Agriculture, Forestry and Aquaculture: Theory, Methodology and Practice

Editors

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DOI: 10.5281/zenodo.17396985

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Publisher
Platanus Publishing®

Editors in Chief
Prof. Ali Salim Bozdoğan, Ph.D. & Prof. Nigar Yarpuz Bozdoğan, Ph.D.

Cover & Interior Design
Platanus Publishing®

The First Edition
October, 2025

ISBN

9978-625-6517-49-3

Platanus Publishing®
Address: Natoyolu Cad. Fahri Korutürk Mah. 157/B, 06480, Mamak, Ankara, Turkey.

Phone: +90 312 390 1 118
web: www.platanuspublishing.com
e-mail: platanuskitap@gmail.com

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CHAPTER 1

Microplastic Pollution in Marine Ecosystems: Sources, Distribution, and Ecological Impacts

Bayram Kızılkaya [1]

1. INTRODUCTION

Plastics have rapidly become widespread since the 20th century due to their synthetic polymer structures, offering advantages such as lightness, durability, flexibility, and cost effectiveness. Today, they are indispensable materials in modern life. The use of plastics continues to increase across nearly every sector, including packaging, automotive, construction, medical equipment, electronic devices, and the textile industry. However, the negative environmental impacts of plastics have emerged as a serious global concern, especially in recent decades. Their long-lasting nature in the environment and high resistance to various environmental conditions lead to persistent and large-scale effects on ecosystems. When plastic waste is released into the environment, it undergoes a degradation process influenced by physical, chemical, and biological factors, during which large plastic items break down into smaller fragments over time. As a result of this process, microplastics defined as plastic particles smaller than 5 mm are formed and have been widely detected in both terrestrial and aquatic ecosystems. (Kye et al., 2023). Microplastics are released into the environment from both primary and secondary sources (Akdogan and Guven, 2019). Primary microplastics are small-sized plastic particles that are intentionally manufactured for industrial purposes and directly released into the environment (e.g., microbeads used in cosmetic products and industrial cleaning agents). Secondary microplastics, on the other hand, are formed over time as a result of the physical abrasion, UV radiation, and other environmental factors breaking down larger plastic debris. The spread of microplastics in marine and freshwater ecosystems has serious impacts across a wide biological spectrum ranging from planktonic organisms to fish, crustaceans, and marine mammals (Thushari and Senevirathna, 2020). Due to their small size, these particles are often mistaken for food and ingested by various species, leading to physiological problems such as digestive tract blockages, nutritional deficiencies, and energy loss. More importantly, the impacts of microplastics are not limited to physical effects; they also pose toxicological risks due to the additives they contain, the environmental pollutants they absorb, and the biologically active compounds associated with them (Lalrinfela et al., 2024). The surfaces of microplastics can adsorb hydrophobic

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pollutants such as heavy metals, polychlorinated biphenyls (PCBs), and pesticides, thereby further increasing their environmental risks (Menéndez-Pedriza and Jaumot, 2020; Fu et al., 2021). Considering these factors, microplastics represent not only an environmental issue but also a significant concern for food safety and human health. With seafood being consumed by humans, there is an increasing risk of microplastics entering the human body through the food chain, prompting a growing number of studies in recent years. Microplastics detected particularly in mussels, oysters, fish, and other seafood necessitate new assessments and regulations in terms of both food safety policies and public health (Figure 1).

Figure 1: Representative image of microplastics in mussels and fish products

This book chapter provides a comprehensive overview of plastics, beginning with their fundamental properties and progressing to the classification of microplastics, their environmental distribution, and their effects on marine organisms. Additionally, it explores the long-term impacts of microplastics on biodiversity, interspecies interactions, and habitat degradation, supported by examples from the scientific literature. Based on literature reviews and recent studies, the chapter examines the accumulation tendencies and biotransfer potentials of microplastics with different sizes and morphologies in organisms, along with the ecological consequences of these processes. Plastic and microplastic pollution is regarded as a complex global environmental problem that requires multidisciplinary approaches. Addressing this issue demands contributions not only from environmental engineering, but also from marine biology, toxicology, public health, law, and economics. In line with this perspective, the chapter aims to contribute to the development of both academic and practical solutions by revealing the scale of microplastic pollution. Framed within the context of environmental sustainability, the study seeks to raise awareness and strengthen the flow of information between policymakers and researchers to support the control and mitigation of microplastic impacts.

2. PLASTICS AND MICROPLASTICS: GENERAL INFORMATION

Plastics are synthetic materials composed of polymer-based organic compounds that are either semi-synthetic or fully synthetic. They are moldable and may contain additives to enhance specific properties during use (Figure 2) (Vert et al., 2012; Costa, et al., 2017). Plastics are synthetic polymer materials with a wide range of applications, owing to their diverse physical and chemical properties. Different types of plastics are classified based on their specific gravities and fields of application, and these characteristics serve as key criteria in determining the intended use of each polymer. The most commonly used types of plastics, along with their primary applications and specific gravities, are summarized in Table 1 below.

Figure 2: Representative image of plastics

Table 1. Commonly Used Plastic Types, Their Main Areas of Use and Specific Densities (Wiley-VCH., 2016; Costa, et al., 2017)

Plastic Type		Main Areas of Use	Densities (g/cm^3)
1.	Low Density Polyethylene (LDPE)	Packaging, general purpose containers, shower curtains, floor tiles	0.91–0.93
2.	Polyethylene (PE)	Grocery bags, plastic bottles	0.91–0.96
3.	High Density Polyethylene (HDPE)	Milk jugs, detergent bottles, pipes	0.94
4.	Polystyrene (PS)	Packaging foam, disposable cups, food containers, CDs, building materials	1.05
5.	High Impact Polystyrene (HIPS)	Electronic products, automatic cups, refrigerator inner surfaces	1.08
6.	Polyvinyl Chloride (PVC)	Pipes, window frames, floor coverings, shower curtains	1.38
7.	Polypropylene (PP)	Packaging, bottle caps, ropes, carpets, laboratory equipment, pipettes	0.83–0.85
8.	Polyamides (PA) (Naylon)	Textiles, toothbrush bristles, fishing lines, automotive parts	1.13–1.35
9.	Acrylonitrile Butadiene Styrene (ABS)	Musical instruments, printers, computer monitors, drain pipes, protective equipment	1.06–1.08
10.	Polycarbonate (PC)	CDs, DVDs, building materials, electronics, lenses	1.20–1.22
11.	Polyester (PES)	Textile	1.40
12.	Polyethylene Terephthalate (PET)	Soft drink bottles, food packaging, heat insulation, blister packs	1.38

Polyethylene terephthalate (PET)-based plastics degrade very slowly by microorganisms due to their high crystallinity structure (30%–50%). Under natural conditions, complete decomposition of these plastics typically takes more than 50 years, while in marine environments, adverse factors such as low temperatures and oxygen deficiency can extend this process to hundreds of years (Mohanan et al., 2020; Thacharodi et al., 2023). Petroleum-derived polymers such as polyethylene (PE), polyethylene terephthalate (PET), polyurethane (PU), polystyrene (PS), polypropylene (PP), and polyvinyl chloride (PVC) are highly resistant to natural biological degradation processes. The persistence of these plastics in the environment varies depending on the structural properties of the polymer and the surrounding environmental conditions; for some, degradation may take only a few days, while for others, it can extend to centuries. This leads to the prolonged presence and accumulation of these polymers in nature (Ward et al., 2019; Thacharodi et al., 2023). Microplastics are defined as plastic particles measured on the millimeter scale and are recognized as a serious threat to environmental quality and ecosystem health. Although these particles are generally described as being smaller than 5 mm, there are varying definitions of microplastic size limits in the literature (Barnes et al., 2009; Costa, et al., 2017). Some studies define microplastics as particles smaller than 1 mm (Claessens et al., 2011; Lee et al., 2013; Costa et al., 2017), others as smaller than 2 mm (Ryan et al., 2009; Lee et al., 2013; Costa et al., 2017), while some consider particles between 2 and 6 mm (Derraik, 2002; Lee et al., 2013; Costa et al., 2017) or smaller than 10 mm (Graham and Thompson, 2009; Costa et al., 2017).

Primary and secondary microplastics constitute the main components of plastic pollution commonly encountered in aquatic environments. Primary microplastics are plastic particles that are designed to be micro-sized during production and are released into the environment in this form. These mainly consist of plastic types such as polyethylene, polypropylene, and polystyrene, which are used in cleaning and personal care products that enter water systems primarily through domestic wastewater (Ziani et al., 2023; Kye et al., 2023). Additionally, primary microplastic sources also include industrial activities such as air spraying processes and the spillage of resin powders and granules used in plastic product manufacturing (An et al., 2020). These types of microplastics are among the pollutants that are particularly difficult to control because they enter the environment directly through production and usage processes. Secondary microplastics, on the other hand, are formed over time as larger plastic products break down due to environmental factors. Exposure to sunlight (especially ultraviolet rays), mechanical abrasion, temperature fluctuations, and other physical-chemical processes accelerate this degradation. As a result, large plastic items gradually fragment into smaller pieces, eventually reaching microplastic sizes. Packaging materials, plastic bags, bottles, and other single-use plastic products are major sources of secondary microplastic formation (Osman et al., 2023). Although primary and secondary microplastics are small in size, they pose significant risks to ecosystems due to their widespread distribution in environmental systems and their easy uptake by organisms. Aquatic organisms may ingest these particles, mistaking them for food, which can lead to bioaccumulation processes extending up the food chain. Therefore, controlling microplastic pollution is critically important both for managing sources and for limiting the degradation processes of plastic waste in nature (Fendall and Sewell, 2009; Gregory, 2009; Lechner et al., 2014; Eriksen et al., 2014; Jiang, 2018).

3. MICROPLASTICS IN MARINE AND AQUATIC CREATURES

Many organisms, especially aquatic species such as whales, shellfish, fish, and sea turtles, may mistakenly ingest or accidentally swallow plastic particles found in the environment. This leads to the accumulation of plastics in their digestive systems, which over time negatively affects their feeding, digestion, and overall health. Ingested plastics can cause various biological problems, including mechanical blockages, suppression of hunger signals, transport of toxic substances, and energy imbalances. In the long term, these issues can shorten the lifespan of individual organisms and result in adverse effects at the ecosystem level (Matsuguma et al., 2017; Rezania et al., 2018). It is well known that microplastics (MP) ingested by marine organisms can cause serious physical and toxicological harm within their bodies. Physical effects include digestive system blockages, injuries, and impaired food intake, while toxicological effects arise from harmful chemicals and additives accumulated on the surfaces of microplastics entering the organism. These toxic substances can cause various health issues at the cellular level, such as stress, inflammation, hormonal disruptions, and genetic damage. Thus, the impacts of microplastics on marine life not only threaten individual health but also negatively affect ecosystem integrity and biodiversity (Rezania et al., 2018). According to the findings, whales can accidentally ingest plastic fragments through secondary ingestion, particularly when consuming prey species that have previously ingested plastic waste. This indicates that not only organisms directly consuming plastics but also those higher up in the food chain are indirectly affected by plastic pollution. In addition to microplastics, the gradual fragmentation of larger plastic debris into smaller pieces also causes multifaceted negative impacts on marine fauna. Considering that plastics can lead to physical blockages, digestive system damage, reduced energy intake, and the transfer of toxic chemicals, these processes pose a serious threat to ecosystem health (Di-Méglio and Campana, 2017; Rezania et al., 2018; Roman et al., 2022).

The bioavailability of microplastics can increase through the flocculation (clumping) process with particles in the marine environment. This allows microplastics to combine with other organic and inorganic materials to form larger aggregates, facilitating their entry into the food chain. These microplastic-containing waste materials (such as fertilizer residues) are then consumed by detritivorous species, continuing the circulation of microplastics within the ecosystem. This mechanism facilitates the transfer of microplastics through different trophic levels in the food chain and contributes to the widespread environmental impacts of microplastic pollution (Wright et al., 2013; Botterell et al., 2019; Ugwu et al., 2020). On the other hand, various studies have demonstrated that marine zooplankton actively consume microplastics and ingest these particles as food (Desforges et al., 2015; Ugwu et al., 2020). The ingestion of microplastics by zooplankton facilitates the spread of plastic pollution starting from the most fundamental links of the food chain, extending its impacts across the ecosystem. This indicates that microplastics affect not only large marine animals but also microscopic organisms, posing serious risks to biodiversity and ecosystem functioning. In addition to the transfer of microplastic particles from mesoplankton to macroplankton, the spread of microplastic pollution throughout marine food webs presents a significant threat. This process allows microplastics to move between different trophic levels, leading to their accumulation along the food chain and resulting in widespread ecological consequences (Setälä et al., 2014; Ugwu et al., 2020). Thus, the presence of microplastics in marine ecosystems threatens not only the health of individual organisms but also the integrity of the ecosystem and marine biodiversity as a whole.

Table 1 provides a comprehensive overview of the types and sizes of microplastics found in marine and freshwater ecosystems, along with the organisms in which these plastics have been detected. Microplastics consist of various polymers such as polystyrene, polypropylene, polyethylene, nylon, polyvinyl chloride, and polyester, and they appear in diverse morphological forms including beads, fibers, fragments, and films. Their sizes range widely from the nanoscale (e.g., 55 nm) to microns and millimeters. These plastics have been reported in a wide variety of organisms, from different phytoplankton species and deep-sea creatures to crustaceans and fish (Sharma et al., 2023; Marcharla et al., 2024). Especially small-sized microplastics (at the nano and micron scales) can be readily taken up by living organisms and have the potential to accumulate throughout the food chain. The varying surface charges and chemical properties of microplastics diversify their effects on the environments they inhabit and on the organisms themselves. Data presented in Table 2 demonstrate that microplastic pollution is widespread and diverse in both marine and freshwater ecosystems. This situation poses significant risks to ecosystem health and seafood safety. Therefore, multidisciplinary and comprehensive research efforts must continue to identify the sources of microplastics, monitor their distribution, and assess their impacts.

Table 2. Microplastics in Some Marine Organisms (Sharma et al., 2023; Marcharla et al., 2024)

	Type of Microplastic	Size or Range (µm)	Organisms containing microplastic	Reference
1.	Polystyrene beads (PS)	Nano-sized plastic beads	Phytoplanktons, Chlorella, Scenedesmus	Bhattacharya et al., 2010
2.	Polypropylene (PP) and high-density polyethylene (HDPE)	400–1000 µm	Chlamydomonas reinhardtii	Lagarde et al., 2016
3.	Fibers	10–100	Stomachs of seabirds	Amelia et al., 2021; Landrigan et al., 2020
4.	Fragments	100–1000	Inside marine sponges and the guts of deep-sea fish	Vázquez ve Rahman, 2021; Woodall et al., 2014
5.	Fragments	100–1000	The eggs of fish and amphibians.	Ji et al., 2021; Kye et al., 2023
6.	Films	>1000	The gills of shellfish and crustaceans	Pothiraj et al., 2023
7.	Fibers	10–100	The stomachs of crabs and the tissues of marine mammals	Kye et al., 2023; Laursen et al., 2023
8.	Negatively charged and uncharged polystyrene particlespolystyrene parçacıkları	0.05, 0.5 ve 6 µm	Thalassiosira pseudonana (marine diatom), Dunaliella tertiolecta (marine flagellate), Chlorella vulgaris (freshwater green microalgae)	Sjollema et al., 2016
9.	Polystyrene (PS) microspheres	2 µm, yellow-green fluorescent particles	Chaetoceros neogracile (Diatom), Tisochrysis lutea (prymnesiophyceae), Heterocapsa triquetra (dinoflagellate)	Long et al., 2017

10.	Polyvinyl microplastics	Average diameter 1 µm	Skeletonema costatum (microalgae)	Zhang et al. 2017
11.	Polystyrene (PS)	0.1 and 1.0 µm microbeads	*Chlorella pyrenoidosa*	Mao et al., 2018
12.	Polystyrene (PS)	55 nm nanoparticles; 1 and 6 µm microparticles	*Thalassiosira pseudonana, Phaeodactylum tricornutum, Dunaliella tertiolecta, Skeletonema grethae*	Shiu et al., 2020
13.	Microplastic (MP) fibers	-	Phytoplankton community (Cyanobacteria species: *Aphanocapsa*, *Pseudanabaena*, other species: *Crucigenia, Chlamydomonas*)	Hitchcock, 2022
14.	Microplastics (MP)	3.0 or 9.6 µm	Zooplankton, Mytilus edulis	Browne et al., 2008
15.	Plastic	Microfilamens	*Nephrops norvegicus* (Norway lobster)	Murray ve Cowie, 2011
16.	High-density polyethylene (HDPE) particles	0–80 µm	Mytilus edulis	Von Moos et al. 2012
17.	Polyfilament nylon	Fragments	Estuarine drums (*Stellifer brasiliensis Stellifer stellifer*)	Dantas et al. 2012
18.	Polystyrene (PS) microplastics of different shapes	Beads (20 µm), fiber and fragment (20 µm × 10 µm)	*Calanus helgolandicus* and *Acartia tonsa* (copepods) Larvae of the European lobster *Homarus gammarus*	Botterell et al., 2020
19.	Plastic debris	Plastic pieces	Fishes and mollusks Planktivorous fish	Boerger et al., 2010
20.	Polyesters (PE) and polyamides (PA) such as nylon	Plastic fibers	Estuarine fish—three catfish species (Cathorops spixii, *Cathorops agassizii*,	Possatto et al., 2011

			and *Sciades herzbergii*	
21.	Nylon	Fragments	3 species of bottom-feeding fish (Eugerres brasilianus, Eucinostomus melanopterus, and Diapterus rhombeus	Ramos et al., 2012
22.	Polyethylenes (PEs) terephthalate and polyamide (PA)	Fibers, fragments and pellets with most common size class found to be less than 250 µm	9 of the most commercially popular species of bivalves from a fishery market of Shanghai, China	Li et al. 2015
23.	Polystyrene (PS)	5 µm, 20 µm	Danio rerio (zebrafish)	Lu et al., 2016
24.	Polyvinyl chloride (PVC)	<300 µm	*Acanthochromis polyacanthus* (spiny chromis)	Peda et al., 2016
25.	Microplastics (MP)	<5 mm	*P. perna* (brown mussel)	Santana et al., 2016
26.	Polystyrene (PS)	2–6 µm in diameter	*Crassostrea giga* (Pacific oyster)	Sussarellu et al., 2016

When examining the types, size ranges, densities, and the biological and environmental contexts in which microplastics were identified in Table 2, it becomes evident that microplastics are widely distributed across both marine and freshwater ecosystems. Microplastics with different polymer compositions such as polystyrene, polypropylene, polyethylene, nylon, polyvinyl chloride, and polyester exist in various morphological forms, including beads, fibers, fragments, films, and microspheres. This diversity is significant in terms of their sources, transport mechanisms, and biological impacts. The data presented in the table show that microplastics have been detected in a wide range of biological groups, from primary producers such as phytoplankton, microalgae, and diatoms, to marine sponges, fish, crustaceans, mollusks, seabirds, and marine mammals. Another noteworthy point highlighted in the table is the detection of microplastics in deep estuarine fish species, indicating that these pollutants can be transported to different parts of the oceans and can be present at all levels of the food web. Moreover, the observation of microplastic accumulation in commercially valuable species such as bivalve mollusks, mussels, and lobsters raises concerns about potential risks to human health. The presence of microplastic pollution in seafood species important for human consumption underscores the need for international-level measures regarding food safety and public health.

Microplastic pollution in marine ecosystems is recognized as one of the most significant and rapidly increasing environmental issues of our time. Due to their small size, microplastics are easily ingested by marine organisms and accumulate across all levels of the food chain, thereby amplifying their ecological impact. These particles often accumulate in the digestive systems of marine animals, causing physical blockages, reduced nutrient intake, and subsequent disruptions in energy balance. In species such as crustaceans, fish, and marine mammals, these physical effects can lead to serious consequences not only for individual health but also for population dynamics. The harmful effects of microplastics extend beyond physical impairments, with their chemical aspects playing an equally critical role. Pollutants and toxic substances that adhere to the surfaces of microplastics can transfer to marine organisms, causing cellular damage, hormonal disruptions, and genetic alterations. This not only reduces the overall quality of life for the affected organisms but also results in decreased reproductive capacity and increased susceptibility to disease. From an ecosystem perspective, the transfer of microplastics through the food chain can disrupt interspecies interactions and contribute to a decline in biodiversity. The bioaccumulation of microplastics threatens not only individual organisms but the health of entire ecosystems. Moreover, the entry of microplastics into the human food chain through seafood poses significant risks to food safety and public health. Therefore, microplastic pollution is not only an environmental issue but also a complex problem with social and economic dimensions. Reducing and controlling microplastic pollution requires multidimensional strategies. First and foremost, changes in plastic production and consumption habits are necessary. Limiting the use of single-use plastics and promoting more sustainable alternatives will play a critical role in reducing plastic waste. At the same time, improving waste management systems and increasing recycling rates are essential steps to prevent plastics from entering the environment. Supporting scientific research and strengthening interdisciplinary collaborations are crucial for better understanding the effects of microplastics on ecosystems and developing effective solutions. In addition, raising public awareness, expanding environmental education programs, and encouraging individuals to adopt sustainable lifestyles are important factors in preventing microplastic pollution. In conclusion, combating microplastic pollution must be addressed with its environmental, economic, and social aspects, and carried out through coordinated policies at individual, local, national, and global levels. The protection of marine ecosystems and the preservation of a healthy environment for future generations can only be achieved through such comprehensive and integrated approaches.

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CHAPTER 2

Comparing Türkiye's Hazelnut (Karnel Basis) Export Competitiveness: A CMS Decomposition across Six European Countries

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I. Introduction

Hazelnut is a hard-shell fruit. It was first cultivated and spread out to the world by Black Sea Region. According to the large number researches in the world, it is described that daily consumption of nuts significantly reduces the risk of death from heart disease and prevent other chronic diseases (Sabate and Ang, 2009; Bao etc. 2013; Guasch-Ferré, 2013). There are many uses of hazelnuts that continuously increase the demand such as direct consumption, as input of food industry and as a fuel (Ciarmiello et al. 2014).

Hazelnut, which is one of the products with an important export income of Türkiye, has experienced a little decrease in exports compared to the past due to the countries that became new hazelnut producers after the 90s (Uzundumlu et al, 2022). Hazelnut is one of the strategic products of Türkiye by its significant production and export values and its superior quality. Türkiye has a significant share of world production of some commercial agricultural products which are hazelnut, cherry, fig, apricot, quince and poppy. Hazelnut has a high commercial value, and Türkiye is the world leader in production. Türkiye exported hazelnut kernel (56.7%), processed hazelnut (16.8%), advanced processed hazelnut (26.5%) and hazelnut shell (0.04%) (BSHEU, 2019; FAO, 2019; RTMAF, 2019; RTMCT, 2019). Hazelnut constitutes approximately 20% of exports of agricultural products of Türkiye (İslam, 2018). Türkiye, producing 684,000 tons hazelnut, meets 60.16% of the world hazelnut production, which is 1,077,117 tons. Türkiye is one of the few countries with excess supply for hazelnut (FAO, 2021). Hazelnuts kernels constitute 86.33% of the world hazelnut imports, which is 321,413 tons. The top 6 importing countries are Germany, Italy, France, Netherlands, Poland and Spain. Türkiye meets 75.15% of hazelnut kernels imports of European countries and 93.44% of hazelnut kernels exported by Türkiye goes to these 6 countries (ITC, 2021).

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Since Türkiye provides most of the world hazelnut production (60.16%) and hazelnut exports (63.64%), the policies implemented in the domestic market have a large impact on the world market. Other important hazelnut exporting countries with their share in world hazelnut export are Italy by 11.77%, Azerbaijan by 5.79, Chile by 5.41% and Georgia by 5.08% (FAO, 2021; ITC, 2021). Although Netherlands, Belgium-Luxembourg, Austria, England, Ireland, Switzerland, Bulgaria, Hungary and Canada are not producers, these countries export hazelnut which are imported in shell, kernel or processed form. The high number of re-exporting countries in the hazelnut market is an indication that Türkiye is not sufficiently active in the hazelnut market.

While 80% of the world hazelnut is used in the chocolate sector, 15% is used in the cake, biscuit, and sweet sector, and 5% is used in marketing as appetizers (Kilic and Alkan, 2006). European countries use hazelnut to a large extent as a raw material in the chocolate and confectionery industry. The EU has a supply deficit in its hazelnut market and is dependent on foreign sources (mostly Türkiye). In this respect, the growth of the chocolate and confectionery industry and their preference for hazelnuts as raw materials determine the increase in demand for hazelnuts.

Türkiye's hazelnut yield is lower than other exporting countries. While hazelnut yield per hectare is 0.92 tons in Türkiye, it is 1.03 tons in Italy, 1.38 tons in Azerbaijan, 1.44 tons in Chile and 1.80 tons in Georgia (FAO, 2021). There is no country that can compete in the short term for Türkiye, which has a large share in world hazelnut production. However, countries that are new to hazelnut production and are trying to increase their production may be a risk in the future. Türkiye's lower yield compared to other producer countries reduce its competitiveness in international markets. The dominant position in production can only be maintained by giving importance to the efforts to increase the hazelnuts yield and quality.

Excluding the period of 2003-2006, Turkish governments has supported hazelnut and growers though support purchasing and prices since 1964. Hazelnut production subsidies given by Turkish governments has had economic impacts on producers and consumers in domestic and export markets (Sisman, 2017). Since 2009, the government purchases over production to get market and price stability and, the Turkish treasury has had to finance the cost of over production. In last decade, extreme climate conditions prevented high crop yields and marketable hazelnut in the country. All these developments can affect both the domestic and international hazelnut markets (Bozoğlu et al, 2019). Türkiye has developed the necessary product standards for the foreign market in order to increase hazelnut exports in the world market. The product standards applied in Türkiye's hazelnut export are compatible with the EU and other countries, and it applies the TS-3074 standard for unshelled hazelnuts and TS-3075 for hazelnut kernels. In the standard for each product, there are regulations on the definition, classification and characteristics of the products, sampling, inspection, way of placing on the market and inspection. The Ministry of Agriculture, gives Control Certificate and Agriculture Certificate by checking whether the exported hazelnut complies with the current standards to improve export quantity and quality.

