caused by rooks in agriculture (Adapted from Feare, 1974)

2.5. Why is Rook helpful for farming?

Despite its superior intelligence, elegance, and significant contribution to the ecosystem, the crow is often mistakenly considered a useless, even harmful, animal by farmers, hunters, and urban dwellers (Porhajašová et al., 2015). In some cases, the rook performs ecological functions useful for agriculture (Figure 9). A significant portion of its diet consists of agricultural pests such as insects, larvae, grasshoppers, wireworms (Elateridae), and mole crickets (Baker & Crick, 2021). Rooks feed primarily on insects, including their larvae, but also on various snails and slugs, small amounts of rodents, and other small vertebrates (Orłowskı et al., 2009). Analysis of the stomach contents of crow chicks found that approximately 46.5% of the diet was of animal origin, 41.2% was mineral components, and only 12.2% of the diet was of plant origin (Orłowskı et al., 2009). The species' insect diet may reduce the need for chemical pesticides (Baker & Crick, 2021). Furthermore, its consumption of small rodents such as mice provides indirect benefits for grain stores and fields (Cramp & Perrins, 1994). Therefore, C. frugilegus is often considered a “both beneficial and harmful” species in the literature. Similarly, the use of abandoned rook nests as nests for other raptors is also significant. For example, it provides nesting opportunities for the critically endangered red-footed falcon (Falco vespertinus L.) (Gúgh, 2009).

In addition to all this, rooks remove dead animals and various food scraps (Roberts & Jähnes, 2013). Therefore, the crow's scavenging and scavenging properties are also ecologically important. In this context, it's not surprising to see crows concentrated in city garbage dumps.

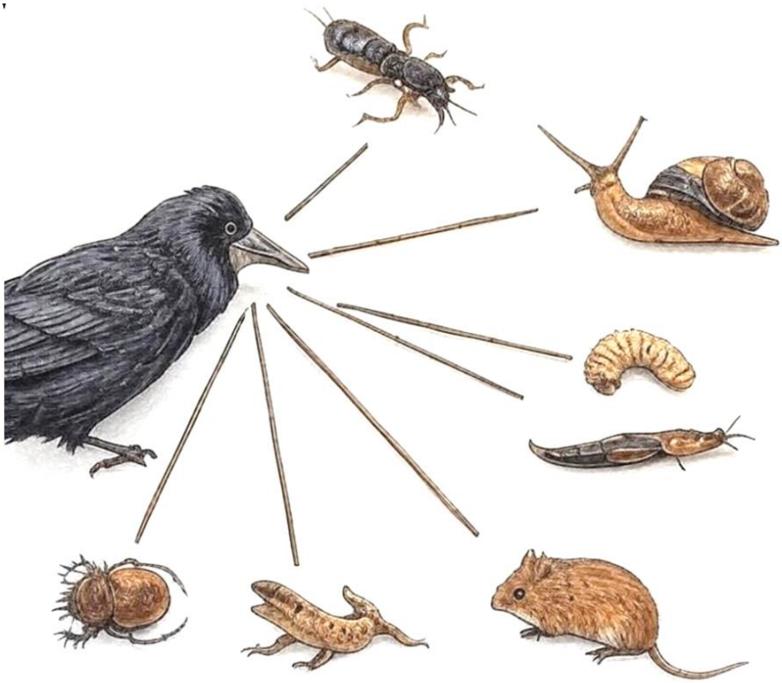

Figure 9. Animal species hunted by Rook in agricultural areas

2.6. Ways to keep Rooks out of fields

Given the serious concerns about bird damage to crops, various prevention methods have been tested to reduce agricultural losses (Klug et al., 2023). Among these methods, numerous non-lethal techniques have been developed to reduce damage. Acoustic or visual scare techniques, such as gas cannons, rockets, bioacoustic scarers, kites, mirrors, dead crow statues, etc., have proven ineffective in the medium term (Sausse and Lévy, 2021) due to rapid habituation of birds (Klug et al., 2023; Linz et al., 2011).

Feare (1974) stated in his study that most methods for keeping rooks away from agricultural fields are ineffective, with only balloons keeping crows away from fields. However, even this is not guaranteed and may become less effective once widespread use is adopted.

Millions of crow species are culled annually in Europe, and it is estimated that this number exceeds 4 million. This number is expected to include approximately 600,000 rooks (*Corvus frugilegus*) and 250,000 jackdaws (*Corvus monedula*) (Hirschfeld and Heyd, 2005). Some researchers in ecology and conservation biology have expressed concerns about the ecological, economic, and ethical implications of this practice (Warburton and Anderson, 2018).

To minimize crow damage to agriculture, methods such as increasing planting depth, tamping down the soil after planting, protecting open grain stores, and using visual/auditory deterrents are recommended (Inglis et al., 1990). While increased pesticide use already threatens crows (Krüger et al., 2020), some political groups are now even denying crows their right to exist in residential areas or rural areas (Niedersächsischer Landtag 2014).

Linz et al. (2011) recommend habitat management of roosting sites, the use of plant dryers to accelerate harvest time, and forage crops. They argue that a damage management strategy combining these three techniques must meet the test of predictable effectiveness, economic viability, and practicality. Similarly, Avery (2002) suggests that alternative food sources, possibly in conjunction with bird repellents, could reduce damage to sunflower crops, although he made this recommendation for a different bird species (blackbird).

3. CONCLUSION AND RECOMMENDATIONS

This book chapter examines the province of Bayburt, which has a relatively cold climate and where agriculture takes place under challenging conditions. While the harsh climate makes farming difficult, the loss of productivity in existing agriculture due to other factors is an undesirable situation for farmers. Crows constitute a large portion of the bird flocks most prominently seen in agricultural areas throughout Bayburt province. Crows have negative consequences for agricultural fields, such as eating plant sprouts, removing sown seeds, and disrupting the structure of newly planted fields. They are also notable for their devastation of winter fruits and their predation on stock crops.

Focusing solely on the negative aspects of *Corvus frugilegus* would be unwise for Bayburt province. This is because the species is known to consume leftovers and eliminate waste products in the city's garbage dumps, where it is most abundant, especially outside the breeding season. Furthermore, in agricultural areas, it consumes insects, insect larvae, mole crickets, and snails, as well as small vertebrates such as mice and lizards. This is a highly agriculturally friendly practice.

In addition to all this, the rook's nests high in poplar trees provide nesting opportunities for herons and birds of prey within the region. Bayburt is already quite diverse in bird species. This contribution to raptors is crucial for the region's biodiversity.

Ultimately, the rook has both positive and negative aspects for Bayburt. It appears that the benefits of the massive flocks of crows that blanket the city's skies outweigh the negative ones. However, it is possible to minimize the damage caused by the rook's damage to farmers and agricultural lands. The following suggestions are offered for this purpose:

Reduce the planting of poplars (*Populus nigra*), which are the birds' nesting trees, in areas near agricultural areas in Bayburt. Studies indicate that the breeding season is when crows cause maximum damage to agriculture. If nesting areas are located further from agricultural areas, the damage will also be reduced.

Pressing the cultivated fields can make it harder for crows to extract seeds.

Harvesting should be shortened, and crops should be harvested as soon as possible.

In areas near agricultural areas, free-range areas can be created where birds can continuously feed and are free of repellents. This way, the birds will feed most frequently in these areas.

Bird repellents can be used. These can be visual or auditory. However, it is also true that birds become accustomed to these repellents over time.

It should never be forgotten that thanks to these birds in our region, we are able to eliminate many insect species without the use of pesticides. It would be wiser to allow these birds to share their share of the fields rather than spending money on chemical pesticides.

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