Since the European hazelnut market is an important market growing day by day and Türkiye is the biggest exporter in this market, it is aimed to find out the comparation of Türkiye' export performance in 6 leading import European countries between the years of 2010-2021.

2. Materials and Methods

Türkiye's hazelnut export performance in European market between the years of 2010 and 2021 was examined using the Constant Market Share (CMS) analysis. Italy, Germany, France, Poland, Netherlands and Spain are consisted of 87.25% of European hazelnut import. Other European countries were not included in the CMS analysis as they have a share of less than 1% in Türkiye's hazelnut exports to Europe.

Production and trade statistics were obtained from The Food and Agriculture Organization (FAO) and International Trade Centre (ITC) database. For the CMS analysis, time series was divided into three as period 1 (2010-2013), period 2 (2014-2017) and period 3 (2018-2021), and each period was calculated as the average of four years. The analysis consists of three-time parts, first analysis of period 1 vs. period 2, then the analysis of the period 1 vs. period 2 and, finally, the analysis of period 2 vs. period 3.

The CMS model allows the decomposition of export growth into distinct effects, providing knowledge about structural and competitiveness-related changes in international trade. The CMS methodology, originally developed by Tyszynski (1951) and later formalized by Richardson (1971), is based on the premise that in the absence of competitiveness changes, a country's export market share should remain stable. Deviations from this baseline are interpreted as resulting either from changes in the product composition of exports or from a shift in relative competitiveness. This methodology has been extensively used in international trade research, particularly in agricultural markets (Ahmadi-Esfahani, 1995; Capobianco-Uriarte et al., 2017; Zdráhal et al.). The CMS model used in this study builds on the modifications introduced by researchers such as Ahmadi-Esfahani (1995), who adapted the approach to specific agricultural contexts, and Capobianco-Uriarte et al. (2017), who applied it to assess competitiveness in fresh fruit exports.

In CMS analysis, each country was analysed separately. Thus, the change in Türkiye's hazelnut export performance for each country was determined by three CMS component and besides, CMS analysis was first used by Tyszynski (1951), later formalized by Leamer and Stern (1970) and developed in our use by Fagerberg and Solie (1987). CMS analysis is mainly used to inspect the changes in a country's export performance for certain markets and periods. If CMS analysis is implemented one to one country, it explains the transformation with three components, which are Market Share Effect (MSE), Commodity Composition Effect (CCE), and Commodity Adaptation Effect (CAE). In this study, the CMS model is implemented through a three-component analytical framework: (1) the MSE, which captures changes in Türkiye's share of a given market, indicating competitiveness dynamics; (2) the CCE, which reflects how the weight of lemons within the overall import portfolio of the target market changes over time, highlighting whether lemons are a suitable export product for that market; and (3) the CAE, which evaluates Türkiye's ability to align its export profile with changing import demand structures in destination markets. Each pairwise comparison yields values for the three CMS components, which are MSE, CCE, CAE, enabling a disaggregated assessment of export performance drivers. This analytical structure allows the identification of whether changes in Türkiye's hazelnut exports are primarily due to competitive gains, structural alignment with market demand, or product-specific preferences. The methodological formulation and explanation of the CMS components are illustrated in Figure 1, serving as a conceptual reference for the empirical analysis presented in the results section.

$S_{ij} = \frac{X_{ij}}{\sum_{i=1}^{N} Mij} = a_{ij} b_{ij}$	$\boldsymbol{X_{ij}}$: Country $\boldsymbol{a}$'s export of commodity $\boldsymbol{i}$ to country $\boldsymbol{j}$
$a_{ij} = {X_{ij}}/{M_{ij}}$	$\boldsymbol{M_{ij}}$: Country $\boldsymbol{j}$'s import of commodity $\boldsymbol{i}$
$b_{ij} = {M_{ij}}/{\sum_{i=1}^{N} Mij}$	$\boldsymbol{S_{ij}}$: Market share of country $\boldsymbol{a}$'s export of commodity $\boldsymbol{i}$ in country $\boldsymbol{j}$'s imports
$\Delta S_{ij} = S_{ij}^{1} - S_{ij}^{0} = a_{ij}^{1} b_{ij}^{1} - a_{ij}^{0} b_{ij}^{0}$	$\boldsymbol{a_{ij}}$: Commodity share of country $\boldsymbol{a}$'s export of commodity $\boldsymbol{i}$ in country $\boldsymbol{j}$'s import of $\boldsymbol{i}$
$\Delta S_{ij} = (a_{ij}^{1} - a_{ij}^{0}) b_{ij}^{0} + (b_{ij}^{1} - b_{ij}^{0}) a_{ij}^{0} + (a_{ij}^{1} - a_{ij}^{0})(b_{ij}^{1} - b_{ij}^{0})$	$\boldsymbol{b_{ij}}$: Commodity share of $\boldsymbol{i}$ in country $\boldsymbol{j}$'s import
$\Delta S_{ij} = (a_{ij}^{1} - a_{ij}^{0}) b_{ij}^{0} + (b_{ij}^{1} - b_{ij}^{0}) a_{ij}^{0} + (a_{ij}^{1} - a_{ij}^{0})(b_{ij}^{1} - b_{ij}^{0})$	**0** and **1**: The change between time
$MSE = (a_{ij}^{1} - a_{ij}^{0}) b_{ij}^{0}$	***MSE:*** The effect of changes in micro shares of country $\boldsymbol{a}$ commodity.
$CCE = (b_{ij}^{1} - b_{ij}^{0}) a_{ij}^{0}$	***CCE:*** It indicates whether country $\boldsymbol{a}$ has concentrated on the export of rapidly growing commodities.
$CAE = (a_{ij}^{1} - a_{ij}^{0})(b_{ij}^{1} - b_{ij}^{0})$	***CAE:*** Adaptability of country $\boldsymbol{a}$ to the changes in commodity composition.

Figure 1. Formulations and explanation of constant market share (CMS)

3. Results

3.1.Hazelnut import profile of selected European countries

Türkiye's hazelnut export to EU28 is 148,556 tons and 93.44 % % of this export is made to selected 6 European countries. The countries to which Türkiye exports the most hazelnuts in the European market are Italy, Germany, France, Poland, Netherlands and Spain, respectively in 2021. While Italy imported approximately 40 thousand tons of hazelnuts in 2010, its import amount reached nearly 70 thousand tons in 2021. Although there is an increasing trend between the 2010 and 2021, increases and decreases were observed when analysed on an annual basis. Whereas France imported more than Germany' hazelnut amount, which is nearly 19 thousand tons, in 2010, Germany started to import more than France in 2016 and afterwards imported more than twice the amount of France's imports until 2021. Although Poland's hazelnut imports doubled from 2010 to 2021, import quantity of Netherlands and Spain remained nearly at the same levels, which are below 5 thousand tons (Figure 2).

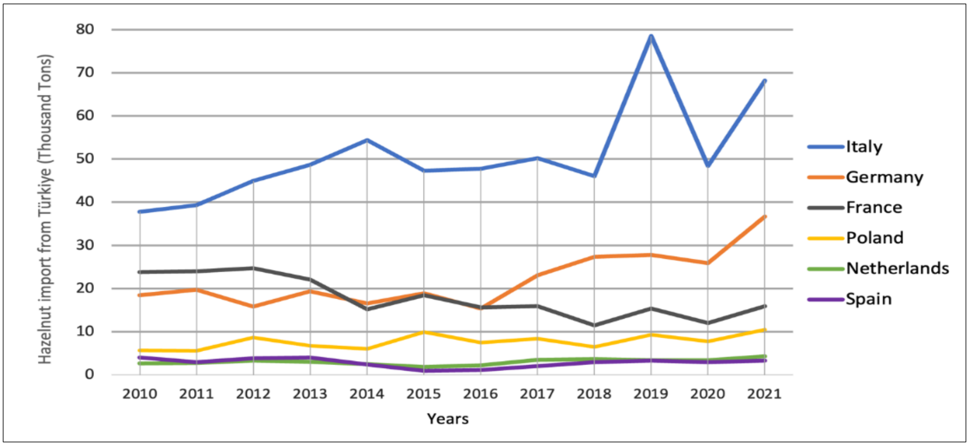

Figure 2. Temporal evolution of the main 6 importers in the European market for hazelnuts kernels exported by Türkiye

3.2. Türkiye's hazelnut export performance in selected European Countries

Türkiye's export performance in the selected European Countries was evaluated using CMS analysis. It was calculated by taking the average of 3 periods determined between 2010-2021 for CMS analysis. Thus, three different CMS analyses have been made for selected countries, allowing us to explain the change of Türkiye's share in the selected country's market and the reasons behind this change with a three components structure. The first of these components is the market share effect, which reflects the increases and decreases in the target market share. The second component, the commodity composition effect, shows the variation of hazelnut imports in the selected target market compared to total imports, in other words, whether hazelnut is a correct export product for the selected target market. The third and last factor, the effect of adjustment to the composition of goods, shows whether Türkiye has adapted to the changes in the import compositions of the selected country's markets (Table 1).

Table 1. Result of the Constant Market Share (CMS) Analysis (%)

	Periods[1]	MSE	CCE	CAE	Total
Italy	**I vs. II**	**-127.06**	407.51	**-88.77**	191.69
	I vs. III	**-155.06**	1225.09	**-325.67**	744.36
	II vs. III	**-47.56**	639.48	**-39.25**	552.67
Germany	**I vs. II**	**-15.95**	**-60.15**	1.39	**-74.72**
	I vs. III	52.56	9.91	0.75	63.23
	II vs. III	84.37	66.03	9.36	159.76
France	**I vs. II**	**-14.33**	89.05	**-2.76**	71.96
	I vs. III	**-40.43**	170.95	**-14.92**	115.61
	II vs. III	**-31.12**	79.37	**-4.62**	43.64
Poland	**I vs. II**	**-14.34**	5.30	**-2.10**	**-11.14**
	I vs. III	43.85	65.82	79.72	189.39
	II vs. III	66.70	36.56	97.27	200.53
Netherlands	**I vs. II**	6.82	43.19	4.47	54.48
	I vs. III	26.90	41.43	16.90	85.23
	II vs. III	28.37	15.69	4.33	48.39
Spain	**I vs. II**	**-67.54**	**-70.94**	25.50	**-112.98**
	I vs. III	**-34.14**	**-33.87**	6.15	**-61.85**
	II vs. III	20.79	23.75	6.59	51.13

[1]Periods: Period I includes between the years of 2010 and 2013, period II includes between the years 2014 and 2017 and lastly period III includes between the years of 2018 and 2021. Numbers in bold mean loss. Source: Compiled by authors using data from International Trade Centre (2021) database.

3.3. CMS analysis 2010-2013 (Period I) vs. 2014-2017 (Period II)

According to the results of the first analysis (Period I vs. Period II), Türkiye's market share increased in Italy, France and Netherlands, respectively. In these countries, most of this increase is due to CCE. In other words, hazelnut imports in these markets increased faster than the imports of other products. MSE and partially CAE support Türkiye's market share increase in the Netherlands. In other words, hazelnuts import increased more than the total imports of goods and Türkiye showed a rapid adaptation to this increase. MSE and partially CAE limited market share increase in Italy and the Netherlands. Türkiye's market share decreased in Germany, Poland and Spain. While the most important reason for this loss in Germany and Spain is the MSE and CCE, it is MSE and CAE in Spain.

3.4. CMS analysis 2010-2013 (Period I) vs. 2018-2021 (Period III)

According to the results of the second analysis (Period I vs. Period III), Türkeye's market share increased in Italy, Poland, France, Netherlands and Germany, respectively. In these countries, most of this increase is due to CCE, which means that hazelnut imports in these markets increased faster than the imports of other products. For the Germany, Poland and Netherland markets, all three components had a similar effect, increasing Türkiye's market share. While MSE partially limited the increase of Türkiye's market share, CAE mostly limited increase of Türkiye's market share in the Italy and France markets. Only for Spain market, Türkeye's market share has decreased. This decrease is due to MSE and CCE, of which effect levels is very close. CAE has an increasing effect but the level of its effect has been very low.

3.5 CMS analysis 2014-2017 (Period II) vs. 2018-20121 (Period III)

According to the results of the third analysis (Period II vs. Period III), Türkiye's market share market share increased in the selected all countries, which are Italy, Poland, Germany, Spain, Netherlands and France, respectively. While CCE is the main reason of the increase for Italy, France and Spain, MSE for Germany and Netherlands and lastly CAE for Poland. Although MSE and CAE suppressed Türkiye's market share in Italy and France, these two components increased Türkiye's market share in Germany, Poland, Netherland and Spain.

4. Conclusion

In this study, the change of Türkiye's market share (for hazelnut kernel basis) in 6 European countries was analysed separately by using CMS analysis. The change in Türkiye's market share is divided into 3 effects. The first effect is the MSE resulting from the change in the hazelnut expor of Türkeye in the hazelnut import of each country. The second effect is the CCE resulting from the change in the ratio of the importing country's hazelnut imports to the imports of all products. The third effect is the CAE, which shows how well Türkiye's exports adapt to the change in the import composition of the importing country. Türkiye's market share in Italy, France and Netherlands increased for all periods. Besides, when investigated last two periods (2014-2017 vs. 2018-2021) Türkiye's market share increased for all countries. However, there are some components surpassing this increase depending on countries. MSE and CAE had negative effects for Italy and France, while all three components had positive effect for the other countries. Türkiye were able to increase market share only with the positive contribution of CCE in Italy and France. In order to ensure sustainable growth in these two big importer countries, it is necessary for Türkiye to turn the negative components into positive. Policymakers and exporters should focus on these unsuccessful performance areas.

Disclosure statement

The authors report there are no competing interests to declare

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CHAPTER 3

Cultural History and Systematic Place of Apple Growing in the World

Selma Boyacı[1]

INTRODUCTION

While the exact origin of the apple is unknown today, it was likely cultivated from the extensive apple forests of Central Asia, particularly Kazakhstan. Because of its unique characteristics, people collected and spread the most popular apple varieties. Apple remains have been found at historical sites dating back to 6500 BC. Long-distance trade routes between the Mediterranean region and various parts of Asia developed as early as 3500 BC, encouraging the spread of both fresh and dried apples. Theophrastus (c. 320 BC) studied apples brought to Greece from Alexander the Great's conquests. He described grafting and general tree care, as well as dwarf apple varieties later used as rootstocks. Members of both the Christian and Islamic faiths played a role in the spread of apples to Europe, Africa, and the New World. By 1826, the Royal Horticultural Society of England had identified 1,200 apple varieties. Commercial production of apples began as complementary trees in gardens and as hedge trees on field margins or pastures. Apples are commercially produced in most temperate countries around the world, as well as in some high-altitude tropical regions. Over the last 100 years, production has been increasingly intensified through the use of dwarfing rootstocks and training systems designed to increase orchard productivity. The apple is unique among fruit species in that it possesses a variety of rootstocks that allow modern orchardists to develop "designer tree size" systems tailored to their training systems and management skills. The development of herbicides, insecticides, and fungicides over the last 50 years has enabled the production of high-quality fruit in many regions where production was previously difficult. Today, as research becomes more sophisticated, there is a growing trend to reduce pesticide inputs through integrated production systems or organic production. Apple growers are developing high-quality varieties resistant to the most serious pests through both traditional breeding and genetic engineering. Research in storage and postharvest handling techniques has significantly improved fruit quality, and apples are now available as a quality product year-round. Many of these current cultural practices are based on research results from detailed studies of the effects of various aspects of the environment on apple growth and development (Ferre and Warrington, 2003).

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The Place of Apple in Systematics

Apples are the most commonly produced temperate fruit species. They shed their leaves during the winter dormancy period. Growing as trees or shrubs, apples are perennial woody plants. While they generally bear fruit, some forms are used as outdoor ornamental plants in parks and gardens. Flowers typically have five petals, five sepals, numerous stamens, and a pistil with compound carpels. The pistil usually consists of five carpels (fruit leaves). The number of styles equals the number of carpels (Özçağıran et al., 2011).

Apples have a high haploid base chromosome number of n=17, and when morphological characteristics are considered, they are generally considered monophyletic (Kalkman, 1988; Phipps et al., 1991).

The apple's place in the plant world is defined as follows.

Division : *Spermatophyta*

Subdivision : *Angiospermae*

Class : *Dicotyledoneae*

Family : *Rosaceae*

Subfamily : *Pomoideae*

Genus : *Malus*

Species : *Malus communis, Malus pumila, Malus sylvestris, Malus baccata, Malus prunifolia, Malus coronaria, Malus ioensis*

There has been a long-standing debate regarding the scientific name of cultivated apples. Various sources give names such as *Malus communis, Pyrus malus, Pyrus malus* var. *paradisiaca, Malus sylvestris*, *Malus sylvestris* var. *mitis, Malus domestica*, and *Malus pumila* Miller. (Juniper and Mabberley, 2006).

Malus domestica (Phipps et al., 1991) and *Malus* x *domestica* Borkh (Korban and Skirvin, 1984) are known as cultivated apples worldwide, while *Malus sieversii* is known as the wild apple of Central Asia. The exact number of species within the *Malus* genus worldwide is unknown. Some authors report only 8 species worldwide, while others report 78 (Atay and Atay, 2011). Özçağıran et al. (2011) reported that there are approximately 30 apple species growing naturally in Asia, Europe, and North America. The characteristics of some apple species are listed below.

Malus communis (Lam.) Poir.: Synonyms for this species are *Pyrus malus* L. and *Pyrus sylvestris* Moench. *Malus communis* is widespread in Western, Central, and Eastern Europe, Anatolia, the Caucasus, Turkestan, and the

Himalayas. The trees are 12-15 m high, vigorous, and long-lived. They are used as rootstocks for cultivated apples.

Malus pumila Mill.: M. pumila, synonymous with *Pyrus pumila* Mill., is widespread in Southeastern Europe, Asia Minor, the Caucasus, Afghanistan, and the Altai Mountains. M. pumila represents dwarf apples. Plants develop as medium-vigorous or dwarf trees or shrubs. The root system is medium-vigorous or weak. It rarely forms a taproot. It forms abundant, superficially developing hairy roots. Apple varieties grafted onto it bear fruit earlier. Trees are short-lived. It can be propagated vegetatively (cuttings, layering, etc.). This species has several important varieties. One of these is M. *pumila* var. *domestica* (Borkh.) Schneid. It is suggested that most European cultivated apple varieties originate from this variety. Another variety is *M. pumila* var. *paradisiaca* Schneid. Also known as the Paradis apple, this variety is the source of important dwarf apple rootstocks. This variety is widespread in the Balkans and Western Asia.

Malus sylvestris Mill.: This variety has the widest distribution among wild apples. Its range begins in Western Europe and extends uninterruptedly through Central and Eastern Europe, Anatolia, the Caucasus, and Iran to the eastern regions of Turkestan. Forms of this species vary in color, shape, fragrance, and flavor in Anatolia, the Caucasus, and Central Asia. This very small-fruited species is most common in Türkiye in Northeastern Anatolia and the regions extending from here to the Taurus Mountains and the Eastern Taurus Mountains. The trees are large, reaching 12-16 meters in height, and have strong roots. The fruits are very sour even when ripe.

Malus baccata (L.) Borkh.: Known as the Siberian wild apple or cherry apple, its homeland begins in the Northern Himalayas, encompassing Northern China and extending into Siberia. Because it is a highly cold-resistant species, it has been used to develop cold-resistant rootstocks and cultivars. Trees can reach heights of up to 9-12 m. The crown is round and densely branched. The fruits are small (1.0-2.5 cm in diameter) and lack sepals. The root system consists of superficial fibrous roots. It is propagated vegetatively.

Malus prunifolia Borkh.: Known as the plum-leaf wild apple. It is native to Siberia and Northern China. The trees have a pyramidal crown shape. The fruits are small and form numerous fibrous roots.

Malus coronaria Mill.: Known as the American wild apple. It is widespread in the eastern states of North America. The trees are small, spreading, and densely branched. Its fruits are long-stemmed, flattened at both ends, and yellowish green. There are also ornamental forms with semi-double flowers.

Malus ioensis Britt.: Native to North America, it is widespread in the states of Indiana, Wisconsin, Missouri, Louisiana, Texas, Kansas, and Nebraska. It forms large trees. Its leaves are veined and rough-textured. Its cylindrical or hemispherical fruits are short-stemmed and green. The flesh is very firm (Özçağıran et al., 2011)

Figure 1.1. Appearance of *Malus* species (Lorenzo et al., 2009)

Figure 1.2. Appearance of *Malus* species (continued).

Cultural History of Apple Cultivation in the World

The origin of cultivated apples, currently cultivated in various parts of the world, is generally accepted as Central Asian. The word "apple" comes from the word "alma," which is used in the same sense in Kazakhstan. The city of "Alma Ata" (father of apples) in Kazakhstan is named after this word. Various sources have reported that *Malus sieversii* (Lebed), a wild apple species that grows naturally in Central Asia, is the primary progenitor of the cultivated apple (*Malus* x *domestica* Borkh) (Ponomarenko, 1986, Vavilov, 1987, Way et al., 1990;Juniper et al., 1998,). Wild *Malus sieversii* apples are distributed from the Altai Mountains on the borders of China, Kazakhstan, Kyrgyzstan, and Tajikistan to the shores of the Caspian Sea. However, the highest genetic diversity in this species is found around the city of Alma Ata (Elma Ata) in Kazakhstan (Luby et al., 2001). World-renowned plant explorer and geneticist Vavilov extensively identified the morphological variations in wild apples found in the forests of the mountainous regions of Kazakhstan. He reported that these wild apples, which bear fruits similar in size to those of today's cultivated apples, differed from the smaller wild apples of the Caucasus. He also pointed out that some of the apples growing naturally in these forests, superior in fruit size and flavor, may have been uprooted, brought to the orchards, and cultivated (Vavilov, 1987). These pioneering selections, thought to have been carried out in these regions, the ancestral homeland of the Turks, indicate that the Turks initiated apple culture worldwide.

Prehistoric remains and historical records examined by Morgan and Richards (1993) provide evidence of the cultivation, spread, and human use of apples throughout Asia and Europe over the past several thousand years. Archaeological apple remains have been found in Anatolia dating to 6500 BC, but it is impossible to know the origin of this fruit or whether it was ever cultivated. Historical evidence of apple cultivation dates back to the 2nd millennium BC, in Anatolia and northern Mesopotamia. By 500 BC, apples were likely widely cultivated throughout the Persian Empire, as orchards figure prominently in writings from this period. When Alexander the Great conquered Persia around 300 BC, fruit cultivation spread throughout the Greek world. During this period, the Greek philosopher Theophrastus distinguished sweet apples from the acrid wild apples.

The seeds and saplings of this valuable fruit, enjoyed by humans, spread via the Silk Road, which extended eastward from Central Asia to China and westward to Europe, used by commercial caravans (Juniper et al., 1998). Historical records indicate that apple cultivation was practiced in Anatolia and Northern Mesopotamia around 2000 BC. According to written documents regarding orchards in Iran, apple cultivation was widespread in the Persian Empire until around 500 BC. With Alexander the Great's conquest of the Persian Empire (around 300 BC), apple cultivation began to spread westward through the Greek world. Indeed, Theophrastus, a philosopher of this period, identified the differences between cultivated sweet apples and wild sour apples. With the rise of the Roman Empire, cultivated apples continued their spread northward and westward through Europe. Here, new varieties likely emerged through hybridization with the cultivated apple, *Malus sylvestris*. The Roman author Pliny described apple varieties. During this period, the Roman goddess Pomona was revered as the cultivator of apples and other fruits. In the following centuries, during the rise and spread of Christianity and Islam, apples were always held in high regard and protected. Orchard maintenance became a duty in monasteries, and the establishment of large apple orchards using *M. domestica* varieties was encouraged. Similarly, in the rising Islamic world of the Eastern Mediterranean and the Iberian Peninsula, fruit cultivation was considered a sacred practice based on Quranic teachings, and practices such as grafting, training, and pruning were reportedly highly developed (Luby, 2003). By 1826, at least 1,200 apple varieties were identified in England. Apples were introduced to South Africa in 1650, to Australia in 1788, and again to North and South America in the 16th and 17th centuries, spreading their cultivation worldwide (Luby, 2003).

Over more than two thousand years, cultivated apples have been developed through various breeding methods and have become one of the most consumed fruits worldwide. Currently, apple genetic resources are being studied to develop new apple varieties for various purposes. Starting recently, more than 50 researchers have examined genetic resources in Central Asia. These researchers are seeking important genetic traits: drought and cold tolerance, resistance to diseases such as black spot and fire blight, and to pests such as apple mealybug and soil-borne pathogens, fruit characteristics, tree habit, late flowering, resistance to sunburn, early fruiting, rooting ability, fruit storage characteristics, and chilling requirements. One of these researchers, Susan Brown of Cornell University's Department of Horticulture, is attempting to obtain and evaluate genetically dwarf varieties from the seedlings of wild apples, which Kazakh scientists have identified as dwarf (Luby et al., 2001).

Global interest in studying apple genetic resources is increasing for the breeding purposes mentioned above. Botanically, the apple belongs to the Malus genus of the Roseaceae family, and 11 gene centers have been identified worldwide (Table 1.1). Some *Malus* species distributed within these gene centers are shown in Table 1.1.

Table 1.1. World apple gene centers (Moore and Ballington, 1991).

Centers	Class
Avrupa Kıtası	*M. pumila* M., *M. sylvestris* M.
Küçük Asya (Anadolu)	*M .pumila* M.
Himalaya	*M .sikkimensis* W.
Güneybatı Çin	*M. prattii C.S., M. yunnanensis* C.S.
Güneydoğu Çin	*M. micromalus* M.
Güneydoğu Çin Merkez Çin	*M. hupehensis* R., *M. honanensis* R.
Kuzeybatı Çin	*M. sieversii* M.R., *M. kansuensis* C.S.
Kuzey & Kuzeydoğu Çin	*M. prunifolia* B., *M. asiatica* N., *M. baccata* B.
Japonya	*M. baccata* B., *M. halliana* K., *M. sieboldii* R.
Kore	*M. prunifolia* B., *M. asiatica* N., *M. baccata* B.
Kuzey Amerika Kıtası	*M. fusca* C.S.

Table 1.2. Apple (*Malus*) species (Lorenzo et al., 2009).

Species	Species
1. *M. sieversii*	20. *M. tschonoskii* (Maxim.) Schneid
2. *M. orientalis*	21. *M.*x *arnoldiana* (Rehd.) Sarg. (*baccata* x *floribunda*)
3. *M. sylvestris*	22.*M.*x *atrosantiginea* (Spaeth) Sehneid (*halliana* x *sieboldii*)
4. *M. baccata* (L.) Borkh	23.*M. domestica* Borkh (M. *pumila* Miller)
5. M. *hupehensis* (Pampan.) Rehder	24. *M. hartwigii* Koehne (*halliana* x *sieboldii*)
6. *M. halliana* (Anon.) Koehne (Spontanea)	25. *M. micromalus*
7. *M. sikkimensis* (Wenzig) Koehne	26. *M.* x *purpurea* (Barbier) Rehd. (n*eidzwetzkyana* x *atrosanguinea*)
8. *M. sieboldii* (Regel) Rehder	27. *M.* x *soulardii* (Bailey) Brit (*ioensis* x *domestica*)
9. *M. toringoides* (Rehd.) Hughes	30. *M.* x *sublobata* (Dipp.) Rehd. (*prunifolia* x *sieboldii*)
10. *M. kansuensis*(Batal.) Schneid	31. *M. asiatica* Nakai
11. *M. transitoria* (Batal.)Schneid	32. *M.* x *dawsoniana* Rehd. (*fusca* x *domestica*)
12.*M. x iaojihensis* Cheng et Jiang	33. *M. floribunda* Siebold
13. *M. fusca* (Raf.) Schneid.	34. *M.*x *magdeburgensis* Schoch. (*spectabilis* x *domestica*)
14.*M. yunnanensis* (French) Schneid	35. *M.* x *platycarpa* Rehd. (*coronaria* x *domestica*)
15. *M. prattii* (Hemsl.) Schneid.	36. *M. prunifolia* (Willd.)Borkh
16.*M. honanensis* Rehd.	37. *M.* x *robusta* (Carr.) Rehd. (*baccata* x *prunifolia*)
17. *M. ioensis* (Wood) Brit	39. *M. spectabilis* (Ait.)Borkh
18. *M. coronaria* (L.) Mill	40. *M. zumi* (Mats.) Rehd. (*mandshurica* x *sieboldii*)
19. *M.angustifolia* (Ait) Michx.	

CONCLUSION

Apples are one of the most widely produced deciduous fruit species in the world. They are produced on all five continents. World apple production has exhibited a long-term growth trend since World War II. The growth rate slowed in the 1980s, but increased rapidly in the 1990s thanks to the remarkable expansion of production in China. Standard apple varieties, important in today's global trade, were discovered in Europe, Russia, North America, New Zealand, Japan, and Australia, beginning in the late 19th century. Among temperate climate fruit species, no other fruit is as universally valued, widely cultivated worldwide, and so closely associated with human social habits as the apple.

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CHAPTER 4

Smart (Precision) Agriculture

***Bahar Sancar*[1]**

1. INTRODUCTION

Agriculture includes the cultivation of plant and animal products (including forestry and fishing activities), the harvesting, transportation, preservation and sale of the products obtained from agricultural production by the producers (Karluk, 1999). Agricultural practices meet the basic nutritional needs of people. Since agricultural production is dependent on climatic conditions, risk and uncertainty are high. Therefore, supply and demand requests in agricultural production are flexible and vary (Turkoglu, 2015).

With the increase in the world population, the need for basic food also increases. While the world population was approximately 7.5 billion in 2016, it is expected to reach 8.5 billion in 2030 and 9.7 billion in 2050, given in Figure 1 (USCB, 2011). Parallel to this population growth, agricultural production is expected to increase by 70% in order to meet the basic food needs (FAO, 2017). In this case, there has been a significant increase in production with the green revolution that took place in the half of the 20th century, the cultivation of species that will achieve maximum efficiency, the use of chemical pesticides and fertilizers and the use of machinery, but the negative effects of the use of excessive chemical products on humans and the environment are also significantly higher (Bhandari, 2014; Walter et al., 2017). Along with these environmental problems, it has become obligatory to make some agricultural lands unusable, to get maximum efficiency in the minimum area and to do this in a sustainable and environmentally friendly way, due to the effects of incorrect agricultural policies and excessive water use in the world (Shamshiri et al., 2018).

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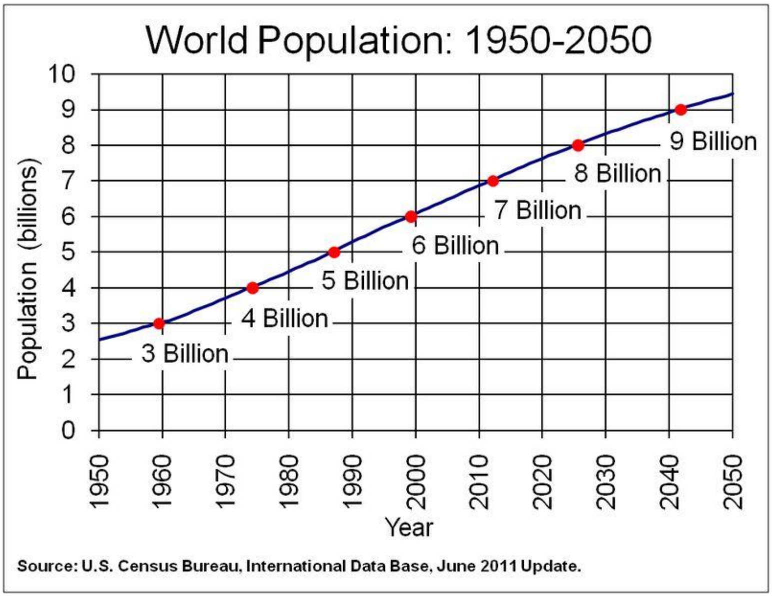

Figure 1. World population : 1950-2050

According to Vagsholm et al. (2020), it is considered inevitable to develop strategies to prevent these wastes and losses in production systems that strive to minimize losses and waste throughout the process of reaching the highest production from the producer to the consumer. The change process in agriculture is based on traditional farming systems, and smarter methods based on data obtained using a number of trend technologies should be included (Lioutas et al., 2021).

In addition to meeting the nutritional needs of the world population, agriculture has an indispensable place in the economy due to its features such as meeting the raw material source in the economy, industry, and contributing directly or indirectly to exports. As the population increases, environmental, social and economic impacts in agriculture are significantly minimized, increasing food production (Pittelkow et al., 2015; Lidicker, 2020, Pineiro et al., 2020; Ofosu et al., 2020; Singh and Singh, 2020; Tamburino et al., 2020). Agriculture plays a key role in the economy for the growth and development of many countries (Abioye et al., 2020). Agriculture accounts for 6.4% of economic productivity worldwide and is a dominant sector in nine countries (Pathan et al., 2020).

In agriculture, Russia has been the country with the highest growth rate since 2012 (Uzun et al., 2020). Agriculture in developing countries is inspiring to develop their economies in 50 years (Mueller and Mueller, 2016; Gusarova, 2019). In developed countries, agriculture acts as a bridge to increase their participation in the international agricultural market and brings them to the top in the sector (Scown et al., 2020; Veeck et al., 2020). Throughout all these agricultural developments, there is a 3.3% decrease in grain production (Minten et al., 2020). While some of this decrease is related to unsuitable weather conditions, it is related to the increased tolerance of diseases and pests and weed presence to chemical pesticides and the unconscious use of technologies in the production chain (Ding et al., 2011; Haile et al., 2019; Baributsa and Njoroge, 2020; Bendinelli et al., 2020; van Leeuwen et al., 2019).

Looking at the current population level, agriculture faces a number of challenges (ONDO, 2020). These difficulties are;

Deteriorated soil quality: The widespread use of chemical fertilizers, pesticides and herbicides has resulted in significant deterioration of soil fertility. Decreased soil quality leads to lower growth rates for all crops. This triggers the need to use more chemical fertilizers, pesticides and herbicides. Moreover, when chemical fertilizers are used in agriculture, they leach into the soil and pollute nearby water sources.

Climate change: The need for more agricultural products causes an increase in the demand for agricultural land. Forests are cut down so that the land can be used for agriculture. The lack of natural cooling factors leads to increased temperatures, which affects plants and their growth processes to a much greater extent, while adversely affecting humans.

Increasing consumption of natural resources: The agricultural sector consumes many natural resources such as water, soil, metals and fuel for agricultural machinery.

Carbon footprint: Another negative result of deforestation in order to provide agricultural land is to increase the amount of carbon in the atmosphere.

Decrease in biodiversity: Deforestation also means killing a wide variety of plants and reducing biodiversity. This in turn seriously affects the flora and fauna in the deforested area.

In traditional farming methods, practices such as excessive use of natural resources and intensive use of chemicals have made fertile lands unproductive and turned them into arid lands. Therefore, it has been understood that innovative practices in agriculture should be included. In this study, agricultural activities and their importance were mentioned and attention was drawn to the developments in the field of agriculture and the factors affecting agriculture from past to present. Afterwards, agricultural methods are explained in detail and why the need for new generation farming methods, their importance and advantages are mentioned.

2. SMART (PRECISION) AGRICULTURE

The rapid increase in the world population increases the demand for nutrition, which is one of the most basic needs of humanity, and new production models and modern agricultural practices that require high investment are developed as a sustainable solution to meet this demand (Smith et al., 2015). In order to meet the food demand of low-income consumers by reducing production costs, it requires the industrialization of the agricultural sector and the use of technology more intensively, given in Figure 2 (Anonymous 1, 2022). Technological solutions are widely used in many areas of the agricultural sector (Tripicchio et al., 2015; Zhang et al., 2015; Hu et al., 2019).

Figure 2. Smart agriculture

In the last periods of the 18th century and the beginning of the 19th century, which is the transition period to industrial and machine power thanks to technological inventions, the replacement of human power-based economic activities with machine power is called the Industrial (Industrial) Revolution. The Industrial Revolution, in its most general sense, refers to the transition to the mode of production in which machines are used effectively instead of human and animal power in production (Kuçukkalay, 1997; Guzel, 2014; Ozdemir, 2014; Ege, 2014). Industrial revolutions, which caused social, economic and cultural changes in the world, took place in certain stages over a long period of time. Therefore, in the period up to the present, 3 different Industrial Revolutions with different effects can be mentioned (Merry et al., 2015).

The first industrial revolution (1.0) emerged with mechanical systems and production benches using steam power. With the second industrial revolution (2.0), mass production was started with electrical energy. In the third industrial revolution (3.0), production was further automated with the development of the use of electronics and information technologies. The fourth industrial revolution (4.0) means reshaping the current understanding of production in the industry thanks to the developing science and technology, given in Figure 3 (Ulbrand, 2013; Burchill et al., 2016; Anonymous 2, 2022). When the industrial revolutions are examined, it is seen that it provides convenience in the production system in all processes. therefore, the fourth industrial revolution is expected to have new features that provide convenience for the production system. The Industrial Revolution (4.0) was first mentioned at the Hannover Messe in 2011. England pioneered the first industrial revolution. The fact that the fourth industrial revolution emerged in Germany allows it to be widely known in Europe and to be better known on a global scale. When the output of Industry 4.0 is examined, Germany and the USA, which lost their production power to countries such as India and China, aim to establish a production system based on more computer-controlled machine power by reducing the impact of manpower in production (Bangkok, 2019).

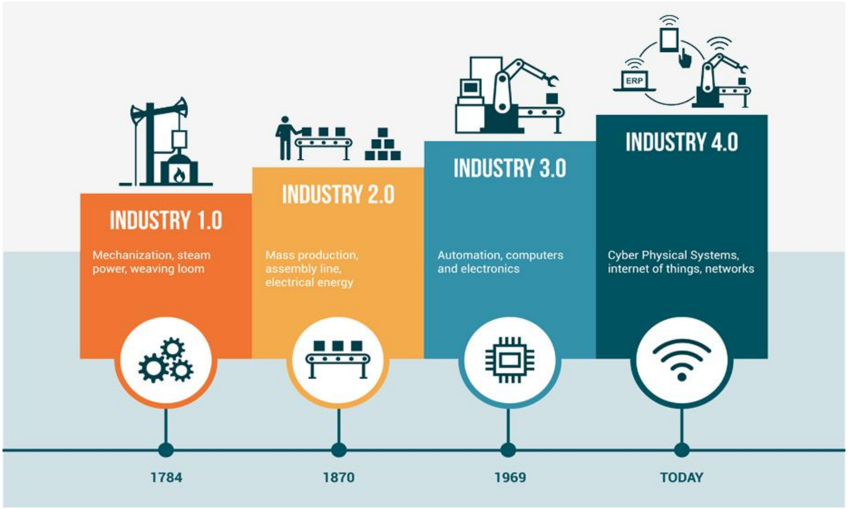

Figure 3. Industrial revolution

It is also known as Agriculture 4.0. Smart Agriculture represents the application of modern Information and Communication Technologies (ICT) to agriculture and can also be called the Third Green Revolution. The Third Green Revolution addresses the agriculture industry based on aggregation of ICT solutions such as precision equipment, Internet of Things (IoT), sensors and actuators, geolocation systems, Big Data, Unmanned Aerial Vehicles (UAV), Robotics etc (Mulla and Miamo, 2016). Smart agriculture means integrating technology into agriculture in order to increase production speed and maximize product quality. With its integration, it is the best use of technology in many parts of agriculture by evaluating issues such as population growth, climate change and workforce. Industry 4.0 is to integrate artificial intelligence technologies and sensors into unmanned aerial vehicles, satellites, robots and agricultural machinery, to meet the nutritional needs of the ever-increasing world population and to include innovative environmentally friendly methods and approaches for the sustainability of agriculture (Balafoutis et al., 2020). Differences between smart agriculture and traditional agriculture Table 1 is given (Balafoutis et al., 2020; Anonymous 3, 2022).

Table 1. Differences between smart agriculture and traditional agriculture

Smart Agriculture	Traditional Agriculture
Each farm is analyzed and applied to see the appropriate crop and water requirements for optimization.	Same set of practices for growing a crop across the region
Satellite images detect different regions in agricultural areas	Geotagging and region detection are not possible
Automated maintenance based on in-situ field and financial data showing profiles, returns and patterns in simple reports	Separate manual maintenance of all field and financial data leading to errors
Instant weather analysis and forecasting	No way to predict current weather conditions
Early detection and implementation in the affected area only, cost savings	Fertilizer and pesticide application across the field

It is predicted that there will be a 70% increase in food consumption, against the possibility that the world population will be more than 9.6 billion by 2050. The way to overcome this increasing need due to the limited arable land is to make the right plans (Sinha and Kumar, 2019). The main focus in the approach to smart agriculture is to increase agricultural productivity and incomes. With smart agricultural practices, productivity, sustainability and economy are aimed by collecting data from crop yield, fertilizer applications, soil mapping, weather effects and using expertise (Hostens, 2019). In addition, climate smart agriculture helps to reduce or eliminate greenhouse gas (GHG) emissions (Patil, 2019).

Among the smart agriculture methods, applications based on artificial intelligence and the internet of things provide real-time data to farmers and agricultural workers, determining the needs of plants such as irrigation, fertilization and spraying, early detection of diseases and pests, weed control, estimation of harvest time, production amount and It provides convenience and speed in a number of activities such as exploration, quantity, mapping, parcel division, which are necessary for field management, given in Figure 4 (Anonymous 4, 2022). The obtained data is processed and it is a platform connected to the web interface that generates the analysis results. This allows, for example, to monitor the cultivation areas by a single device and to intervene in any situation. Thus, factors such as minimizing labor and cost and maximizing productivity contribute positively to the welfare of those engaged in agricultural work and enable their youth to turn to agriculture (Kırkaya, 2020). Approaches and studies aimed at achieving maximum efficiency with the minimum input provided by smart farming methods have an important place. It is thought that smart agricultural practices will give agriculture a different direction and shape its future positively (Godde et al., 2020).

Figure 4. Smart agriculture

Smart agriculture has the potential to provide more productive and sustainable agricultural production based on a more resource efficient and precise approach. From the farmer's point of view, Smart Agriculture should provide added value to the farmer in the form of better decision making or more efficient business operations and management (Rose et al., 2021). In this sense, smart agriculture is strongly associated with three interconnected technology domains. These areas are Management Information Systems, Precision Agriculture and Agricultural automation-robotics (Rad et al., 2015; Mulla and Miamo, 2016; Okayasu et al., 2017).

- Management Information Systems are planned systems to perform the activities and functions of an agricultural area and to collect, process, store and disseminate data for the system.

- Precision Agriculture is defined as the management of spatial and temporal variability to improve economic returns and minimize environmental impacts. Conserving resources, optimizing the return of inputs by enabling the creation of spatial variability maps of many measurable variables such as crop yield, land characteristics/topography, organic matter content, moisture levels, nitrogen levels with GPS, GNSS, aerial imagery of drones and next generation imaging technology provided by satellites is intended. For this purpose, it includes Decision Support Systems (DSS) for the management of the entire agricultural area.
- Agricultural automation and robotics covers the process of applying robotics, automatic control and artificial intelligence techniques in all types of agricultural production, including farmbots and farmdrons.

2.1. Application Areas of Smart Technologies in Agriculture

Smart agriculture applications include unmanned aerial vehicles (drones), autonomous robots, smart applications on devices such as phones and tablets, and sensors that detect the inputs and status of inputs in the agricultural field and given in Figure 5 (Dastgheibifard and Asnafi, 2018; Kim et al., 2019; Anonymous 5, 2022). For example, autonomous robots are actively used in agriculture (greenhouse or open field conditions), they can do many jobs alone and provide maximum efficiency. Because of these features, it is used successfully in agricultural processes (Moorehead et al., 2010; Quoted by Vasconez et al., 2018). The usage areas of autonomous robots in agriculture are as follows, disease-pest and weed control / targeted applications, phenotyping, pruning, harvesting, product sorting, exploration of agricultural area and data collection, meteorology stations (Shamshiri et al., 2018b; Adamides et al., 2017; Oberti et al., 2013; Ishigure et al., 2013; Zhang et al., 2015; Comba et al., 2016; Kırkaya, 2020; Bauer and Aschenbruck, 2018).

Application areas of IoT-based remote sensing technology in agriculture include pH sensor, PIR (passive infrared) sensor, UV sensor, weed identification and pesticide application searcher, wind speed, water and soil content, soil moisture measurement, temperature, humidity and gas sensor, motion detector sensor, GPS, photoperiod and tensiometer are included (WMO, 1983; Santos et al., 1996; Arshak et al., 2007; Channe et al., 2015; Mat et al., 2016; Krishna et al., 2017; Suma et al., 2017; Boursianis et al., 2020; Yanes et al., 2020; Clay and Dille, 2021; Deepa et al., 2021; Kumar et al., 2021; Li et al., 2021; Yu, 2021).

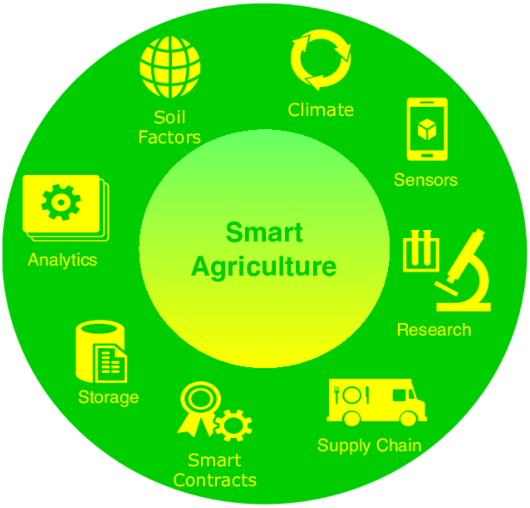

Figure 5. Smart agriculture application

Drone technology in agriculture connection with artificial intelligence technology includes areas of use monitoring plant health, monitoring the agricultural field and inspecting the health of conditions such as soil and field, planting seeds, planting seedlings, spraying liquids such as medicine, fertilizer, water, ensuring field safety, pollination of plants (Dastgheibifard and Asnafi, 2018; Kim et al., 2019). It can benefit from advanced technology in many parts of agriculture from planting to harvesting. Smart farming practices in the agricultural sector will be explained under headings.

2.1.1. Autonomous Robots

These vehicles, which perceive their environment without human support and have the ability to navigate and direct, are called "Autonomous Vehicles". Along with Industry 4.0, many tractor and agricultural vehicle manufacturers provide regular driving without the need for a driver who can adapt to smart agricultural applications. By using technologies and techniques such as radar (Srivastava et al., 2018), lidar (Coelho et al., 2020), GPS (Poonam and Mulge, 2013), odometry (Dagar et al., 2018), sensors, computer vision, they started the production of autonomous vehicles, mainly tractors and combines, which have a detection system (Marvin et al., 2016).

Figure 6. Autonomous robots

Land vehicles are designed as driverless, position information is determined autonomously, optional speed can be adjusted, and they are programmed to overcome obstacles that may be created by living or inanimate objects in the area and given in Figure 6 (Anonymous 6, 2022). During the installation of smart farms, people are still needed to create area and boundary maps, determine and program the most suitable routes to the area, carry out the planned basic operations and determine other working conditions. It provides convenience in operations such as less soil compaction, zero error risk, and savings in fuel, pesticides, seeds, fertilizers and labor, which can scan the entire area quickly and perform sensitive processing without being affected by weather conditions with its automatic steering systems and given in Figure 7 (Van Henten et al., 2002; Takai et al., 2011; Weiss and Biber, 2011; Biber et al., 2012; Moorehead et al., 2012; Anonymous 7, 2022).

Figure 7. Automatic system in agriculture

Automatic steering systems, with the different signal types and sensitivity values received from the satellite, do the steering themselves during the work and try to maximize the efficiency of the work. It is known that the use of these systems, especially in plants that need a certain row such as corn, cotton and sunflower, helps the correct use of inputs such as seeds, pesticides and fertilizers and reduces costs (Agrobot, 2020; Naio Technologies, 2016; FarmBot, 2021).

Figure 8. Agricultural robots

Agricultural robots are generally divided into two as open field and closed field robots, given in Figure 8 (Anonymous 8, 2022). Open field robots, GPS assisted steering system, spraying robots, pasture robots, silage robots, sowing/planting robots, pruning robots. Indoor robots are milking robots, harvesting robots and barn robots. Cultivation operations such as planting seeds, fertilizing, spraying and harvesting could be carried out by fleets of autonomous agricultural robots in the future (Emmi et al., 2014; Dastgheibifard and Asnafi, 2018).

2.1.2. Drones

The use of drone technology in many agricultural activities such as spraying is increasing, as well as detecting the moisture rate in the soil with aerial imaging and, accordingly, the detection of processes such as irrigation time, product monitoring, yield evaluation, diagnosis of diseases. Drones have been equipped with new generation technologies such as maintenance programming systems, cameras, GPS and location detection systems, and planned flight system (Silva-Perez et al., 2017). Thanks to drones, maps are created for early soil analysis, so that plans can be made for planting, irrigation and nitrogen supplementation. For example, by using drone technology, it will be possible to determine whether there is a problem by detecting soil quality, nutrient content or infertile areas of the soil with 3D maps in an agricultural land and given in Figure 9 (Anonymous 9, 2022). The products need regular spraying and fertilization in order to achieve maximum yield and maintain this yield. These operations can be done by hand, spraying machines or even an airplane. These methods affect efficiency, require intensive labor and cost high costs. Large tanks can be attached to drones to apply chemical fertilizers, pesticides or herbicides, given in Figure 10 (Anonymous 10, 2022). The use of drones (unmanned aerial vehicles) for spraying and fertilizing products is safer and more economical than other applications. Drones operate autonomously and can be scheduled to fly according to timetable and routes (Klerkx et al., 2019).

Figure 9. Drone technology

Figure 10. Drone technology

2.1.3. IoT Based Remote Sensing

IoT-based remote sensing is another smart technology in the field of agriculture, which is sensed by sensors positioned in the fields such as weather stations to obtain observations sent to analytical devices for analysis (Figure 11)

(Anonymous 11, 2022; Rajalakshmi and Mahalakshmi, 2016). IoT includes agricultural land real-time monitoring and forecasting systems (Bauer and Aschenbruck, 2018; Jon Deere, 2021). Farmers can follow their products from an analytical display screen and have the opportunity to intervene immediately in case of any problem. Many applications have been made in smart agriculture with the internet of things. Some of these applications are monitoring and automatic irrigation of agricultural areas (Mohanraj et al., 2016; Rajalakshmi and Mahalakshmi, 2016). Analysis of soil quality helps to determine the nutritional value and drier areas of farmland, soil drainage capacity or acidity, allowing to adjust the amount of water required for irrigation and to select the most beneficial planting type. It can also intervene in a timely manner to significant changes in humidity, water, air quality, and the health of crops and soil. This smart technology enriches the farming system by constantly monitoring all agricultural areas. IoT-based remote sensing system in agriculture farmers are engaged in agriculture to save time and prevent excessive use of natural resources (Barbedo, 2019; Silva-Perez et al., 2017).

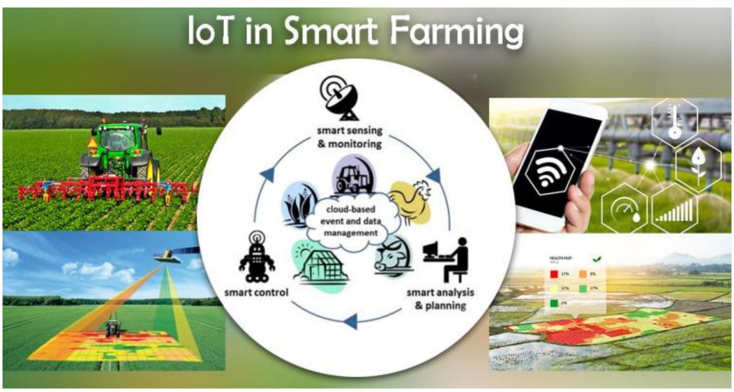

Figure 11. IoT in smart farming

Various sensors (soil PH, temperature, humidity, light intensity, etc.) are placed in the product area to measure different parameters. Each device is located on the network with its assigned IP (Internet Protocol) address for identification purposes. The data collected from the product area with the sensors is sent to the cloud using a gateway connected to the internet via wireless or other methods. Data in the cloud environment is analyzed or transmitted directly to farmers' smartphones or computers and given in Figure 12 (Anonymous 12, 2022). Thus, it is ensured that farmers take appropriate and as accurate decisions as possible (Gondchawar and Kawitkar, 2016; Rajakumar et al., 2018). Suma et al. (2017) conducted a study using wireless sensor networks to monitor soil properties and environmental factors. Various sensor nodes are located at different points of the farm. The control of the parameters in the system was made from any remote device or internet service. Operations are handled by interface sensors, Wi-Fi and cameras with microcontrollers.

Figure 12. Smart technology

Gondchawar and Kawitkar (2016) realized an intelligent irrigation system with intelligent control and intelligent decision making based on real control within the scope of the Internet of Things. Intelligent warehouse management including temperature maintenance, humidity maintenance and theft detection in the warehouse has also been developed in the study.

2.1.4. Smart Irrigation Systems and Smart Fertilization

Smart irrigation is applications based on the principle of providing water and nutrients directly and as needed to the roots of each plant in metered doses that keep the plant root zone at optimum moisture levels. Smart automatic irrigation solutions that feed the plant, not the soil, combine drip irrigation and automation systems to further increase the yield and savings from the product, given in Figure 13 (Anonymous 13, 2022). This prevents excessive water use and saves water (Kumar and Ramasamy, 2017).

Figure 13. Smart irrigation systems and smart fertilization

Fertilization, spraying and irrigation prescriptions are prepared by taking into account the weather and soil analysis parameters and the yield map of the field for the previous periods. Thus, it is possible to produce more efficiently and to minimize the damage to the environment. For example, the efficiency of the used manure/discarded manure by the plant is 20-40%. This means that only 200-400 kilos of a ton of fertilizer used/discarded can be taken by the plants, and the rest is washed in the soil. The purpose of smart fertilization is to calculate and apply the appropriate amount of fertilization to the soil at the appropriate time and amount (Bodake et al., 2018; Pallottino et al., 2021).

2.1.5. Smart Greenhouses

Greenhouse types that are compatible with the change in external weather conditions in a way that will provide the least input, and that can strategically manage the plant's water use, development, greenhouse climate, and plant food within the total automation management system are called greenhouse types. It has many advantages such as correct and automatic ventilation to provide instant climate control and balancing falling/rising indoor temperatures, adjusting radiation and CO_2 rates at levels that will not harm plant growth, pH balance, smart irrigation, fertilization and drainage system management, given in Figure 14 (Anonymous 14, 2022). The smart automation system in greenhouses is set up to monitor and report the situation inside the greenhouse to optimize product performance and operating costs (Wangmo et al., 2020; Hamdi et al., 2021).

Figure 14. Smart greenhouses

2.1.6. Animal Husbandry Applications

In animal husbandry practices in smart agriculture, it appears as Cattle Step and Location Tracking, Milk Measurement and Milking Systems, Tracking Solutions, Smart Barn/Pasture and Herd Management Systems, Poultry Tracking System, Hive Tracking System. Thanks to the appropriate low frequency (LF) RFID barcodes and tags, one of the animal tracking devices used to create an animal tracking system, it enables the tracking of cattle and small cattle in the most efficient way. These technologies provide an efficient method for rapid, safe and automated data collection for animal identification and given in Figure 15,16 (Anonymous 15, 2022; Anonymous 16, 2022). Thanks to these electronic tags, the farm management makes it possible to track, archive and report processes such as nutrition, weight measurement, disease management, reproduction completely electronically (Marchant, 2002; Helwatkar et al., 2014; Giordano et al., 2018; Kumar et al., 2021).

Figure 15. Animal husbandry applications

Figure 16. Animal husbandry applications

3. COMPARISON OF TRADITIONAL AGRICULTURAL METHODS AND NEW GENERATION AGRICULTURAL METHODS

New generation agriculture methods are popular applications in recent years, and most of the people dealing with agriculture have an idea about these applications but do not know the full content. As modernization and globalization become dominant, traditional agriculture methods, knowledge and experience have begun to lose their importance. As a result, agricultural practices have shifted to a system organized by businesses, not individually (Dastgheibifard and Asnafi, 2018). While new generation agricultural practices come to the fore with their features such as maximum yield and profit, product reliability, and minimum area, traditional agricultural practices come to the forefront as localization, biodiversity, protection and sustainability of genetic resources and production of a wide variety of products (Kim et al., 2019).

The transition from traditional agriculture methods to new generation agriculture methods has significant impacts on the biodiversity of cultivated and wild plants and the protection of genetic resources. In the face of increasing environmental problems, it is essential that agriculture be sustainable in order to ensure and maximize food security (Baributsa and Njoroge, 2020). Cultural and biodiversity is inevitable for agricultural resilience, if successful results cannot be obtained from a method or product, there is a chance to go back and try again. Therefore, traditional agriculture methods should be continued as well as new generation agriculture methods. New generation agriculture methods have many positive effects as well as negative aspects compared to traditional agriculture and Table 2 is given (Balafoutis et al., 2020).

Table 2. Comparison of traditional agriculture methods and new generation agriculture methods

	Traditional Agriculture	**New Generation Agriculture**
Equipment	It is made using legacy practices and traditional equipment. Plowing fields using oxen or horses is an example.	Made using modern and technical methods. The use of driverless tractors to plow the field is an example.
Cultivation	The products are made using high yielding seed varieties.	The crops are grown using High Yielding Variety (HYV) seeds.

Irrigation	Irrigation is done with ancient techniques. Therefore, the groundwater level does not fall.	Irrigation is done using tube wells. Therefore, the groundwater level is gradually depleted.
Labor	This type of farming offers more labor and more job opportunities for local people.	Job opportunities are fewer as machines are required for most of the processes.
Productivity	Production is low as traditional seeds and natural fertilizers are used.	Yield is high due to the use of HYV seeds and chemical fertilizers (agriculture).
Soil Fertility	Soil Fertility does not deteriorate due to the use of natural fertilizers.	Soil fertility gradually decreases due to the use of chemical fertilizers (agriculture).
Biological and cultural diversity	In this method, it is constantly maintained.	In this method, biological and cultural diversity is not preserved.

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CHAPTER 5

Molecular Traceability and Challenges in Protecting Geographical Indication Products

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INTRODUCTION

Geographical Indication (GI) products are commodities whose unique characteristics, quality, and reputation are intrinsically linked to their geographical origin. These include agricultural goods, foodstuffs, and beverages, which hold substantial economic, cultural, and trade value. The importance of GI products extends far beyond their market price, as they represent the rich history, craftsmanship, and traditions of the regions they originate from (Shafi, 2022). From the renowned Parmigiano Reggiano cheese of Italy to the delicate Darjeeling tea of India, GI products are deeply woven into the fabric of their respective cultures and often serve as a testament to local agricultural practices, biodiversity, and culinary heritage (Becchi, Rocchetti, Vezzulli, Lambri, & Lucini, 2023; Besky, 2014).

In the global economy, GI products have become significant assets, generating employment opportunities and sustaining rural economies (Muça, Pomianek, & Peneva, 2022). By protecting the unique qualities of these products, GI certifications enable producers to command higher market prices, thus increasing their economic stability (C. Y. Li, Ban, Gao, Ge, & Xu, 2024; Menapace & Moschini, 2024). For instance, regions known for specific GI products have witnessed substantial growth in tourism, as consumers seek authentic experiences tied to these products. Additionally, GI products are crucial in maintaining biodiversity, as they often involve the cultivation and preservation of local plant varieties and animal breeds that might otherwise be threatened by industrial farming practices (De Rosa, 2015; Kennedy, Wang, Hunter, & Maundu, 2022; Mariani, Casabianca, Cerdan, & Peri, 2021).

However, globalization has amplified concerns regarding the authenticity and traceability of GI products (Katerinopoulou, Kontogeorgos, Salmas, Patakas, & Ladavos, 2020; Piatti & Dwiartama, 2020). As the demand for these goods grows,

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so does the temptation for counterfeiters to exploit their reputation. Counterfeiting, mislabeling, and fraudulent substitutions pose significant risks to both producers and consumers, threatening the economic benefits that GI certifications bring to authentic producers (Rupprecht, Fujiyoshi, McGreevy, & Tayasu, 2020). In response, molecular tracing techniques have emerged as a reliable scientific approach for validating the authenticity and geographic origin of GI-certified products. This chapter focuses on these molecular tracing techniques and the challenges of tracing the GI certificated products.

1. MOLECULAR TRACING TECHNIQUES OF GI-CERTIFICATED PRODUCTS

Geographical Indication (GI)-certified products require reliable verification methods to ensure their authenticity and prevent fraud. Molecular tracing techniques offer precise tools for confirming the origin and quality of these products by analyzing their genetic, chemical, or isotopic markers. In general, these methods fall into four main categories: DNA-based techniques, isotopic and elemental analysis, metabolomics, foodomics (Herrero, Simó, García-Cañas, Ibáñez, & Cifuentes, 2012), and proteomics, each offering distinct insights into a product's biological and chemical composition (Afzaal et al., 2022). These scientific techniques enhance supply chain transparency and regulatory enforcement, protect consumers from food fraud, and safeguard the cultural heritage of traditional products (El Sheikha, 2018). As the demand for origin-certified goods continues to grow, molecular tracing ensures compliance with GI regulations, preserving their economic and cultural significance in global markets.

2.1 Proteomics

Proteomics is the analysis that investigate the structures, functions, modifications, and interactions of proteins in a particular biological system at a specific time (Afzaal et al., 2022). It has a wide range of applications in the food industry, spanning various areas such as quality, traceability, optimisation, storage, nutrition and safety (Creydt & Fischer, 2018).

DNA represents an organism's genetic identity, while proteins reflect genetic and environmental influences. These properties make DNA and proteins useful for analyzing processed products and animal-derived foods, and for assessing their authenticity and quality (Creydt & Fischer, 2018).

The proteomics used to characterize GI products involve several key steps. First, it includes sample collection and preparation of protein extracts. Next, proteins are separated using different analytical techniques. At this stage, 2D gel electrophoresis (which separates proteins by isoelectric point and size) (Gygi, Corthals, Zhang, Rochon, & Aebersold, 2000) and SDS-PAGE (which separates by molecular weight) (Gallagher, 2012) are commonly employed. The third step is to characterize the proteins identified using mass spectrometry techniques, which determine their mass-to-charge ratio, MALDI-TOF (Greco et al., 2018) or LC-MS/MS (Gallien, Duriez, Demeure, & Domon, 2013). Finally, the resulting protein fingerprint is compared with reference databases, and peptides are matched with known proteins using bioinformatics software. For example, to identify of Parmigiano Reggiano cheese and establish its provenance, differentiation based on the protein profile is applied (Corrado, 2016). Similarly, in the identification of Iberico cured ham, muscle-specific proteins and post-translational modifications are examined (Gaspar et al., 2022).

2.2 Metabolomics

Metabolomics is the study of the small molecules found in biological samples, such as sugars, amino acids, organic acids, phenolic acids and lipids (Hu, Liu, & Liu, 2022). These metabolites are the end products of cellular processes, influenced by factors such as genetics, environmental conditions, agricultural practices, and geographical origin (Cassago, Artêncio, Giraldi, & Da Costa, 2021). Metabolomics involves analyzing the unique chemical composition of products to verify their geographical origin, production method and quality.

Unlike DNA and proteins, metabolites are closely related to the phenotype. As they reflect external factors, they are ideal for identifying biological information, as well as regional and quality differences, in products with geographical indications (Markos, Tola, Kebede, & Ogah, 2023). Metabolomics is particularly useful for such products if they are processed or fermented, as this breaks down DNA and proteins of plant or animal origin. The metabolomic workflow for tracking GI products comprises three steps. The first involves processing products such as wine, olive oil, honey and cheese, and extracting their metabolites using solvents such as methanol and water. The second step involves analytical techniques. For example, gas chromatography-mass spectrometry (GC-MS) is used to analyze volatile compounds in products such as wine (Ivanova et al., 2012), aromas (C. Li, Al-Dalali, Wang, Xu, & Zhou, 2022) and honey (Dekebo, Kwon, Kim, & Jung, 2018). LC-MS is used to identify volatile or polar metabolites (Fang, Liu, Xiao, Ma, & Huang, 2023). NMR is used for comprehensive, non-destructive metabolic profiling (Smolinska, Blanchet, Buydens, & Wijmenga, 2012), and FTIR is used for rapid screening and fingerprint analysis (Cebi, Bekiroglu, & Erarslan, 2023). A targeted analysis of phenolic amino acids is performed using high-performance liquid chromatography (HPLC) (Luykx & Van Ruth, 2008). Data analysis (Large, complex datasets (metabolite fingerprints), Multivariate statistics: PCA, PLS-DA; Machine learning tools for classification and prediction) takes place in step three (Liebal, Phan, Sudhakar, Raman, & Blank, 2020).

Various parameters are examined when researching the authenticity of GI products. For instance, catechins, amino acids and methylxanthines are analyzed in teas such as Darjeeling and matcha (De, Hazra, Das, & Ray, 2025), while sugars, methylglyoxal and organic acids are examined in honey (Sun et al., 2021). Cheese varieties are analyzed for volatile acids, peptides, and aroma compounds (Ma et al., 2024).

2.3 DNA-Based Fingerprinting Techniques

DNA-based methods are fundamental for tracing the genetic origins of plants, animals, or microbial communities associated with Geographical Indication (GI) products (Galimberti et al., 2013; Madesis, Ganopoulos, Sakaridis, Argiriou, & Tsaftaris, 2014; Wirta, Abrego, Miller, Roslin, & Vesterinen, 2021). The process begins with careful sample collection to avoid contamination, followed by DNA extraction using optimized protocols tailored to different product types. For instance, plant samples may require the use of the cetyltrimethylammonium bromide (CTAB) method (Richards, Reichardt, & Rogers, 2001), while animal products may undergo the phenol-chloroform extraction process (Ozdemir, Bener, & Akcay, 2024). Once the DNA is extracted, polymerase chain reaction (PCR) and quantitative PCR (qPCR) are employed to amplify specific DNA regions for species identification. These techniques target barcode regions that are known to provide reliable markers for different species. For plants, regions such as rbcL and matK are frequently used (Ferri et al., 2015), while cytochrome oxidase I (COI) is commonly utilized for animals (Waugh, 2007). For fungi and spices, internal transcribed spacer (ITS) sequences serve as ideal genetic markers due to their variability and specificity (Schoch et al., 2012).

High-throughput sequencing technologies, including Illumina, Oxford Nanopore, and PacBio, further advance DNA analysis by enabling large-scale sequencing of genomic data, allowing for the identification of complex genetic signatures in GI products (Kamilari, Tomazou, Antoniades, & Tsaltas, 2019). These technologies can process vast amounts of data quickly, making them ideal for high-volume product testing. For complex food matrices, such as honey and cheese, DNA metabarcoding offers a powerful method for identifying multiple botanical or microbial components in a single sample (Kamilari et al., 2019;

Wirta et al., 2021). By analyzing DNA from all sources in the matrix, metabarcoding allows for a comprehensive understanding of the product's genetic composition, ensuring that all ingredients are authentic and from the claimed origin.

Additionally, microsatellite markers (SSRs) and single nucleotide polymorphism (SNP) analysis are utilized to generate high-resolution genetic profiles that differentiate between regional varieties of crops (Grazina, Amaral, & Mafra, 2020; Verdone, Rao, Coppola, & Corrado, 2018). These molecular markers are especially useful in distinguishing subtle genetic differences between varieties of wine grapes, olive trees, and rice, which are crucial for verifying the authenticity of GI products. Microsatellite markers, with their high mutation rates, offer a precise method for distinguishing different populations or cultivars, while SNPs allow for even finer distinctions based on single-base genetic. Together, these DNA-based techniques provide robust tools for ensuring the traceability and authenticity of GI products, maintaining both their economic value and cultural integrity.

2.4 Isotopic and elemental analysis

Isotopic and elemental analysis techniques are powerful tools for tracing the geographical origin of Geographical Indication (GI)-certified products (Drivelos & Georgiou, 2012; Xu et al., 2021). These methods focus on measuring the isotopic ratios and elemental composition of a product, which are influenced by environmental factors such as climate, soil type, and water quality. The unique geographic conditions in a particular region leave a distinctive "fingerprint" on the products, which can be used to verify their authenticity and protect them from fraudulent claims (Camin, Bontempo, Perini, & Piasentier, 2016; Dehelean, Cristea, Puscas, Hategan, & Magdas, 2022). The two primary techniques in this category are Isotopic Ratio Mass Spectrometry (IRMS) and Inductively Coupled Plasma Mass Spectrometry (ICP-MS), along with Nuclear Magnetic Resonance (NMR) spectroscopy, which provides additional insights into the chemical composition of products.

2.5 Isotopic ratio mass spectrometry (IRMS)

Isotopic Ratio Mass Spectrometry (IRMS) is a highly sensitive technique used to measure the relative abundance of stable isotopes of elements such as carbon (C), nitrogen (N), oxygen (O), hydrogen (H), and sulfur (S). These isotopic ratios are influenced by environmental variables such as climate, soil composition, and altitude, all of which vary significantly between regions. The isotopic "signature" of a GI product reflects the environmental conditions in which it was produced, making IRMS a key tool for verifying its geographical origin (Dou et al., 2023; Schimmelmann et al., 2020; Zhao et al., 2020).

For example, in wine authentication, IRMS can distinguish wines from different regions by analyzing the carbon and oxygen isotope ratios in the water and grape sugars (Kokkinofta et al., 2017). The ratio of carbon-13 to carbon-12 (δ13C) is influenced by factors such as the type of soil and climate conditions, while the oxygen isotope ratio (δ18O) can indicate the regional water sources used for irrigation (Jiao et al., 2023; Reiffarth, Petticrew, Owens, & Lobb, 2016). Similarly, IRMS is used in coffee, tea, and dairy products to confirm their origin, as the isotopic composition of these products is shaped by the unique environmental conditions of the growing regions (Liu, Zeng, Zhao, & Tong, 2020a; Peng et al., 2019; Zhao et al., 2020).

Isotopic analysis can be particularly useful in cases where the DNA-based techniques may struggle, such as in processed products where DNA degradation occurs, or when products are blended from different sources. By examining isotopic ratios, IRMS can help trace the product back to its specific geographical origin, even in complex food matrices (Katerinopoulou et al., 2020).

2.6 Inductively coupled plasma mass spectrometry (ICP-MS)

Inductively Coupled Plasma Mass Spectrometry (ICP-MS) is another highly effective technique used for tracing the geographical origin of GI-certified products by analyzing their elemental composition. ICP-MS measures trace elements, including calcium (Ca), magnesium (Mg), strontium (Sr), and potassium (K), which can vary depending on the regional soil and water composition (Liu, Zeng, Zhao, & Tong, 2020b; Vezzulli, Fontanella, Lambri, & Beone, 2023). These trace elements accumulate in the product during its growth or production, and their relative concentrations create a unique elemental "fingerprint" (Vezzulli et al., 2023).

In the case of tea and coffee, the elemental composition of the leaves is influenced by the soil in which they are grown, as different regions contain varying levels of specific trace elements. Similarly, in dairy products like cheese or milk, the elemental signature can be influenced by the mineral content of the feed consumed by the animals and the water they drink (Mazarakioti et al., 2022). The ability of ICP-MS to analyze minute amounts of trace elements with high precision makes it an invaluable tool for detecting geographical variations in the elemental composition of these products.

ICP-MS is particularly useful for differentiating products produced in regions with distinctive soil characteristics (Mazarakioti et al., 2022). For example, the presence of specific trace elements such as strontium or lead can be used to confirm whether a product originates from a particular region with known geological features. In the case of wines, elemental analysis can help determine whether the product comes from a vineyard with particular soil conditions, as trace elements from the soil are absorbed by the vines and incorporated into the wine during production (Nardin et al., 2024).

2.7 Nuclear magnetic resonance (NMR) spectroscopy

Nuclear Magnetic Resonance (NMR) spectroscopy is another powerful analytical tool used to trace GI-certified products by providing detailed information about their chemical composition (Esslinger, Riedl, & Fauhl-Hassek, 2014). Unlike IRMS and ICP-MS, which focus primarily on isotopic ratios and elemental analysis, NMR spectroscopy offers a non-targeted approach that examines the molecular structure of a product by detecting the behavior of atomic nuclei in a magnetic field (Dimitrakopoulou & Vantarakis, 2023).

In the context of GI products, NMR can be used to generate a "chemical fingerprint" by analyzing the metabolites, organic compounds, and other chemical constituents present in the product. Similar example in wine, NMR can identify specific phenolic compounds and organic acids that are influenced by the grape variety and the terroir (the environmental factors such as soil, climate, and topography) (López-Rituerto et al., 2022). This allows NMR to distinguish wines from different regions, even when the grapes are from the same variety.

NMR is also widely used in the analysis of dairy products, oils, and beverages like tea and coffee (Q. Q. Li et al., 2017; Maestrello, Solovyev, Bontempo, Mannina, & Camin, 2022; Sobolev, Ingallina, Spano, Di Matteo, & Mannina, 2022). In olive oil, for example, NMR can differentiate between oils from different regions based on their fatty acid profiles and the presence of certain markers indicative of the specific production methods used (Maestrello et al., 2022). NMR spectroscopy is particularly valuable for differentiating products from regions with similar climatic conditions, as it provides more detailed chemical information compared to other isotopic or elemental techniques.

2. CHALLENGES İN TRACEABİLİTY OF GI PRODUCTS

While molecular tracing techniques provide powerful tools for ensuring the authenticity of Geographical Indication (GI) products, several challenges hinder their widespread application and effectiveness. These challenges span from technical limitations and lack of standardization to financial and logistical barriers that can impede full traceability in GI supply chains. Addressing these issues is crucial for realizing the potential of molecular methods in protecting GI products from fraud and misrepresentation.

3.1 Lack of standardized protocols

One of the most significant obstacles in the traceability of GI products is the absence of universally accepted standards for molecular authentication (Bayen et al., 2024; Kumar, Rani, Singh, & Kumar, 2022). Different regions and certification bodies may adopt varying protocols, creating inconsistencies in testing procedures and data interpretation. Without a unified approach, the effectiveness of molecular techniques in verifying GI authenticity can be compromised (Bayen et al., 2024). For instance, variations in the DNA extraction methods or sequencing platforms used across different laboratories may yield different results, making cross-comparison difficult. This lack of standardization not only affects the reliability of testing but also complicates the development of a comprehensive global database for GI products.

Moreover, while molecular methods are advancing, there remains a need for harmonized protocols between academic research, industry practices, and regulatory frameworks. Collaboration among international organizations and stakeholders is essential to create common guidelines that can be adopted globally, ensuring consistency and transparency in the traceability process.

3.2 Complexity of GI product supply chains

GI products often have intricate and multi-layered supply chains, with various stages of production, processing, and distribution spread across different regions. This complexity makes it difficult to track and authenticate products at every point in the chain. For example, a product like tea may pass through several stages—from field cultivation and harvesting to drying and packaging—each involving different actors (Miyake & Kohsaka, 2023). The challenge lies in ensuring that each of these stages maintains the integrity of the GI designation and complies with traceability protocols.

Additionally, for products like cheese or wine, which undergo significant processing such as aging, fermentation, or blending, tracking their authenticity becomes even more complex. In some cases, the molecular signatures of raw materials can change during processing, potentially complicating the identification of origin and authenticity. For instance, aging processes in wine or cheese may alter their chemical or isotopic profile, making it harder to trace the product back to its original source (Cardin et al., 2022; Popirda et al., 2021).

3.3 Cost and accessibility

While molecular techniques such as DNA sequencing and isotopic analysis are highly accurate, they often come with high costs (Katerinopoulou et al., 2020). For many small-scale producers, especially in developing countries, the expense of implementing advanced traceability technologies can be prohibitive. Laboratory analysis, equipment maintenance, and expert knowledge required for molecular testing represent significant financial burdens that may discourage producers from adopting these methods. As a result, the traceability system may be accessible only to larger producers with the necessary resources, leaving smaller producers vulnerable to fraudulent practices.

Moreover, even when small producers can afford testing, the lack of infrastructure in some regions may limit their access to advanced laboratory facilities. In such cases, ensuring the authenticity of GI products becomes a logistical challenge, as testing may require transporting samples to distant laboratories, causing delays and increasing costs further (Cardoso, Lourenzani, Caldas, Bernardo, & Bernardo, 2022; Tregear, Török, & Gorton, 2016).

3.4 Data interpretation and expertise

Molecular traceability involves the generation of large amounts of complex data, particularly when techniques like genomics, isotopic analysis, and metabolomics are employed (Bayen et al., 2024; Creek et al., 2012). While these methods provide a wealth of information, interpreting this data accurately requires a high level of expertise. Misinterpretation or errors in data analysis can undermine the effectiveness of traceability efforts and lead to incorrect conclusions about a product's authenticity (Charlebois, Sterling, Haratifar, & Naing, 2014). Additionally, as molecular methods evolve, keeping up with new technologies and analytical techniques can be resource-intensive, demanding continuous investment in training and capacity building.

The complexity of these techniques also necessitates the use of specialized software and bioinformatics tools to process and interpret data. As the scope of molecular traceability expands, it will be crucial to develop user-friendly platforms that can assist with data analysis and interpretation, making the process more accessible to a wider range of stakeholders, including producers, certifiers, and regulators.

3.5 Resistance to change

Another significant challenge in the traceability of GI products is resistance to adopting new technologies among producers and stakeholders in the supply chain. Many traditional producers may be wary of implementing molecular tracing techniques due to perceived costs, complexity, or lack of understanding (Lai, Vergamini, & Brunori, 2025; Masi, De Rosa, Vecchio, Bartoli, & Adinolfi, 2022). Additionally, there is often reluctance to adopt technologies that might expose vulnerabilities in established practices or reveal potential weaknesses in product quality or authenticity. Overcoming this resistance requires education and awareness campaigns to highlight the benefits of molecular traceability, including enhanced product reputation, market access, and consumer confidence.

Furthermore, the legal and regulatory frameworks around GI products are often slow to evolve (Schober, Balling, Chilla, & Lindermayer, 2023). Many certification systems and traceability models were developed before the advent of molecular technologies, and incorporating these tools into existing frameworks can be a complex and time-consuming process. Policymakers, regulators, and industry leaders must work together to integrate molecular traceability into established GI certification schemes, ensuring that these systems remain relevant and effective in addressing the challenges posed by modern global supply chains.

3.6 Fraudulent substitution of ingredients

In some cases, GI-certified products may be subject to fraudulent substitution of ingredients or misrepresentation of origin at specific points in the supply chain. Even when molecular methods are employed at the final stages of production, fraud can still occur earlier in the chain (Jurica, Karaconji, Lasic, Kovacevic, & Putnik, 2021; Lord, Elizondo, Davies, & Spencer, 2022; Romano et al., 2021). For instance, adulteration may take place during the raw material sourcing stage, where producers use non-GI ingredients and misrepresent them as authentic. In such instances, molecular traceability must be applied not only to the final product but also to earlier stages of production, requiring a more robust and holistic approach to authentication (Liberty, Lin, Kucha, Sun, & Alsalman, 2024).

Combating this form of fraud requires a comprehensive traceability system that spans the entire supply chain, from raw materials to finished products. This includes rigorous documentation, certification, and regular testing of intermediate products. As GI products are often highly valued in the market, continuous monitoring and enforcement efforts are critical to ensuring that fraudulent practices are detected and addressed promptly.

3. CONCLUSION

The authentication and traceability of Geographical Indication products are vital for preserving their economic cultural and heritage value. Molecular tracing techniques such as DNA based methods isotopic analysis and elemental profiling provide strong tools to verify the origin and authenticity of these products helping to combat fraud and build consumer trust. However challenges including lack of standardized protocols complexity of supply chains high costs need for specialized expertise and resistance to new technologies limit the widespread use of these methods. Overcoming these issues requires international cooperation harmonized regulations and greater awareness among producers and stakeholders. By addressing these challenges molecular tracing can effectively protect GI products support rural economies conserve biodiversity and maintain the cultural legacy embodied in these unique goods.

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CHAPTER 6

Jet Fuel Production From Renewable Feedstocks: Potential of Lignocellulosic Materials

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1. INTRODUCTION

Today, the growing global energy demand and escalating climate pressures have significantly increased interest in low-carbon and sustainable fuel alternatives. In high energy-intensive sectors such as transportation and aviation, the need for renewable resources that can replace conventional fossil fuels has become central to global sustainability strategies (IEA, 2021). In aviation, recent syntheses estimate that aircraft operations contributed ~2.4% of global fossil CO_2 in 2018 and a larger share of effective radiative forcing when non-CO_2 effects are included, underscoring the need for mitigation beyond efficiency gains (Lee et al., 2021). According to the International Civil Aviation Organization, the aviation sector currently accounts for approximately 2–3% of global CO_2 emissions, and this share is expected to triple by 2050 if no effective alternatives are implemented (ICAO, 2019).

The increasing challenges posed by climate change, unsustainable resource consumption, and ineffective waste management have intensified the urgency to replace fossil-based and non-renewable materials with safer, bio-based, and more sustainable alternatives. Fossil fuels not only contribute substantially to greenhouse gas emissions, but also involve hazardous production protocols and problematic end-of-life scenarios. Anthropogenic global warming has already reached approximately 0.87 °C and is projected to rise to 1.5 °C between 2030 and 2050, potentially triggering severe climate shifts, intensified droughts and floods, and critical risks to public health, food security, and water availability (Peace et al., 2020). To address these threats, robust policy actions must be paired with technological innovations that promote the substitution of pollutant-intensive resources with bio-based and non-toxic materials (Himmel et al., 2007; Cheng et al., 2011). In this context, lignocellulosic biomass stands out as a highly promising feedstock due to its natural origin, global abundance, low carbon footprint, and the functional versatility of its primary components. These attributes not only support climate mitigation goals but also enable the transition

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towards more resilient and secure energy systems by diversifying renewable resource options.

Furthermore, the integration of renewable feedstocks into manufacturing systems is increasingly recognized as a strategic step to minimize the environmental impacts of fossil fuel dependence while aligning with the principles of the circular economy and sustainable development. Bio-based systems utilizing agricultural residues, forestry by-products, and microalgae not only offer alternatives to fossil inputs but also serve as carbon sinks, thereby enhancing ecosystem resilience (Sawin & Moomaw, 2009; Cherubini, 2010). Their industrial-scale application is also aligned with global frameworks such as the United Nations Sustainable Development Goals (SDGs), particularly SDG 7 (Affordable and Clean Energy) and SDG 13 (Climate Action) (Nazari et al., 2021; Vera et al., 2022).

Within this transformation, lignocellulosic biomass emerges as a key renewable feedstock. Lignocellulosic materials particularly wood, lignin, and microalgae – are remarkable raw materials for the production of carbon-neutral or low-carbon fuels. Wood is a naturally renewable biological material that captures and stores atmospheric carbon through photosynthesis, and contains high levels of cellulose, hemicellulose, and lignin (Pettersen, 1984). These structural polymers are especially suitable for producing energy-dense liquid fuels via thermochemical conversion processes. The most important advantage of lignocellulosic materials is that they are waste-based, sustainable resources that do not directly compete with food production (Isikgor and Becer, 2015).

Lignin, an aromatic polymer found in plant cell walls, possesses a high energy content due to its carbon-rich structure. Industrial lignin is commonly obtained as a by-product during paper and biofuel production processes, such as kraft, sulfite, or organosolv pulping (Ragauskas et al., 2014). In recent years, lignin has been explored not only for energy applications but also for the development of high-value chemicals and nanomaterials, making it an attractive precursor for bio-based jet fuel production (Figueiredo et al., 2018). On the other hand, microalgae are another promising biomass feedstock due to their high lipid content and rapid growth capabilities. These non-food resources photosynthetically capture CO_2 and convert it into biomass, producing oils and carbohydrates with high volumetric efficiency under optimal conditions (Chisti, 2007; Brennan and Owende, 2010). With such properties, microalgae offer a compelling vision for sustainable and environmentally friendly fuel systems.

In this study, we present a comprehensive synthesis of the potential of lignocellulosic biomass (particularly residual woody feedstocks and lignin-rich sidestreams) for the production of sustainable aviation fuels. Rather than focusing solely on environmental impacts, this work explores the characteristics and conversion pathways of lignocellulosic materials, reviews recent advances in thermochemical and biochemical processes, and highlights the strategic role of biomass-derived jet fuels in the decarbonization of the aviation sector. By situating these insights within the broader context of circular bioeconomy principles and low-carbon transition strategies, the study aims to outline how lignocellulosic resources can contribute to scalable, resilient, and sustainable aviation fuel systems.

1.1. CHEMICAL STRUCTURE OF WOOD AND LIGNOCELLULOSIC PROPERTIES

Wood is primarily composed of three major biopolymers cellulose, hemicellulose, and lignin that together account for approximately 85–90% of its dry weight. These components form the structural framework of plant cell walls, conferring mechanical strength, flexibility, and resistance to environmental degradation. Cellulose, the most abundant constituent, is a linear polymer of β-D-glucose units organized into highly ordered microfibrils, which provide tensile strength and rigidity (Pettersen, 1984; Sjöström, 1993). Hemicelluloses, in contrast, are amorphous, branched heteropolysaccharides composed of pentose (xylose, arabinose) and hexose (glucose, mannose) sugars. They are more readily hydrolyzable than cellulose and act as a matrix material that binds cellulose microfibrils together, contributing to cell wall cohesion and flexibility (Isikgor and Becer, 2015).

Lignin is an irregular, three-dimensional aromatic polymer composed of monolignols namely p-coumaryl, coniferyl, and sinapyl alcohols. Its presence imparts hydrophobicity, rigidity, and decay resistance to the lignocellulosic matrix, making it critical for terrestrial plant evolution (Ragauskas et al., 2014). Besides these structural macromolecules, wood also contains extractives and ash-forming minerals in smaller proportions. Extractives are a diverse group of low-molecular-weight compounds such as terpenes, tannins, and phenolics, which influence the color, odor, and decay resistance of wood. Inorganic ash constituents like potassium, calcium, and silica are present in minor amounts but can affect combustion behavior and process residue in thermochemical conversions (Fengel and Wegener, 1984). Understanding this compositional complexity is essential for optimizing the conversion of wood into value-added products such as biofuels and biochemicals. Percentage values and chemical structures of the main chemical components of wood are summarized in Figure 1.

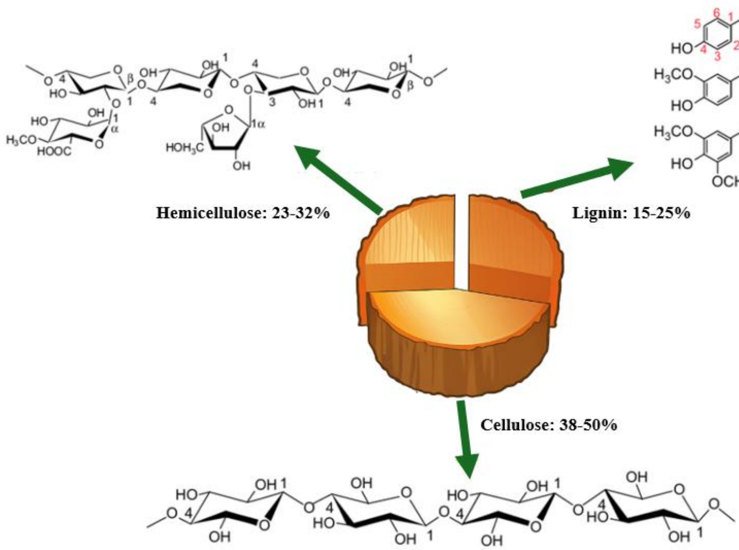

Fig. 1. Percentage values and chemical structures of the main chemical components of wood

2. THE USAGE AREAS OF LIGNOCELLULOSIC MATERIALS

Lignocellulosic biomasses are used in many different industrial areas due to their high carbon content, wide raw material diversity and biorenewability. First of all, energy and chemical sectors such as biofuel production (e.g., biodiesel, bioethanol and hydrocarbon-based jet fuels), bioplastic production and synthesis of bio-based chemicals come (Borrero-López et al., 2022; Mujtaba et al., 2023).

Lignocellulosic raw materials have great potential in the bio-based materials market. Cellulose nanofibrils, structural elements such as polylactic acid (PLA) and polyurethane matrix biocomposites, agricultural waste-based nanomaterials and lignin-based binders are used as recyclable alternatives in the bioplastic and construction sectors. Technological processes for these materials aim to increase mechanical performance while reducing the dependence on petrochemicals used in the plastics industry and the environmental impact.

Especially agricultural wastes and forest residues stand out as sustainable biomass sources that do not compete with food and are used to optimize the feedstock cycle in integrated biorefinery models (Mujtaba et al., 2023). Thanks to processes such as thermochemical conversion methods pyrolysis, torrefaction, hydrothermal liquefaction—lignocellulosic biomass is gaining value, especially in the production of high-energy-density biofuels and bio-intermediate products (Mujtaba et al., 2023). Value-added products produced from lignocellulosic biomass and their production methods are summarized in Figure 2.

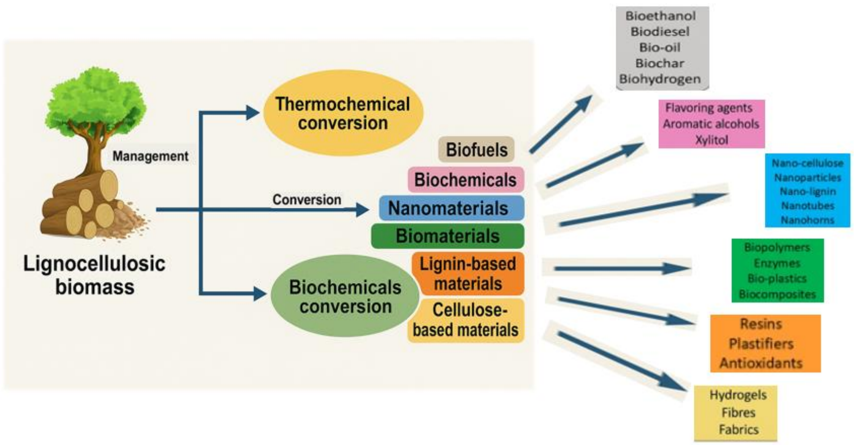

Fig. 2. Value-added products derived from lignocellulosic biomass via thermochemical and biochemical conversion pathways (adapted from Ingle et al. 2025).

Lignocellulosic biomass can be processed through both thermochemical and biochemical conversion processes to produce a wide variety of end products. Thermochemical conversion (e.g., pyrolysis, gasification, hydrothermal treatment, etc.) yields biofuels (biodiesel, biohydrogen, biochar, biooil) and various biochemicals (aromatic alcohols, sweeteners, xylitol, etc.). Polymer-derived materials such as lignin-based resins, plasticizers, and antioxidants can also be produced through this conversion.

Furthermore, biochemical conversion methods (enzymatic hydrolysis, fermentation, etc.) enable more precise and selective degradation of lignocellulosic structures, enabling the production of bio-based materials such as biopolymers, bioplastics, and biocomposites. These processes also form the basis for the production of nanomaterials derived from cellulose and hemicellulose (nanocellulose, nanotubes, nanolignin, etc.) (Ingle et al. 2025). Furthermore, the resulting biomaterials form the basis of advanced products that can be used in industrial applications, such as fibers, hydrogel structures, and textile fabrics.

These versatile transformation pathways demonstrate that lignocellulosic biomass offers the potential not only for energy production but also for the sustainable production of high-value-added products in many sectors, including chemical, materials, and environmental technologies. In this respect, lignocellulosic biomass is considered a fundamental building block of the circular bioeconomy.

2.1. LIGNIN: STRUCTURE, CHEMISTRY, AND CONVERSION POTENTIAL

Lignin is an amorphous, highly branched aromatic heteropolymer synthesized via oxidative radical coupling of three primary monolignols: p-coumaryl, coniferyl, and sinapyl alcohols (Del Río et al., 2012). These monolignols are biogenetically produced from phenylalanine via the phenylpropanoid pathway; their monomeric forms differ in terms of hydroxyl and methoxyl groups, and this structural difference determines the S/G/H ratio of lignin (Boerjan et al., 2003). The linkages formed during polymerization processes, such as β-O-4, β–β, β-5, and 5–5, give lignin a three-dimensional, covalently cross-linked structure. This complex structure integrates lignin with cellulose and hemicellulose in the cell wall, providing plants with water repellency, mechanical strength, and decay resistance (Boerjan vd., 2003).

Lignin valorization is directed towards energy carriers, platform aromatics (vanillin, phenol, guaiacol, BTX) and advanced materials (polyurethane/epoxy additives, activated carbon, carbon fiber) via thermochemical (pyrolysis/gasification/hydrothermal), catalytic (hydrogenolysis, hydrodeoxygenation) and biocatalytic (laccase/peroxidase-based modification) approaches (Ragauskas et al., 2014; Beckham et al., 2016). The transition of lignin, produced on a scale of tens of millions of tonnes annually by the paper and pulp industry (≳50–70 Mt yr^{-1}), from low-value, high-volume energy uses to high-value, low-volume chemical and material applications is considered critical for circular economy and carbon reduction; However, structural heterogeneity, sulfur/ash content, and polydispersity make selective conversion difficult (Laurichesse & Avérous, 2014; Ralph et al., 2019). Therefore, current research focuses on "lignin-first" biorefinery strategies and integrated process design that prioritizes bioavailability for high carbon-efficient and selective processes (Ragauskas et al., 2014; Shuai et al., 2016). The chemical structure of lignin, its transformation possibilities and potential uses are summarized in Figure 3.

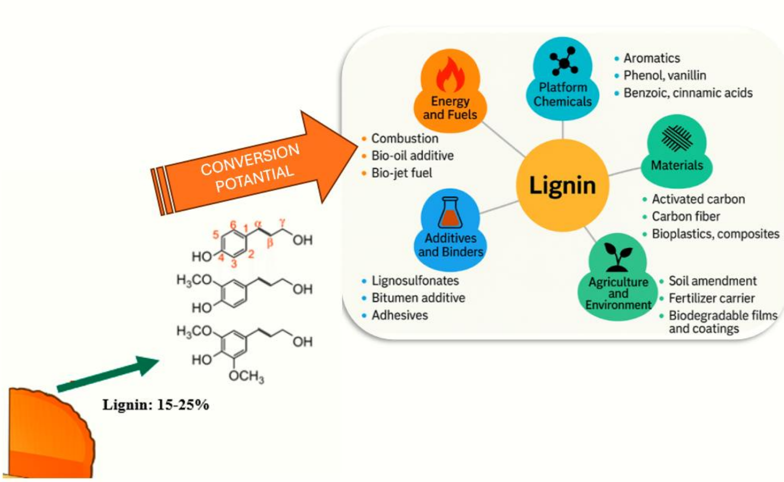

Fig 3. Conversion potential of lignin: structure and applications

Industrially, technical lignin is separated as a by-product during kraft, sulfite or organosolv processes and its annual production is in the order of millions of tons. Technical lignin is being investigated for conversion into high value-added products, especially through catalytic conversion routes. For example, aromatic hydrocarbons and cycloalkanes can be produced from lignin-derived phenolic compounds by catalytic hydrodeoxygenation (HDO) methods using Ru, Ni, Mo-based heterogeneous catalysts (Ying & Jang, 2020). According to the literature, the conversion efficiency in HDO reactions directly performed from lignin bio-oil generally varies between 16–63% (Shu et al., 2020), while this rate can approach 100% with model compounds (Margellou et al., 2020). Moreover, when catalytic hydropyrolysis techniques are carried out with catalyst systems such as Ni, Mo or Fe/ZrO_2, oxygen-free cyclic hydrocarbons can be obtained with yields of 18–26% and aromatic hydrocarbons with yields of 65–67% (Borrero-López et al., 2022). These processes are promising for hydrogen-saturated, high-energy jet-range fuel components.

3. JET FUEL PRODUCTION PROCESS FROM LIGNOCELLULOSIC MATERIALS

Recent research on lignocellulosic biomass-to-jet fuel conversion has explored a variety of feedstocks, technological routes, and environmental implications. Table 1 summarizes representative studies, highlighting their feedstocks, conversion pathways, product yields, and key environmental insights.

Table 1. Studies on jet fuel production from lignocellulosic biomass: feedstock, pretreatment, conversion routes, products and main findings

Reference	Feedstock & Pre-treatment	Conversion Pathway	Products & Yields	Environmental Notes
Ganguly et al. (2018)	Residual woody biomass – mild bisulfite	Biocatalytic fermentation + oligomerization (ATJ-IPK)	IPK	78% lower GWP (WoTW vs WTW fossil jet)
Murphy et al. (2015)	Lignocellulosic biomass (Queensland)	Pyrolysis + hydrotreating	1 tonne biomass → 620 L bio-oil, 290 L HC, 90 L jet fuel	Indicative only; scale-up strategy
Cavalett & Cherubini (2018)	Forest residues	FT (gasification + FT) & ATJ (alcohol-to-jet)	RJF-FT, RJF-ATJ; FT higher efficiency, ATJ lower	TRL high but not yet commercial (CAPEX barrier)
Deuber et al. (2023)	Sugarcane lignocellulosic residues	HTL → upgrading	—	Techno-economic and life-cycle analysis conducted (Brazilian context)
Ahire et al. (2024)	Forest residues	Gasification → syngas → FT → SAF (FT-SPK)	—	GHG emission ~24.6 g CO_2 eq/MJ SAF (cradle-to-gate)
Oghyanous & Eskicioglu (2025)	Five different biomass types	HTL vs. fast pyrolysis + upgrading	Biofuel yield comparison, effect of process severity	HTL particularly advantageous for wet biomass; comparative analysis focusing on fuel quality and yield
Baisch et al. (2025)	General biomass	HTL → biocrude-oriented conversion	—	Comprehensive review of HTL operational parameters, by-products, and current trends

Note: ATJ: Alcohol-to-Jet, IPK: Iso-paraffinic kerosene, GWP: Global Warming Potential, WoTW: Woods-to-Wake, WTW: Well-to-Wake, FT: Fischer–Tropsch, RJF: Renewable Jet Fuel, HC: Hydrocarbons, TRL: Technology Readiness Level, CAPEX: Capital Expenditure, ASTM: American Society for Testing and Materials (fuel standards), SAF: Sustainable Aviation Fuel, HTL: Hydrothermal Liquefaction, SPK :Synthetic Paraffinic Kerosene

In recent years, there has been a noticeable increase in the literature on the production of sustainable aviation fuels (SAFs) from lignocellulosic biomass. Especially after 2020, studies have moved beyond reporting laboratory-scale yields and now increasingly incorporate life cycle assessment (LCA), techno-economic assessment (TEA), and technology readiness level (TRL) indicators (Ahire et al., 2024). This trend highlights a shift in research focus from process-level performance evaluation toward system-level impacts. The majority of studies concentrate on thermochemical routes; in particular, gasification followed by Fischer–Tropsch (FT) synthesis, hydrothermal liquefaction (HTL), and pyrolysis combined with hydrotreating have been identified as advantageous pathways for achieving the desired carbon chain length and energy density in jet-range hydrocarbons (Deuber et al., 2023). Meanwhile, the alcohol-to-jet (ATJ) route continues to be investigated due to its reliance on existing ethanol and isobutanol production infrastructure, although its LCA outcomes are reported to be more scenario-sensitive because of the high indirect energy and chemical inputs required (Cavalett & Cherubini, 2018). Additionally, niche research has demonstrated that hydrogenated turpentine can serve as a bio-based blending component, showing compatibility with Jet A-1 at up to 50% while improving fuel properties (Donoso et al., 2020). Overall, the recent body of literature reveals both an increase in publication volume and a broadening of reported performance metrics, indicating that research on lignocellulosic jet fuel production is gradually moving from experimental scales toward considerations of commercial feasibility.

4. DECARBONIZATION OPPORTUNITIES OF BIOMASS BASED AVIATION FUEL USAGE

Before addressing the decarbonization opportunities of biomass-based aviation fuels, it is important to contextualize their place within the broader evolution of biofuels. Table 2 summarizes the classification of biofuel generations, showing the transition from first-generation food-based fuels to second-generation lignocellulosic feedstocks and third-generation algal resources.

Table 2. Classification of biofuel generations based on feedstock, products, and conversion pathways (Dharani et al., 2024; Bisht & Pandey, 2025).

Generation	Feedstock	Fuel Products	Conversion Pathway(s)
1st Generation	Food crops, animal fats	Bioethanol, Biodiesel	Biochemical
2nd Generation	Lignocellulosic biomass	Bioethanol, Biodiesel, Bio Jet	Biochemical, Thermochemical
3rd Generation	Algal biomass	Bioethanol, Biodiesel, Bio Jet	Biochemical, Thermochemical

Guided by this classification, the following paragraphs synthesize recent evidence on decarbonization opportunities across lignocellulosic and algal SAF pathways. The aviation sector faces unique challenges in decarbonization, as alternatives such as electrification and hydrogen remain technically and economically limited at large scales. Consequently, renewable jet fuels derived from biomass have emerged as one of the most promising pathways to reduce greenhouse gas (GHG) emissions while maintaining aviation safety and performance standards. Recent studies highlight that bio-based jet fuels can play a central role in aligning the aviation industry with global climate goals. Cavalett and Cherubini (2018) demonstrate that biojet derived from forest residues not only offers substantial reductions in life cycle emissions but also contributes to the achievement of multiple Sustainable Development Goals (SDGs), provided that appropriate policy mechanisms are in place to overcome economic barriers. In fact, future scenarios consistent with limiting warming to 2 °C project an expansion of renewable jet fuel use up to ~7 EJ by 2050, representing about half of global jet fuel consumption.

Beyond lignocellulosic residues, other biomass routes have also been explored. Donoso et al. (2020) investigated hydrogenated turpentine as a blending component with Jet A1, showing that partial hydrogenation reduces sooting tendency and allows blending levels up to 50%, fulfilling ASTM specifications. Similarly, Braz and Mariano (2018) assessed alcohol-to-jet pathways based on eucalyptus feedstocks and found that both ethanol- and butanol-derived routes could yield competitive minimum jet fuel selling prices (~2.1 US$/L), with significant carbon footprint reductions. These results suggest that biomass-derived jet fuels are not only environmentally attractive but also potentially viable within existing pulp and bioethanol industry infrastructures.

The strategic importance of biomass-based aviation fuels is further emphasized by global consumption patterns. According to Gollakota et al. (2021), aviation jet fuel consumption reached 13 quadrillion BTU in 2018 and is projected to more than double by 2030, underscoring the urgency of sustainable alternatives. Their analysis categorizes biofuels into three generations: first-generation fuels derived from food crops and animal fats (with limitations due to food security and land use concerns), second-generation fuels based on lignocellulosic and waste feedstocks (which align better with sustainability and ASTM standards), and third-generation algal biofuels, which hold promise due to high oil yields and cultivation on non-arable land. This evolution illustrates the growing emphasis on lignocellulosic and algal sources as long-term, scalable options for aviation decarbonization.

Moreover, the diversification of feedstock bases is increasingly seen as a prerequisite for sustainable expansion. Morgan et al. (2019) stress the need to optimize the utilization of agricultural residues and to develop new plant production systems tailored to aviation fuel supply chains, particularly in tropical regions. Such diversification strategies would not only enhance resource security but also mitigate risks associated with overdependence on a limited set of feedstocks.

Taken together, these studies underline that biomass-based aviation fuels represent a credible and scalable decarbonization pathway for the aviation industry. While techno-economic barriers and supply chain challenges remain, the convergence of environmental benefits, resource availability, and technological progress positions biomass-derived jet fuels as central to aviation's low-carbon transition.

5. CONCLUSION

Biofuels continue to attract attention primarily for their favorable environmental profile. Their research and development are inherently interdisciplinary (spanning economics, biology, agronomy, ecology, microbiology, engineering, and chemistry) and therefore intellectually and technologically dynamic. In particular, non-traditional and not-yet-commercialized plant species are emerging as attractive, cost-effective feedstocks (Malode et al., 2021). For countries prioritizing low-carbon energy in transport and other sectors, biofuels offer a credible means to diversify the energy mix and supplement conventional fuels. Interest in algal biotechnology has also accelerated due to its potential for emissions abatement and bioenergy applications; nevertheless, given the current state of technology and infrastructure, biofuels are unlikely to fully displace fossil fuels in the near term (Alam et al., 2015).

In conclusion, biofuels represent a practical and promising complement to petroleum fuels, with demonstrated potential to enhance energy security, reduce greenhouse-gas emissions, and support environmental sustainability. Progress across successive "generations" (from food and non-food crop biomass to algal and other advanced biobased resources) reflects significant technological maturation and a widening portfolio of sustainable options. That said, logistical constraints in feedstock collection, transportation, storage, and distribution remain persistent bottlenecks. Realizing biofuels' full commercial potential will require robust, sustainable supply chains, alongside continued improvements in conversion efficiency and feedstock processing.

Based on the findings of this section, we recommend prioritizing residues and sidestreams in raw material selection to maximize environmental performance: in particular, the use of forest/wood processing residues and lignin-rich streams from kraft/organosolv processes reduces competition with food systems and land conversion pressure; if additional biomass is needed, energy crops should only be grown on marginal/degraded land and with ecosystem protection measures. End-to-end life cycle assessments (WCAs) should be mandated at every project level, and fueling plants with renewable electricity and, where possible, using green (or CCS-supported) hydrogen is essential. For scalability and operational efficiency, co-locating plants with pulp-paper or bioethanol infrastructures is recommended, along with streamlining feedstock logistics, sharing utilities (steam, water, heat), heat recovery, and systematizing energy/process integration. This approach not only reduces emissions and costs by reducing logistics and energy inputs, but also creates a financially investable biofuel supply model that is compatible with sustainability criteria.

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CHAPTER 7

The Chicken Industry in Türkiye

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1. INTRODUCTION

Animal-based foods are crucial for a healthy and balanced diet. Chicken and eggs, in particular, stand out in this group for their affordability and nutritional properties. The human body requires nutrients rich in protein, vitamins, and minerals for growth, development, and healthy functioning. Chicken and eggs are essential sources for meeting these needs. Chicken meat is rich in many nutrients, especially protein. Its lower fat and cholesterol content compared to other types of red meat makes it particularly valuable for cardiovascular health. Chicken meat contains high amounts of protein, the building blocks of the body. Proteins are used in vital functions such as the construction and repair of muscle tissue, the production of hormones and enzymes, and the strengthening of the immune system. Consuming high-quality protein is especially important for children, adolescents, athletes, and individuals with muscular diseases. A healthy individual's daily protein requirement is approximately one percent of their body mass. In other words, an individual with a body mass of 70 grams should consume 70 grams of protein, 50% of which should come from animal-based proteins. Chicken meat generally contains less fat than red meat, especially the breast. This lower energy value makes it a popular choice for individuals seeking weight control. Saturated fat and cholesterol are nutrients that increase the risk of cardiovascular disease. Chicken meat, especially when consumed skinless, offers significant advantages in these regards. This makes it an ideal meat for individuals with high cholesterol levels and those looking to maintain heart health. Chicken meat is rich in B vitamins (B6, B12, niacin, riboflavin). These vitamins are essential for nervous system health, energy production, and blood cell formation. It also contains minerals such as iron, zinc, and phosphorus, which support the immune system and contribute to bone health. Chicken meat is more easily digested than other types of red meat. Its affordability also makes it suitable for individuals of all ages to consume it regularly. Eggs are one of the highest quality and most balanced sources of protein found in nature. "Egg protein" is the protein most effectively utilized by the body, and for this reason, it is considered a reference protein. Eggs contain all the essential amino acids in appropriate proportions. This provides all the protein building blocks necessary for body development, tissue repair, and a strengthened immune system. Eggs are rich in many vitamins, especially vitamins A, D, E, B_2 (riboflavin), and B_{12}, as well as minerals such as iron, phosphorus, selenium, and zinc. These vitamins and

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minerals play an important role in eye health, bone health, brain function, and the immune system. Eggs can be cooked quickly and easily. Furthermore, their affordability and long-term storage make them a valuable part of the diet for individuals of all ages. Eggs play a crucial role in meeting the increased protein and nutrient needs, especially during childhood, pregnancy, breastfeeding, and old age. Consuming one egg per day is appropriate for healthy individuals. Eggs, thanks to their choline content, are particularly valuable for brain development and memory. Eggs are recommended for breakfast for children's mental development.

Poultry farming stands out as one of the most dynamic, innovative, and rapidly developing areas of the animal production sector, both globally and in Türkiye. Chicken meat and egg production are notable for their high productivity, low production costs, environmental sustainability, and their place in human nutrition. These products offer numerous advantages, both economically and nutritionally. Chickens' ability to quickly convert feed into meat and eggs makes them significantly more efficient than other forms of animal production. Only 1.4 kilograms of feed are required for one kilogram of live weight gain in poultry farming. However, the same live weight gain requires 8 kilograms of feed in cattle farming and 4 kilograms in pig farming. Similarly, chickens consume only 1.6 kilograms of feed to produce one kilogram of eggs. Thanks to these strong feed conversion rates, poultry farming consumes fewer environmental resources and keeps production costs low. Genetic improvement efforts in the poultry sector, focusing on both live weight gain and egg production, and improving environmental conditions, are continuously increasing the sector's productivity. In addition to these developments, differences between species in terms of feed utilization are also expected to increasingly benefit poultry farming. Today, the poultry sector stands out as the branch of livestock farming most receptive to technological advancements and the one that undergoes the most rapid transformation in applications. In Türkiye, the poultry industry is considered the most advanced sector of the livestock sector, attracting attention with its ease of production, rapid speed, and low costs. From a nutritional perspective, chicken meat and eggs are among the cornerstones of a healthy and balanced diet. Chicken meat, with its high protein content, low fat content, and lower saturated fat and cholesterol levels compared to red meat, is frequently recommended as a substitute for red meat in healthy diet recommendations. Chicken breast meat, in particular, is preferred for its minimal fat content, promoting cardiovascular health. Eggs, on the other hand, stand out as the highest quality protein source found in nature; their protein content is optimally utilizable by the body and contains all essential amino acids in ideal proportions. The vitamins and minerals contained in eggs are essential for brain and nervous system development, as well as for supporting the immune system, maintaining bone health, and maintaining cellular functions. In recent years, consumers have been turning to lower-fat, more affordable chicken meat instead of red meat to address the global animal protein gap and promote healthy eating. Thanks to their affordability, chicken and eggs are becoming accessible to all segments of society and an essential part of daily nutrition.

Global meat production has increased significantly over the last 50 years. Since 1950, total meat production has more than quadrupled, reaching 370 million tons. Initially consumed less than pork and beef, chicken has overtaken other meats and is now the most consumed meat. Increasing population and economic development, particularly in Asia, have led to rapid increases in global poultry production and consumption. According to 2024 data, global consumption of beef will reach 130 million tons, pork 101 million tons, and chicken 139 million tons. This indicates that chicken has become the most in-demand and consumed animal protein source today. For the last 20 years, a steady increase in poultry production and consumption has continued. The current number of poultry animals worldwide has reached approximately 30 billion. Chickens constitute 94.5% of this number, ducks 3%, Türkiyes 1.5%, and other species such as geese, quail, and guinea fowl. Global poultry meat production is projected to increase by 2.1% year-on-year to 139 million tons in 2024. Of this production, 88.8% is chicken, 4.4% duck, 3.7% Türkiye, and 3.2% goose and guinea fowl. According to data published by the Institute for Turkish Agricultural Economics and Policy Development (TEPGE), affiliated with the Ministry of Agriculture and Forestry, per capita poultry meat consumption in Türkiye in 2024 reached 24.1 kilograms. This figure exceeded the per capita consumption of 23.14 kilograms in 2023. Global chicken egg production in 2024 was 91 million tons. China, accounting for 30 million tons of this production, is the leading egg producer. Other leading countries with chicken egg production were India with 6.6 million tons, the US with 6.5 million tons, and Indonesia with 5.9 million tons. In 2024, the Netherlands was the largest exporter, while Germany became the largest importer. Türkiye saw a 2.7% increase in egg production in 2024, ranking ninth in global production with a 1.5% share. Türkiye ranked third in global egg exports in 2024. Per capita egg production in Türkiye is around 250, of which exports account for approximately 20-25%. Chicken egg production was projected to reach 91 million tons in 2023. The sustainability of the poultry sector is not limited to economic efficiency. It also reduces environmental impact. The high conversion rate of chickens from feed to meat and eggs means less agricultural land and water consumption. Furthermore, chicken farming offers advantages over other red meat production methods in terms of carbon footprint and greenhouse gas emissions. With increasing concerns about animal welfare, environmental awareness, and health, consumers have begun to prefer chicken and other poultry meats over beef and pork. This trend is likely to continue in the coming years. Consequently, chicken meat and egg production are becoming both economically and economically viable. It also offers significant nutritional and environmental advantages. Factors such as high productivity, low production costs, sustainability, and accessibility to all segments of society strengthen poultry farming's leadership in animal production. Including chicken meat and eggs on our tables for a healthy and balanced diet is crucial for both individual health and social well-being. Poultry farming will continue to play a fundamental role in meeting the growing population's need for safe and sustainable animal protein in the modern world.

2. HISTORY OF CHICKEN PRODUCTION IN TÜRKİYE

Chicken production in Türkiye can be divided into two categories: industrial and backyard. While the industrial poultry sector is one of the world's leading production areas today, its history is not very old. In contrast, traditional chicken farming has a deep-rooted history in Türkiye. Chickens are a creature that many people can easily raise in their backyards and hold an important place in people's daily lives, both economically and socially. Raising chickens in backyards remains a common practice, especially in rural areas, and even in metropolitan areas that still maintain neighborhood culture and traditional architecture. The widespread popularity of chickens stems from their relatively easy care, low cost, and ability to produce eggs and meat in a short time. These characteristics have made chickens valuable both for meeting the needs of small-scale families and for commercial production. The historical basis for this deep-rooted and widespread practice of chicken farming is profound. During the Ottoman Empire, the vast majority of the population lived in rural areas, earning their living through agriculture and animal husbandry. However, chickens have been an integral part not only of rural life but also of urban life throughout history. In the Ottoman Empire, especially in major cities like Istanbul, chicken farming and the chicken trade constituted a significant element of both daily life and economic activity. The world's first incubator was invented in Cairo, then part of the Ottoman Empire, and from there it spread to Europe. This information demonstrates that the origins of mass-produced chick production and modern poultry farming lie in Ottoman lands. Therefore, it would be fair to say that the foundations of today's global industrial chicken production were laid in the Ottoman lands. Chickens and eggs have a deep-rooted place in Istanbul's social and economic life. The Tavukpazarı (Chicken Market), one of the city's busiest spots and the main gates of the Grand Bazaar, is a prominent example of this tradition. The history of the Tavukpazarı dates back to the Byzantine period, and the sale of live chickens and eggs continued here after the conquest of Istanbul. This market traded not only local producers but also various chicken breeds brought to the city from around the world. In addition to Istanbul, large cities like

Bursa and Edirne also boast streets and markets known as "Chicken Markets," which were considered centers of the chicken trade. These markets not only met city residents' daily protein needs but also facilitated the cultural circulation of different chicken breeds and eggs.

In the Ottoman Empire, public incomes were generally low, and economic crises were frequent. Therefore, chicken farming provided a significant benefit to the people, whether urban or rural. Because chickens were easy to care for, inexpensive, and yielded quickly, they became one of the most reliable sources of protein for families. Many households raised chickens in their gardens, and selling their eggs at the market, in addition to daily consumption, became an important source of income. In large cities like Istanbul, it became almost a tradition for every household with a courtyard or small garden to have chickens. This practice was intertwined with urban culture and became an integral part of neighborhood life. Chicken farming held great importance not only among the public but also in the Ottoman palace. Special chickens were raised for the Ottoman sultans and other courtiers, and particularly striking and rare breeds were favored. Ornamental chickens, brought from both domestic and foreign countries, were carefully cared for in special coops set up in the palace. Foreign ambassadors brought rare and spectacular chicken breeds from their home countries as gifts to the Ottoman sultans, leading to these breeds gaining a prominent place in the palace gardens. This reflected the palace's pursuit of luxury and grandeur, while also fostering the spread of chicken breeds from diverse cultures across Ottoman lands. Chicken and eggs also held a prominent place in Ottoman cuisine. Dishes made from eggs, eggs used in pastries, and various chicken dishes were frequently featured both in the palace kitchen and on the public table. The vibrancy of Istanbul's chicken and egg markets is a significant indicator of the indispensability of these products in urban life. With a tradition stretching from the Ottoman period to the present day, chicken and eggs have held a deeply rooted place in both urban and rural life, economically, culturally, and socially. In major cities like Istanbul, chicken breeding and trade shaped not only daily life but also urban culture. The importance the Ottomans placed on this practice, both among the public and in the palace, clearly demonstrates the continuity and value of chicken and eggs in Anatolia and the Ottoman landscape. Hearing chickens crowing in neighborhoods and gardens today is a reflection of this rich cultural heritage that has been carried from the past to the present.

Today, almost all of the hybrid material used for chicken meat and eggs in Türkiye is imported as parent breeders or partially grandparent breeders. An increasing number of parent breeders and partially grandparent breeders are imported each year for the production of hybrids used in egg and chicken meat production. 95.0-97.5% of the breeders used for egg production and 98.0% of the breeders used for meat production are sourced from abroad. However, this situation is not unique to Türkiye; it is similar in many countries around the world. Four companies in broiler production and five companies in laying hens meet 98% of the world's poultry product demand. This is related to the demand for poultry, and is the result of genetic improvement efforts, particularly in the United States, that began in the 1920s and continued throughout the century. While there used to be numerous breeding companies, today, due to mergers, their numbers can be counted on the fingers of two hands. Since the great-grandparents in the hands of these companies were obtained as a result of many years of selection work, it is not possible to achieve similar levels of genetic progress.

After the founding of the Republic of Türkiye, efforts were made to utilize high-yielding animals in poultry farming. The Ankara Central Poultry Institute was established in 1930, and its purpose was to provide a trained workforce for poultry farming and to implement modern methods in chicken production. For 20 years, efforts were made to raise low-yielding domestic animals and chickens of unknown genotype. At that time, poultry slaughterhouses in Türkiye were only located in the Marmara region, and chickens were brought here from all over the country for slaughter. Slaughtered chickens or poultry industry products were not yet being produced. At that time, chickens were difficult and expensive to obtain. Egg production was also very poor, feed raw materials were hard to find, and producing between 80 and 100 eggs annually from low-yielding chickens was considered unsuccessful. By the 1950s, efforts to import qualified animals from abroad had begun. For this purpose, animals of the Leghorn, New Hampshire, White Plymouth Rock, Rhode Island Red, Cornish, Barred Plymouth Rock, and Amrock breeds were imported from the United States, bred in public institutions, and then distributed to breeders. The body size of the New Hampshire, Cornish, and Plymouth Rock breeds, and the egg production of the Leghorn and Rhode Island Red breeds, in particular, attracted the attention of producers and led to a surge in interest in poultry farming. Around the same time, feed mills began to be established and poultry feed was produced.

After 1960, some units affiliated with the Ministry of Agriculture conducted poultry breeding studies. Furthermore, in 1963, private companies were allowed to import hybrid parent stock from abroad. For both laying hens and broiler chicken production, foreign breeding stock dominated the Turkish market. None of the genotypes developed by the Ministry were as successful as their foreign counterparts, and they never became a preferred choice for commercial producers.

3. CHICKEN INDUSTRY IN TÜRKİYE

The poultry sector in Türkiye ranks among the top food sectors among EU countries in terms of both production volume and technology use, and it competes with global giants. The sector's significant employment generation and its status as one of the most well-organized food sub-sectors demonstrate its importance for Türkiye. The sector has developed rapidly, amassing significant knowledge and boasting some of the world's best production technologies. Approximately 750,000 people are employed in the sector, and when these individuals, along with their families, are considered, the multiplier effect is estimated to affect three million people in the country.

Approximately ten thousand enterprises operate in the poultry sector in Türkiye, three-quarters of which produce broiler chickens and one-quarter of which produce commercial eggs. The total number of poultry houses is approximately 20,000, with a utilization rate exceeding 90%. Poultry production is regionally categorized, with broiler chickens concentrated in the Marmara and Aegean regions and laying hens in Central Anatolia.

In Türkiye, broiler chicken production is carried out through a contract model. Large integration companies enter into agreements with producers, providing them with daily broiler chicks, feed, and veterinary services, and requiring them to raise them to a certain age. Producers who meet these requirements receive a bonus. In this production model, growers only provide poultry houses and labor, while large companies process the resulting muscle into various products and market them. Türkiye ranks among the top 10 countries in the world for broiler chicken production, producing approximately 2.5 million tons of chicken meat annually, approximately one-fifth of which is exported. The largest buyers of chicken meat are Iraq, Iran, Syria, Azerbaijan, and some African countries.

Table egg production in Türkiye is largely carried out by specialized companies, with large producers having capacities ranging from 750,000 to 2,000,000 hens. The number of large-capacity establishments is approximately 400, and marketing of the eggs produced is handled through various unions. Approximately 20 billion eggs are produced annually in Türkiye, a quarter of which are sold abroad. The largest buyers of table eggs are Iraq, Syria, the United Arab Emirates, the Turkic Republics, and some African countries.

4. CONCLUSION

The Turkish poultry industry is a shining star in Europe thanks to its use of modern technology and production capacity. In recent years, exports have been experiencing some problems, particularly with regard to exports, and fluctuations in purchase volumes from exporting countries are evident. The Ministry of Trade must take various initiatives to address this situation, particularly with regard to customs duties. Similarly, initiatives should be undertaken to create new export opportunities. Feed constitutes the largest cost in the poultry sector, and corn and soy, the two most important components of poultry rations, are imported. Efforts should be undertaken to produce these products domestically at lower costs. Almost all poultry health-related vaccines, antibiotics, premixes, and similar products come from abroad and must be produced domestically. Institutions should be established to integrate international poultry innovations domestically, and services should be provided for these innovations. For example, in 2023, some European countries banned the use of conventional layer hen hybrids in production, encouraging the use of genotypes suitable for two-way production instead. However, there is no genotype suitable for two-way production in Türkiye. A similar situation occurred with the enriched cage production models that began to replace conventional cage production in the early 2000s. Studies are needed to produce poultry material suitable for such production models.

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CHAPTER 8

Comparative Analysis of ARIMA, ANN, and LSTM Models in Agricultural Commodity Price Forecasting: A Data-Driven Approach for Sustainable Agriculture

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1. Introduction

Agricultural sustainability has become a strategic priority today, not only in terms of ensuring food security, but also in terms of maintaining economic stability, environmental balance, and social welfare. The growing global population, production uncertainties caused by climate change, limited natural resources, and fluctuations in agricultural markets require agricultural production systems to be more resilient, predictable, and efficient. In this context, accurately and timely forecasting of agricultural product market prices plays a critical role in production planning, supplydemand balance, stock management, and decision-making processes for policymakers.

Volatility in agricultural commodity prices remains a significant ongoing issue for policymakers and all stakeholders in the food supply chain, and there is a need for a better understanding of its future trajectory [1]. Agricultural commodity prices are influenced by numerous variables such as seasonality, production costs, global trade policies, and geopolitical developments, and these multidimensional interactions cause price series to have a highly volatile and complex structure. In particular, the impact of abnormal weather conditions in recent years has increased fluctuations in agricultural product prices, placing a burden on consumers and disrupting the income stability of farming households, thereby making it difficult for governments to develop policies to ensure supplydemand balance [2]. In this regard, developing accurate and reliable models for forecasting fluctuations in agricultural commodity prices is of great importance both for protecting the welfare of producers and consumers at the micro level and for strengthening economic stability at the macro level. At this point, modern forecasting methods, such as classical statistical approaches, deep learning, and machine learning-based methods, can contribute to the creation of

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more effective strategies by reducing uncertainties in price movements. In particular, combining the trend and seasonality information provided by time series analysis with the complex, non-linear relationships captured by machine learning and deep learning algorithms allows for a significant improvement in forecasting performance. This makes it possible to support the sustainability of agricultural production processes and to make agricultural markets more predictable.

The primary objective of this study is to predict barley, corn, and wheat prices in Türkiye using ARIMA, ANN, and LSTM methods and to determine which approach provides higher accuracy. Thus, by revealing the success levels of different modeling techniques in price forecasting, the goal is to obtain more reliable forecasts that can be used in decision-making processes by policymakers, producers, and market actors within the scope of agricultural sustainability.

The original value of this study stems from its comparative application of traditional time series methods (ARIMA) and artificial intelligence-based methods (ANN and LSTM) on the same dataset, offering a comprehensive approach to determining the most suitable model for agricultural product price forecasting. Furthermore, the motivation for this study stems from the increasing global uncertainties, the effects of climate change on agricultural production, and concerns regarding food supply and demand security, which necessitate a scientifically based solution specific to Türkiye. In this context, the research aims to make a significant contribution not only in terms of economic efficiency but also in line with environmental and social sustainability goals.

The article is structured as follows: Section 2 includes a literature review on agricultural product price forecasts. Section 3 is the Materials and Methods section, which briefly introduces the methods used in the study. Section 4 presents the analysis find-ings. Section 5 contains the Discussion section, which evaluates the findings. Finally, the Conclusion and Recommendations section provides general assessments and recommendations for the future.

2. Literature

Studies on forecasting agricultural commodity prices have created a rich research field at the intersection of agricultural economics, statistics, artificial intelligence, and data science. Early studies typically favored classical time series methods such as ARIMA and ARCH/GARCH to examine the trend, seasonality, and volatility structure of price series [3-8]; these methods have shown significant success, particularly in short-term forecasting. However, the non-linear relationships, structural breaks, and sudden price shocks observed in agricultural markets have limited the effectiveness of forecasts based solely on linear models.

To overcome these limitations, machine learning and deep learning-based approaches have increasingly been used in agricultural price forecasting in recent years. Methods such as ANN, Support Vector Regression (SVR), Random Forests (RF), and LSTM provide higher prediction accuracy compared to traditional methods due to their ability to model complex and non-linear relationships within the data. In this context, studies in the literature on the prediction of agricultural product prices cover a wide range in terms of both methodological diversity and data scale.

Pantazi et al. (2016) [9] compared Supervised Kohonen Networks, Counter-Propagation Artificial Neural Networks, and XY-Fused Networks models using normalized soil properties and NDVI data for wheat yield. According to the findings, the Supervised Kohonen Networks model was evaluated as an effective tool for both predicting yield and dividing the field area into different yield potential zones. Crane-Droesch (2018) [10] used corn yield data from the Midwestern United States in their study to predict the effects of climate change on agriculture using a semiparametric deep neural network method. The results revealed that climate change negatively affected corn yield, particularly in hot regions and under hot scenarios, demonstrating that this approach provided more successful predictions than classical statistical methods and fully nonparametric networks. Inyaem (2018) [11] compared decision tree and ANN techniques to determine the best machine learning model to help farmers increase their income by predicting rice production quantity and sales price, using a dataset of 1,000 farmer records obtained from the Agricultural Development Department. The results showed that the ANN algorithm provided the highest accuracy, making it the most suitable model for rice production prediction.

Yuan and Ling (2020) [12] aimed to develop a price prediction software to help farmers in Malaysia increase their profits by more effectively tracking agricultural product prices, and in this context, they compared the ARIMA, LSTM, SVR, XGBoost, and Prophet algorithms. Analyses conducted on a dataset containing economic and environmental factors related to the price history of agricultural products revealed that the LSTM algorithm provided the highest accuracy in handling increasing amounts of data and complex data structures and was the most suitable model for implementation in the software. Chen et al. (2021) [13] compared ARIMA, LSTM, SVR, Prophet, and XGBoost algorithms through two-stage experiments to develop a web-based system capable of automatically predicting agricultural commodity prices. In the study, which used chicken, pepper, and tomato price data from Malaysia, the LSTM model achieved the lowest error rate and was determined to be the most suitable and effective algorithm for the system's prediction engine. RL and Mishra (2021) [14] predicted the daily spot prices of cotton seed, castor oil seed, rapeseed, soybean, and guar seed traded on the National Commodity and Derivatives Exchange of India using ARIMA, Time-Delayed Neural Network (TDNN), and LSTM models. The findings show that the LSTM model accurately captures the direction of price changes and outperforms other models.

Gu et al. (2022) [2] proposed the Dual Input Attention LSTM (DIA-LSTM) model, which combines feature and temporal attention layers with LSTM, to more accurately predict fluctuations in agricultural commodity prices. Using cabbage and radish prices, trading volume, and meteorological data from dynamically determined main production regions for the period 2013–2021, the analysis determined that the model provided a lower error rate compared to both the static region approach and benchmark models. Mao et al. (2022) [15] analyzed fluctuations in Chinese cabbage, carrot, and eggplant prices during the COVID-19 pandemic using 51,567 price data points from 2020 and made short-term forecasts using the ARIMA model. The findings revealed that prices were significantly affected by the pandemic and seasonal factors, and that the ARIMA model provided high accuracy, especially in forecasts for less volatile se-ries (e.g., carrots). Meeradevi et al. (2022) [16] developed a hybrid decision support system combining ARIMA and LSTM models to support farmers in India with preplanting crop selection and agricultural planning. The model, trained with local rice prices from 2015–2018, achieved high accuracy with low error and low AIC in its 2019–2020 predictions. Zhou et al. (2022) [17] compared single and multi-input feature models in their study aiming to forecast agricultural commodity prices using corn, oat, soybean, and soybean oil price data from 2016–2021, and the Advanced LSTM (AI-LSTM) model showed the best performance. It was noted that the model has strong potential for market trends and price forecasting in smart agricultural trading platforms.

Amirteimoori et al. (2023) [18] compared artificial neural networks, deep learning, and gradient boosting algorithms to estimate the export volume of saffron, one of Iran's major export products, for the years 2012–2019. While all models showed high accuracy, the deep learning network demonstrated the best performance in terms of export forecasting. Das et al. (2023) [19] developed Empirical Mode Decomposition (EMD)-based hybrid machine learning models for predicting agricultural commodity prices using monthly wholesale price index data for vegetables from January 2005 to November 2020. In this context, price series were decomposed into components using the EMD method, ANN and SVR were applied to each component, and the obtained predictions were combined. The study findings showed that the developed hybrid models provided higher prediction accuracy compared to ANN and SVR models used alone. Deepa et al. (2023) [20] predicted cotton prices using Linear Regression, Bayesian Linear Regression, Boosted Decision Tree, Decision Forest, and Poisson Regression algorithms to support farmers' product selection and reduce income losses in India; The results revealed that the Boosted Decision Tree algorithm provided the highest accuracy, while the Decision Forest algorithm performed worse than the other models.

Murugesan and Radha (2023) [21] developed three different hybrid models combining ARIMA and SVR techniques to forecast agricultural product prices in India and reduce risks in farmers' product selection. The findings revealed that the hybrid model, in which ARIMA forecast values and their residuals were used as additional inputs to the SVR model and the final forecast was obtained by summing these two values, had the lowest error rate compared to other models and provided high accuracy in agricultural price forecasting. Patil et al. (2023) [22] analyzed fluctuations in agricultural commodity prices to make future price predictions. They examined wheat, barley, sorghum, corn, and rice produced in developing countries using the Hybrid SARIMA-LSTM approach. The findings revealed that the proposed hybrid model provided a high level of accuracy. Zeng et al. (2023) [23] developed a PSO-CS-based optimal prediction combination framework to forecast corn and wheat futures prices. The method, which includes data decomposition with EWT, SSA, and VMD, component restructuring with CGCD, and individual forecasting steps with ARIMA, ETS, BPNN, and ELM, achieved the highest accuracy with the Full-PSO-CS model.

Addankı et al. (2024) [24] applied machine learning and deep learning techniques to a dataset containing variables such as production, rainfall, fertilizer, and pesticide use from 1997 to 2020 to improve the accuracy of agricultural yield forecasts in India. The results showed that ensemble techniques and deep learning approaches such as long short-term memory/convolutional neural networks, in particular, produced highly accurate predictions. Avinash et al. (2024) [25] developed a hybrid prediction model combining Hidden Markov Models (HMM) and deep learning methods using the 2006–2023 weekly potato price series for the Champadanga market in West Bengal. The model, enriched with hidden states and technical indicators obtained from HMM, was integrated with RNN, CNN, LSTM, GRU, BiLSTM, and BiGRU; the results revealed that the HMM-DL hybrid approach provided higher accuracy than basic DL models in all forecasts. Benjamin et al. (2024) [26] applied linear regression, Bayesian regression, XGBoost, LightGBM, CatBoost, K-Nearest Neighbor (KNN), decision tree, random forest, and various hybrid/ensemble approaches to more accurately predict agricultural product prices shaped by environmental factors in India. The analysis revealed that the KNN model demonstrated the highest performance, outperforming other methods.

Van Le et al. (2024) [27] used GARCH and Multivariate LSTM models on transaction data from 2010 to 2023 to predict price volatility in the agricultural commodity market and provide decision support to investors. In comparative analyses, the Multivariate LSTM model achieved a high accuracy rate and performed better than the GARCH model. In particular, it more successfully predicted sudden and extreme volatility periods. El-Kenawy et al. (2025) [28] conducted a comparative analysis using machine learning and deep learning algorithms to predict potato yields. According to the results, graph neural networks and long short-term memory networks models provided the highest accuracy in yield prediction, with the graph neural networks model emerging as the most successful model. Manogna et al. (2025) [29] predicted the prices of 23 agricultural products using daily wholesale price data from January 2010 to June 2024 with stochastic models (ARIMA), machine learning methods (SVR, XGBoost, MLP), and deep learning approaches (RNN, LSTM, GRU, Echo State Networks). The results obtained prove that deep learning models the volatility and complex structures of agricultural commodity prices with a lower error rate and higher prediction accuracy. Zhao et al. (2025) [30] propose a hybrid model based on Temporal Convolutional Network and LightGBM to make more accurate and stable predictions against fluctuations in global agricultural trade. The dataset, which includes various agricultural products, covers 5 continents and the years 2011-2021. According to the findings, the proposed model demonstrates superior performance compared to classical single models.

As can be seen, agricultural product price forecasts conducted using various methods in different countries contribute significantly to the literature. However, studies in Türkiye that address basic grain prices comparatively using both traditional and artificial intelligence-based methods are limited, and research emphasizing the agricultural sustainability dimension of these forecasts is particularly insufficient. Barley, corn, and wheat, which are among Türkiye's staple agricultural products, play a vital role in ensuring food security, supporting the feed industry, and maintaining economic and social stability. Fluctuations in the prices of these products directly affect not only the agricultural sector but also food inflation, rural development, and sustainable production policies. Therefore, accurate and reliable price forecasting will contribute to strengthening the economic dimension of agricultural sustainability, protecting producer and consumer welfare, ensuring the efficient use of resources, and securing long-term food supply security.

3. Materials and Methods

The methods used in time series forecasting can exhibit different performance levels depending on the structure and characteristics of the series. While traditional statistical methods produce robust results for series dominated by linear dependencies, machine learning and deep learning methods come to the fore for series with nonlinear and complex relationships. This study examines

ARIMA, ANN, and LSTM models together. The combined use of the three methods offers the opportunity for a more reliable and comprehensive comparison by bringing together the advantages of both classical time series models and modern machine learning and deep learning approaches. In order to better highlight the strengths of the selected methods, the operational logic and mathematical framework of each method are presented in detail below.

3.1. Autoregressive Integrated Moving Average (ARIMA)

The ARIMA model, commonly used in statistical time series analysis, is a generalized version of Autoregressive Moving Average (ARMA) models for non-stationary series and periodic variation. It was introduced into the literature in 1970 by George E. Box and Gwilym M. Jenkins as a systematic method for time series forecasting and seasonal adjustment.

The ARIMA model is classified as ARIMA(p, d, q), where p denotes the autoregressive component, d denotes the differencing component, and k denotes the moving average component, each of which is a zero or positive integer [31]. The estimation process involves first applying d differencing to make the series stationary, then determining appropriate p and q values, and finally optimizing the model's error terms. This process is typically repeated several times until a satisfactory model is selected, and the final model is used for estimation purposes [32].

In the ARIMA model, the future value of a variable is expressed as a linear combination of previous values and errors, and its mathematical form is as shown in Equation 1 [33]:

$$Y_t = \emptyset_1 Y_{t-1} + \emptyset_2 Y_{t-2} + \cdots + \emptyset_p Y_{t-p} + \epsilon_t - \theta_1 \epsilon_{t-1} - \theta_2 \epsilon_{t-2} - \cdots - \theta_q \epsilon_{t-q} \quad (1)$$

Here, Y_t represents the actual value at time t, ϵ_t represents the random error at time t, $\emptyset_i$ represents the autoregressive coefficient reflecting the effect of past values, θ_j represents the moving average coefficient reflecting the effect of past errors, and p and q represent the degrees of the autoregressive and moving average terms, respectively.

Three criteria are commonly used in evaluating ARIMA models: Akaike Information Criterion (AIC), Adjusted AIC (AICc), and Bayesian Information Criterion (BIC). AIC is a criterion that quantitatively expresses how well a statistical model fits the data and is widely used to measure model suitability; the adjusted version of AIC for finite sample sizes is called AICc. BIC is a criterion that penalizes model complexity more heavily and provides an alternative measure for model selection [31]. These measures guide the selection of the most appropriate model by considering both the model's fit to the data and its adherence to the principle of parsimony.

ARIMA has become one of the indispensable methods for time series analysis in many fields such as finance, economics, and engineering due to its high predictive power, statistical reliability, and flexible structure that can adapt to different data types. However, in order to achieve the expected performance from the model, assumptions such as stationarity and white noise properties of the error terms must be taken into account.

3.2. Artificial Neural Networks (ANN)

ANNs are computational models developed as mathematical analogues of biological neural networks, inspired by the human brain's information processing mechanism. The common feature of both systems is the input–processing–output cycle. The basic building block of ANN is the artificial neuron, and its operation is based on three fundamental principles: Inputs are multiplied by weights, the resulting values are summed with bias, and the result is passed through an activation function to produce the output [34]. This multi-layered structure is defined as the input layer, hidden layer(s), and output layer.

The operation of an artificial neuron is functionally expressed as shown in Equation 2 [35]:

$$z_k = \sum_{i=1}^{m} w_{ki} x_i + b_k, \; y_k = \varphi(z_k) \tag{2}$$

Here, x_i represents the input signals, w_{ki} represents the connection weight between the input and the neuron, b_k represents the bias term, $\varphi(z_k)$ represents the activation function, and y_k represents the output of the neuron.

The ANN learning process is based on minimizing the error between predicted and actual values, and the most commonly used ANN architecture is the Multi-Layer Neural Network. The Multi-Layer Neural Network has a feedforward network structure and uses the backpropagation technique for learning [36]. When there are multiple layers and neurons, the mathematical representation of the entire network formed by the combination of neurons is given in Equation 3:

$$\hat{y} = \varphi(W^{(2)} \cdot \varphi\left(W^{(1)} x + b^{(1)}\right) + b^{(2)}) \tag{3}$$

The structure given in Equation 3 for the two hidden layers and the output layer consists of the weight matrix $W^{(1)}$ from the input to the first hidden layer, the bias vector $b^{(1)}$ of the first hidden layer, the weight $W^{(2)}$ of the second layer, and the bias $b^{(2)}$ of the second layer. $\varphi(\cdot)$ represents the activation function, $\hat{y}$ represents the output prediction. The architectural structure of an ANN model with two hidden layers is presented in Figure 1. The figure shows the data flow from the input layer through the hidden layers H_k and H_m to the output layer y, along with the weights W.

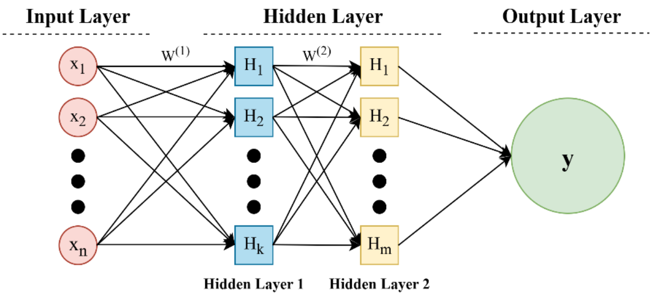


Figure 1. ANN architecture.

ANN holds a significant position in various applications such as regression and time series forecasting due to its ability to model complex and non-linear relationships, uncover hidden patterns within data, and perform predictions and classifications with high accuracy. It is used as one of the most powerful decision support tools among statistical and machine learning methods in economics, finance, healthcare, engineering, and many other fields.

3.3. Long Short-Term Memory (LSTM)

LSTM has the ability to effectively predict future steps thanks to its capacity to process sequential data and store information from previous steps in the sequence [37].

The LSTM architecture consists of special units called memory blocks in the recurrent hidden layer, and these units comprise self-connected memory cells that store temporal information, as well as input, output, and forget gates that control the flow of information [38]. In its initial design, the LSTM had only input and output gates. With the addition of the forget gate, it gained the ability to control the cell state and update its memory when necessary, thereby improving learning performance on long sequences. Furthermore, the look-ahead connections in modern LSTM architecture directly link the gates to the memory cells, improving the ability to learn the precise timing and counting of internal states [38, 39].

Each LSTM cell receives the input vector x_t, the previous hidden state h_{t-1}, and the previous cell state C_{t-1}, and processes them through four main gates: the input gate i_t, the forget gate f_t, the update gate $\tilde{C}_t$, and the output gate o_t. The operating mechanism of an LSTM cell with a single memory block is presented in Figure 2. The figure shows how the input, forget, and output gates, along with the cell state C_t and hidden state h_t, are updated over time steps.

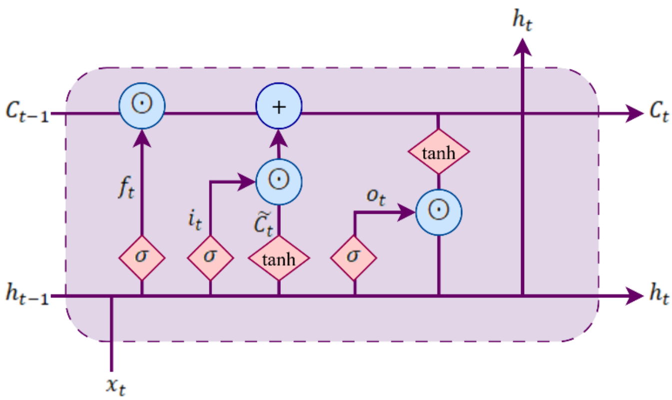


Figure 2. The operating mechanism of the LSTM cell.

The mathematical operation of the LSTM mechanism, including the input, forget, update, and output gates, as well as the current cell and hidden states, is presented in Equations 4–9, respectively:

$$i_t = \sigma(W_i \cdot [h_{t-1}, x_t] + b_i \quad (4)$$

$$f_t = \sigma(W_f \cdot [h_{t-1}, x_t] + b_f \quad (5)$$

$$\tilde{C}_t = tanh(W_c \cdot [h_{t-1}, x_t] + b_c \quad (6)$$

$$o_t = \sigma(W_o \cdot [h_{t-1}, x_t] + b_o \quad (7)$$

$$C_t = f_t \odot C_{t-1} + i_t \odot \tilde{C}_t \quad (8)$$

$$h_t = o_t \odot \tanh(C_t) \quad (9)$$

In the given equations, σ represents the logistic sigmoid function, W represents the weight matrix, tanh represents the hyperbolic tangent function, and $\odot$ represents element-wise multiplication. The LSTM model minimizes the risk of gradient vanishing and exploding through gates, enabling flexible information flow by controlling which information is stored or forgotten. Thanks to its superior ability to learn long-term dependencies and model complex dynamics in time series, it stands out as a reliable method widely used in areas such as financial time series forecasting, natural language processing, and speech and voice processing.

3.4. Performance Evaluation Metrics

Performance evaluation comprehensively analyzes the overall success of models using error metrics such as Mean Squared Error (MSE), Root Mean Squared Error (RMSE), Mean Absolute Error (MAE), and Mean Absolute Percentage Error (MAPE). MSE calculates the average of the squares of prediction errors, giving greater weight to large deviations, thereby revealing the model's sensitivity to error magnitudes. RMSE is calculated by taking the square root of MSE and allows for the interpretation of error values in the original data scale. MAE is calculated by taking the average of the absolute values of prediction errors, while MAPE is the average of errors expressed as a percentage. These metrics are commonly used in regression models, with lower values indicating better prediction performance of the model. The relevant metrics are mathematically formulated as follows, respectively, in Equations 10-13:

$$MSE = \frac{1}{n}\sum_{i=1}^{n}(y_i - \hat{y}_i)^2 \tag{10}$$

$$RMSE = \sqrt{\frac{1}{n}\sum_{i=1}^{n}(y_i - \hat{y}_i)^2} \tag{11}$$

$$MAE = \sum_{i=1}^{n}\frac{|y_i - \hat{y}_i|}{n} \tag{12}$$

$$MAPE = \frac{1}{n}\sum_{i=1}^{n}\frac{|y_i - \hat{y}_i|}{y_i}x100, \quad y_i \neq 0 \tag{13}$$

4. Findings

This section presents findings from machine learning and deep learning methods, along with a time series model approach, for forecasting the prices of three important agricultural commodities (barley, corn, and wheat) that are of strategic importance for agricultural sustainability in Türkiye and are staple grain products.

4.1. Data

The dataset used in the study includes daily closing prices for barley, corn, and wheat commodities obtained from the Turkish Mercantile Exchange (TMEX) [40] for the period 07/30/2019-07/25/2025. For model predictions, 80% of the study data was used for training and 20% for testing. The model performance evaluation criteria were calculated based on the predicted values for the period 07/30/2019-07/25/2025. Figure 3 shows the graphs for the three agricultural commodity products.

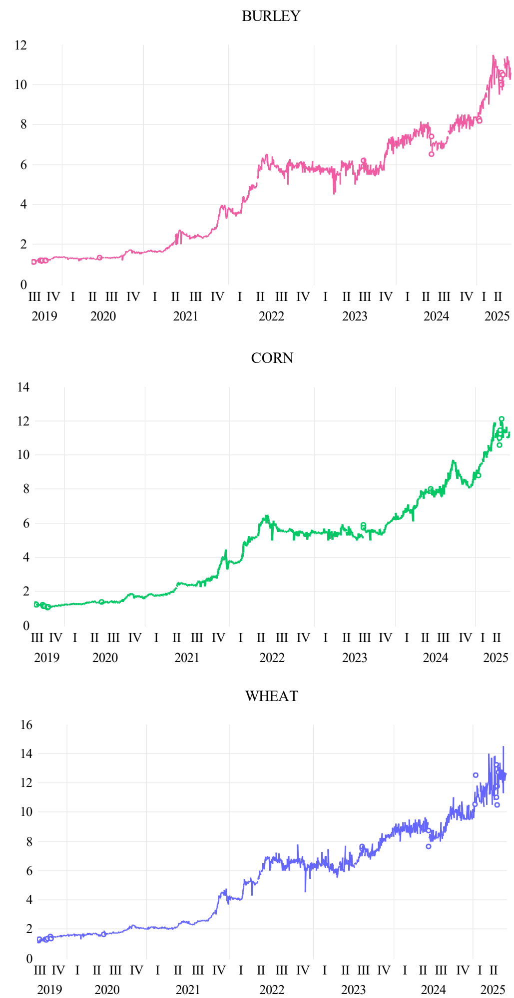


Figure 3. Agricultural commodity prices (barley, corn, wheat)

Table 1 presents descriptive statistics for agricultural commodity price series.

Table 1. Descriptive statistics.

	Barley	**Corn**	**Wheat**
Mean	4.6869	4.7068	5.4750
Median	5.5	5.25	6
Maximum	11.49	12.1	14.5
Minimum	1	1.06	1.17
Std. Dev.	2.7810	2.8536	3.2794
Skewness	0.2665	0.4649	0.3265
Kurtosis	2.0342	2.3702	2.0060
Jarque-Bera	71.3485	73.9556	82.9303
(Probability)	(0.0000)	(0.0000)	(0.0000)

When examining the descriptive statistics in Table 1, the mean, median, and standard deviation values of barley, corn, and wheat prices, along with the Jarque-Bera statistics, indicate that the price distributions do not follow a normal distribution.

4.2. Model Results

This section presents the findings of the time series approach ARIMA model, machine learning method ANN, and deep learning method LSTM for agricultural commodity price forecasts in Türkiye, separately for three agricultural products.

4.2.1. ARIMA Model

In this section, ARIMA(p, d, q) models were applied to estimate the closing prices of barley, corn, and wheat for different p and q lag values. The most suitable model was selected based on coefficient significance and model selection criteria such as AIC, SIC, HQ, and LogL. The results for barley, corn, and wheat prices are presented in Tables 2-4, respectively.

Table 2. ARIMA(2,1,1) model results for barley prices.

Dependent Variable: DLBARLEY				
Variable	Coefficient	Std. Error	t-Statistic	Prob.
C	0.0017**	0.0005	3.1109	0.0019
AR(1)	-0.2504**	0.0579	-4.3264	0.0000
AR(2)	-0.1817**	0.0315	-5.7629	0.0000
MA(1)	-0.2686**	0.0607	-4.4255	0.0000
SIGMASQ	0.0011**	0.0000	47.1494	0.0000
R-squared	0.2215	AIC	-3.9536	
LogL	2217.0565	SIC	-3.9312	
F-statistic (Prob(F-statistic))	79.2620 (0.0000)	HQ	-3.9452	

** 5% indicates statistical significance. (AIC: Akaike Information Criterion, SIC: Schwartz Information Criterion, HQ: Hannan-Quinn Information Criterion, LogL: Log likelihood).

Table 2 shows the forecast results of the ARIMA (2,1,1) model selected as the most appropriate for barley prices. All coefficients are statistically significant at the 5% level. The ARIMA (2,1,1) model actual-forecast values graph is shown in Figure 4.

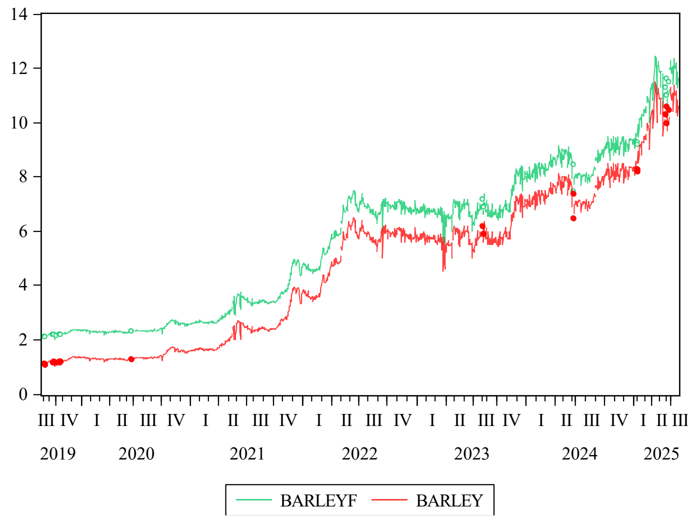


Figure 4. ARIMA(2,1,1) model actual (BARLEY) -prediction (BARLEYF) graph.

Although the ARIMA(2,1,1) model is the most suitable model for the series in Figure 4, its predictions differ from the actual values.

Table 3. ARIMA(1,1,2) model results for corn prices.

Dependent Variable: DLCORN				
Variable	Coefficient	Std, Error	t-Statistic	Prob.
C	0,0015**	0,0006	2,6654	0,0078
AR(1)	0,8838**	0,0922	9,5882	0,0000
MA(1)	-1,3352**	0,0888	-15,0303	0,0000
MA(2)	0,4169**	0,0359	11,6207	0,0000
SIGMASQ	0,0007**	0,0000	46,0016	0,0000
R-squared	0,1705	AIC	-4,4674	
LogL	2504,5334	SIC	-4,4450	
F-statistic (Prob(F-statistic))	57,2618 (0,0000)	HQ	-4,4590	

** 5% indicates statistical significance. (AIC: Akaike Information Criterion, SIC: Schwartz Information Criterion, HQ: Hannan-Quinn Information Criterion, LogL: Log likelihood).

When examining the estimated results of the most suitable ARIMA (1,1,2) model for corn prices in Table 3, it is seen that the model coefficients are statistically significant at the 5% significance level. Figure 5 shows the ARIMA(1,1,2) Model Actual-Forecast graph.

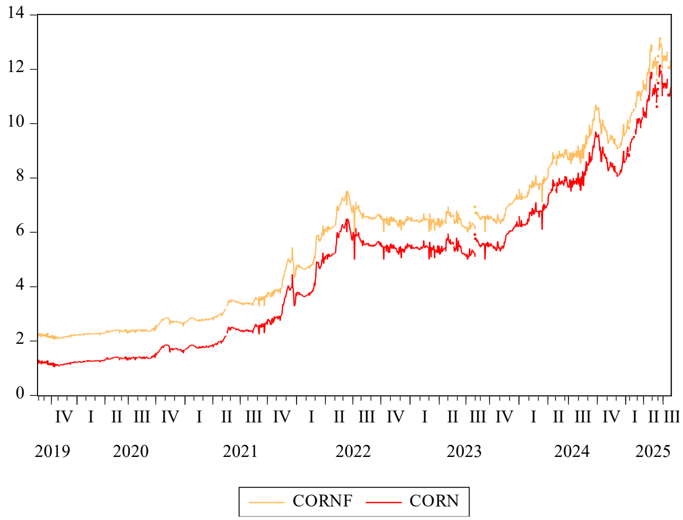


Figure 5. ARIMA(1,1,2) model actual (CORN)-prediction (CORNF) graph.

It is possible to state that the predicted values of the ARIMA(1,1,2) model, selected as the most suitable model for the series from Figure 5, differ from the actual values.

Table 4 shows the findings of the ARIMA(*p, d, q*) model for wheat commodity prices.

Table 4. ARIMA(1,1,2) model results for wheat prices.

Dependent Variable: DLWHEAT				
Variable	Coefficient	Std. Error	t-Statistic	**Prob.**
C	0.0017**	0.0005	3.7609	0.0001
AR(1)	-0.6207**	0.0179	-34.6163	0.0000
MA(2)	-0.3513**	0.0231	-15.1815	0.0000
SIGMASQ	0.0014	0.0000	51.2014	0.0000
R-squared	0.2801	AIC	-3.7085	
LogL	2078.886	SIC	-3.6905	
F-statistic (Prob(F-statistic))	144.5725** (0.0000)	HQ	-3.7017	

** 5% indicates statistical significance. (AIC: Akaike Information Criterion, SIC: Schwartz Information Criterion, HQ: Hannan-Quinn Information Criterion, LogL: Log likelihood).

According to the ARIMA(1,1,2) model estimation results in Table 4, the coefficients are statistically significant at the 5% significance level and have been used for wheat price forecasting. Figure 6 shows the ARIMA(1,1,2) model actual-forecast values graph.

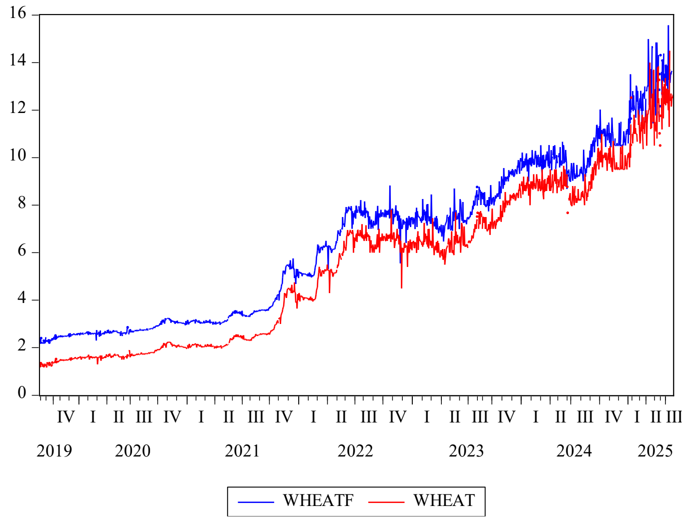


Figure 6. ARIMA(1,1,2) model actual (WHEAT)-prediction (WHEATF) graph.

Figure 6 shows that the predicted values of the ARIMA(1,1,2) model, selected as the most suitable model for the series, do not match the actual values very well.

4.2.2. ANN Model

This section presents the results of predicting barley, corn, and wheat commodity prices using the ANN approach from machine learning methods.

ANN modules use nonlinear autoregressive models (NAR) to predict future period values using different past period values. A NAR neural network, which has excellent fitting capability for a nonlinear time series and consists of three layers (Input, Hidden, and Output), was used in the study to predict the prices of barley, corn, and wheat. The delayed agricultural emptia price series was entered into the model as an input variable, and the NAR network was created using the MATLAB program's ntstool module. 80% of the data was introduced to the network for training, 10% for validation, and 10% for testing, and the Levenberg-Marquardt algorithm was selected for training. The ANN-NAR(1:20:1) model was estimated for 2-lagged daily barley, corn, and wheat commodity prices with 1 input layer, a hidden layer with 20 neurons, and 1 output layer formed by the current price series. The general ANN-NAR network structure for predicting barley, corn, and wheat commodity prices is shown in Figure 7.

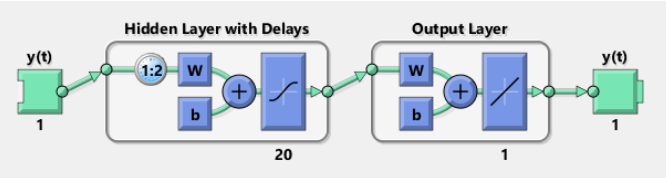
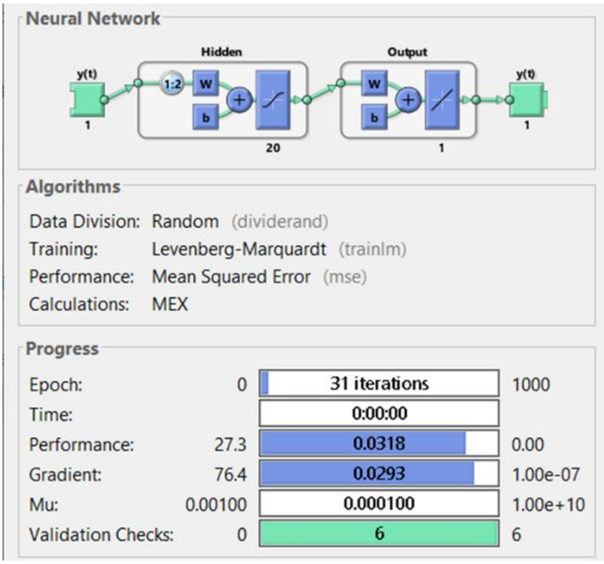


Figure 7. ANN neural network model structure.

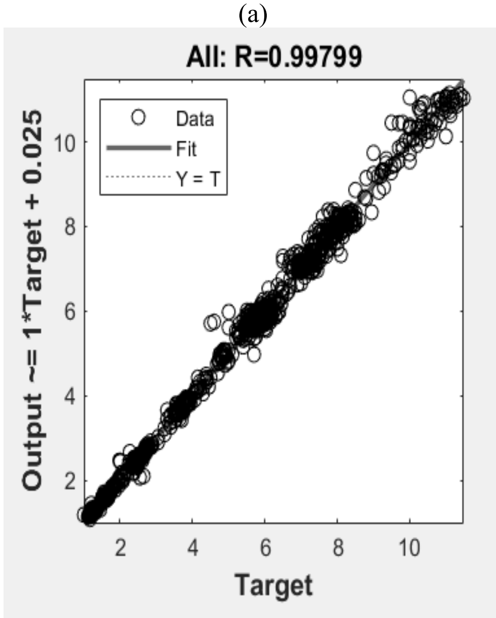
In the following section, ANN-NAR model predictions are presented separately for agricultural commodity prices.

4.2.2.1. ANN Model Prediction Results for Barley Commodity Price

For barley commodity prices, an ANN neural network structure as shown in Figure 5 is used, featuring 1 Input, 1 Output, and a 20-Neuron Hidden Layer. Training was completed after 31 iterations, and the model achieved its best network performance with the iteration values shown in Figure 8(a).



(a)



(b)

Figure 8. (a) ANN-NAR barley commodity price prediction screen; (b) barley commodity price actual-predicted value graph.

The total success rate of the network for barley commodity price data covering the period from 07/30/2019 to 07/25/2025, as shown in Figure 8(b), is the correlation value of the regression obtained with the values in Figure 8(a). The total success of the artificial neural network for barley commodity data is seen to be 99.799% with the "All R" value. Since this ratio is close to 1, Figure 9 shows that the ANN-NAR neural network prediction is quite successful for barley commodity price data.

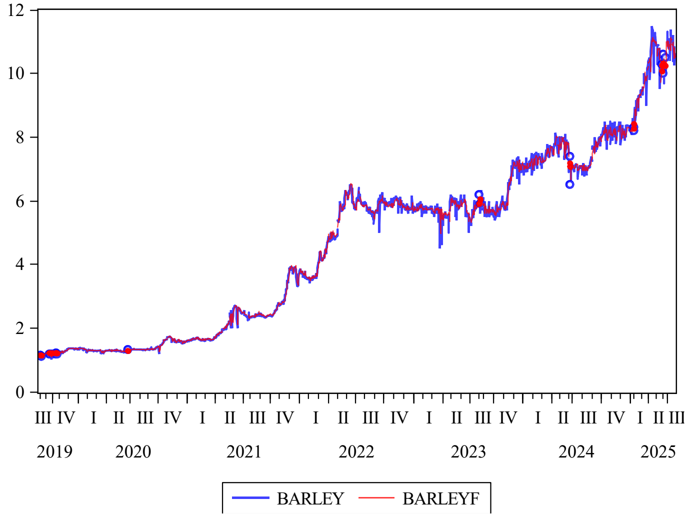


Figure 9. ANN model actual (BARLEY) -prediction (BARLEYF) graph.

4.2.2.2. ANN Model Prediction Results for Corn Commodity Price

For corn commodity prices, an ANN-NAR structure with 1 Input, 1 Output, and a 20-Neuron Hidden Layer, as shown in Figure 7, was used. The model achieved the best network performance with the iteration values in Figure 10(a).

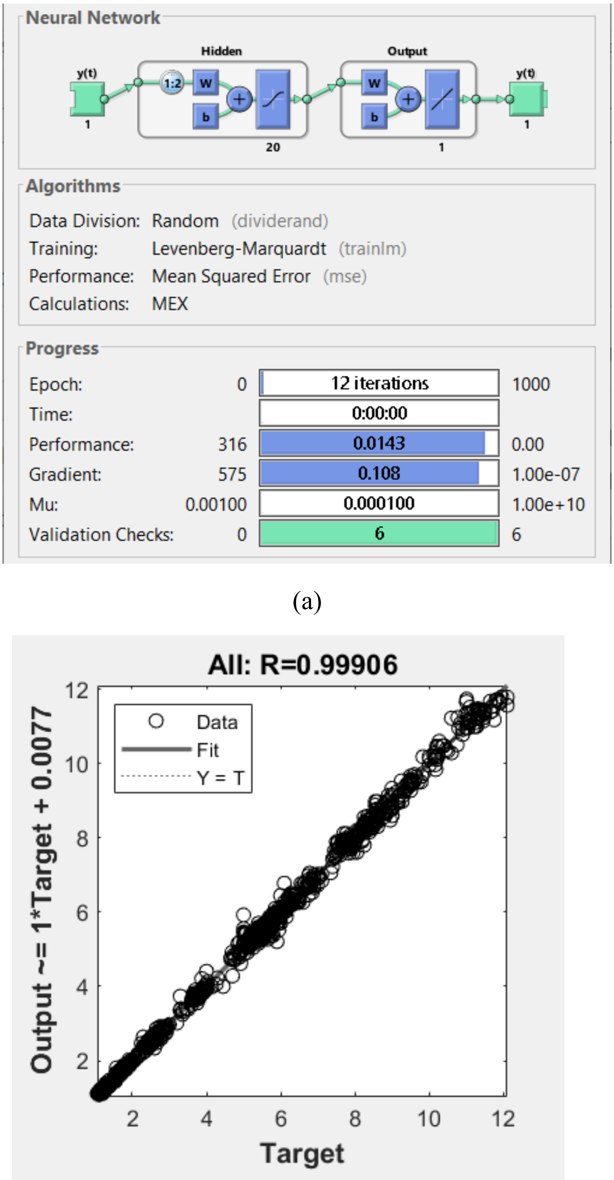


Figure 10. (a) ANN-NAR with corn commodity price prediction screen; (b) corn commodity price actual-predicted value graph.

The correlation value of the regression obtained with the values in Figure 10(a) shows the total success rate of the network covering the period 07/30/2019-07/25/2025 for the corn commodity price data in Figure 10(b). The total success of the artificial neural network for corn commodity data is seen to be 99.906%

with the “All R” value. Figure 11 shows the actual-prediction value graph indicating that the ANN-NAR prediction yielded successful results for corn commodity price data.

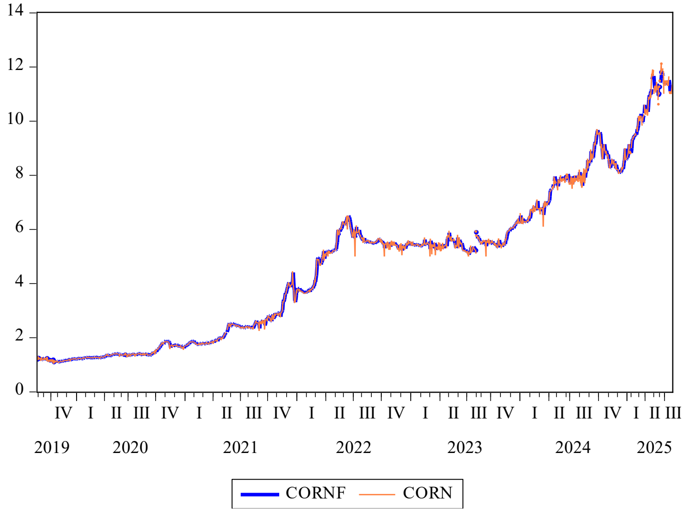
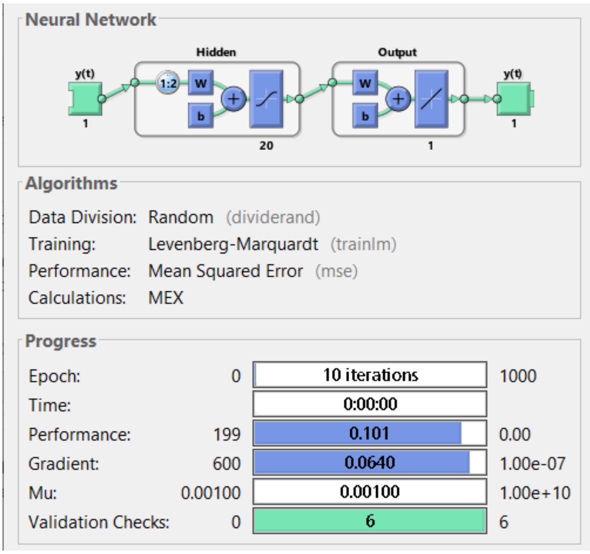


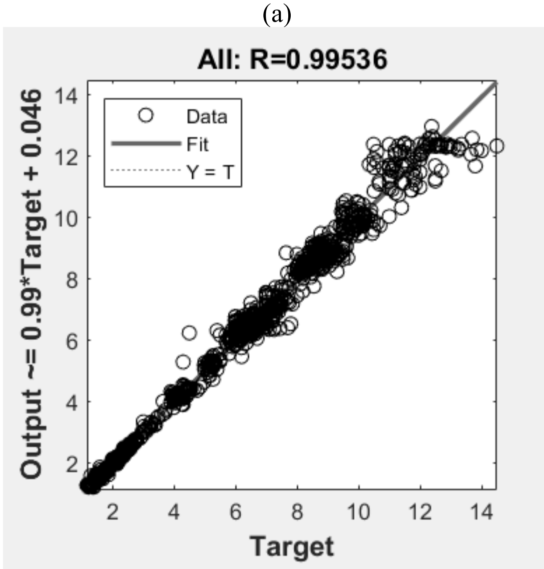
Figure 11. ANN model actual (CORN)- prediction (CORNF) graph.

4.2.2.3. ANN Model Prediction Results for Wheat Commodity Price

For wheat commodity prices, an ANN-NAR structure with 1 Input, 1 Output, and a 20-Neuron Hidden Layer, as shown in Figure 12, is used. Training was completed after 10 iterations, and the model provided the best network performance with the iteration values shown in Figure 12(a).



(a)



(b)

Figure 12. (a) ANN-NAR wheat commodity price prediction screen; (b) wheat commodity price actual-predicted value graph.

The correlation value of the regression obtained with the values in Figure 12(a) and Figure 12(b) show the total success rate of the network for the wheat commodity price data covering the period 30/07/2019 - 25/07/2025. It is seen that the total success of the artificial neural network for the wheat commodity data is

99.536% with the "All R" value. As can be seen in Figure 13, the ANN-NAR estimation yielded successful results for the wheat commodity price data.

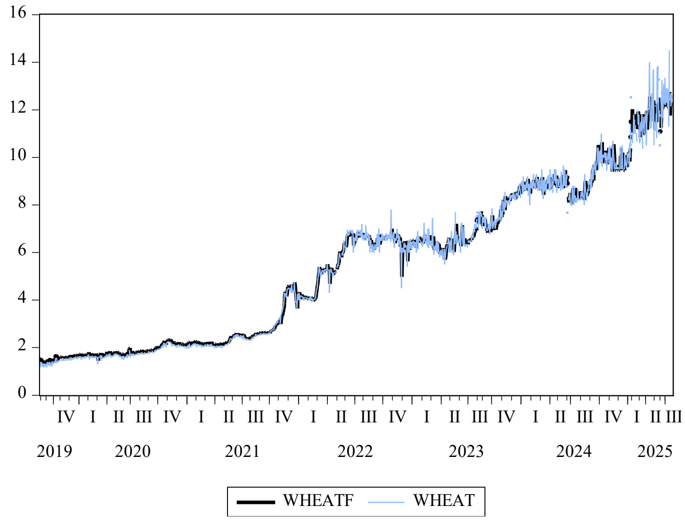
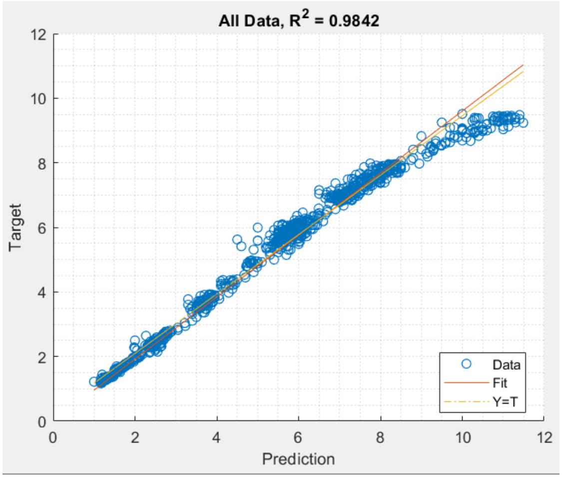


Figure 13. ANN model actual (WHEAT)-prediction (WHEATF) graph.

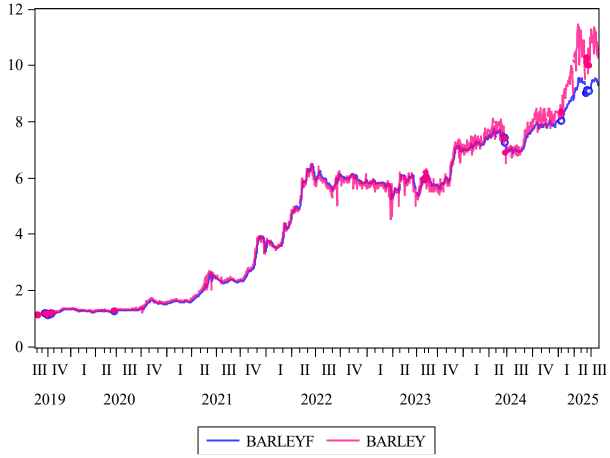
4.2.3. LSTM Model

In this section, the LSTM model, a deep learning method, was used to predict agricultural commodity prices (barley, corn, wheat). The best-performing model for training the LSTM neural network with 200 epochs is presented for prediction findings.

4.2.3.1. LSTM Model Forecast Results for Barley Commodity Price



(a)

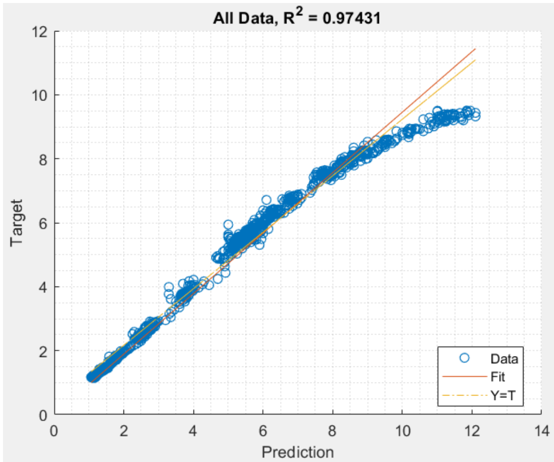


(b)

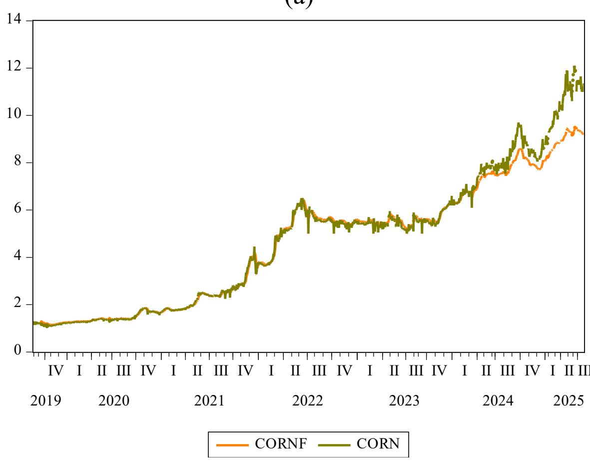
Figure 14. (a) LSTM model prediction success; (b) LSTM model actual and prediction graph (barley).

Figure 14(a) shows the total success rate of the network covering the period 30/07/2019 - 25/07/2025. The total success rate of the LSTM neural network for the barley commodity data is seen to be 98.42% with the "All R" value. As seen in Figure 14(b), the LSTM estimation yielded successful results for the barley commodity price data.

4.2.3.2. LSTM Model Forecast Results for Corn Commodity Price



(a)

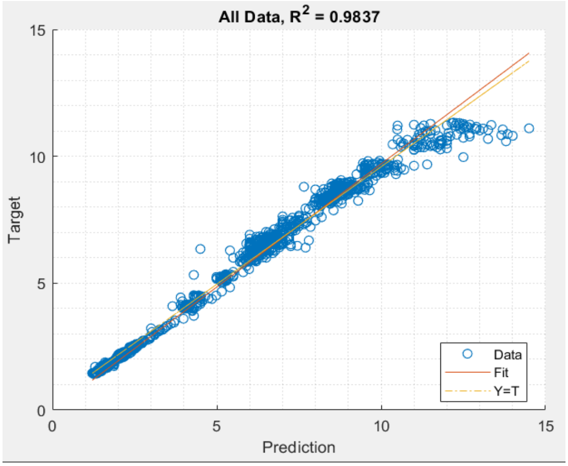


(b)

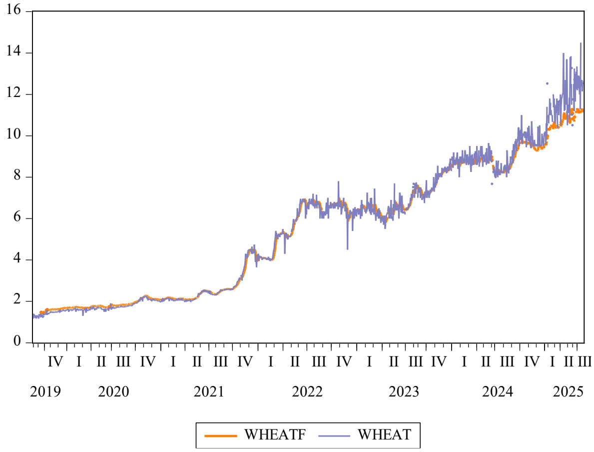
Figure 15. (a) LSTM model prediction success; (b) LSTM model actual and prediction graph (corn).

Figure 15(a) shows the total success rate of the network covering the period 30/07/2019 - 25/07/2025. The total success rate of the LSTM neural network for the corn commodity data is seen to be 97.43% with the "All R" value. As seen in Figure 15(b), the LSTM estimation yields successful results for the corn commodity price data.

4.2.3.3. LSTM Model Forecast Results for Wheat Commodity Price



(a)



(b)

Figure 16. (a) LSTM model prediction success; (b) LSTM model actual and prediction graph (wheat).

Figure 16(a) shows the total success rate of the network covering the period 30/07/2019 - 25/07/2025. The total success of the LSTM neural network for the wheat commodity data is seen to be 98.37% with the "All R" value. As seen in Figure 16(b), the LSTM estimation yields successful results for the wheat commodity price data.

4.2.4. Model Performance Comparison

Table 5 shows the error criteria values calculated based on the prediction results of ARIMA from the time series models, ANN from the machine learning methods and LSTM from the deep learning methods, where the prediction performances for agri-cultural commodity prices (barley, corn, wheat) in Türkiye are compared.

Table 5. Model performance comparison (ARIMA, ANN, LSTM).

Model	Barley	Corn	Wheat
MSE			
ARIMA	1.003451	1.003812	1.003970
ANN	**0.015391**	**0.031464**	**0.105243**
LSTM	0.255758	0.134639	0.187709
RMSE			
ARIMA	1.001724	1.001904	1.001983
ANN	**0.124061**	**0.177381**	**0.324411**
LSTM	0.505725	0.366932	0.433254
MAE			
ARIMA	1.001664	1.001745	1.001983
ANN	**0.077003**	**0.110122**	**0.207174**
LSTM	0.238632	0.195582	0.233815
MAPE			
ARIMA	34.496115	34.865140	29.361938
ANN	**1.679932**	**2.220473**	4.146396
LSTM	3.557176	3.608788	**4.131567**

As seen in Table 5, the MSE, RMSE, and MAE error metrics for agricultural commodity prices for barley, corn, and wheat are the lowest in the ANN approach, one of the machine learning methods, while the LSTM deep learning method provides the lowest MAPE metric. Forecasting the prices of strategically important agricultural commodities in Türkiye is crucial for agricultural sustainability. The study findings support the conclusion that machine learning and deep learning methods provide more consistent and reliable results in agricultural commodity price forecasting than traditional time series methods.

5. Discussion

Agricultural sustainability carries different meanings across disciplines: for agriculturists, it is the continuation of the Green Revolution; for ecologists, it is food production while preserving natural resources; for economists, it is the efficient use of re-sources; and for sociologists, it is agriculture that upholds traditional values [41]. Bathaei and Štreimikienė view sustainable agriculture as a holistic approach that aims to improve the living standards of farmers and society in terms of environmental, economic, and social dimensions while meeting current and future food needs. They emphasize that it is crucial for all components to adhere to sustainability for this improvement to be achieved [42]. The common denominator of these different approaches is to ensure the continuity of agricultural production and food security. In this regard, agricultural price forecasting stands out as a crucial component of sustainable agriculture. Agricultural product prices directly impact not only producer incomes but also consumer welfare, price stability, and food security, thus the entire world. Price fluctuations in agricultural products with high global demand and production, such as barley, wheat, and corn, have a wide impact, from producers to consumers, market stability, and economic policies. Future price forecasts for these products reduce the risk of overproduction or scarcity, ensuring efficient use of resources, preventing market volatility, and providing a scientific basis for the development of sustainable agricultural policies. In today's world, with increasing uncertainties such as global warming and supply-demand shocks, the need for statistical and artificial intelligence-based models for agricultural price forecasting is increasingly urgent.

This study presents a forecasting framework to support sustainable agricultural policies by demonstrating the success of three different modeling techniques in price forecasting. Forecasts for barley, corn, and wheat, key commodities for Türkiye due to their share of producer income and their role in the economy, offer important implications. Of the three models used, ANN and LSTM performed better than ARIMA in terms of error measures. This can be explained by the ability of AI-based methods to more effectively capture the volatility, nonlinear dynamics, and long-term dependencies inherent in agricultural commodity markets, based on barley, corn, and wheat prices. ANN, in particular, generally provided the most stable and reliable results, consistent with similar findings reported in the literature. ARIMA, on the other hand, underperforms other models in capturing fluctuations in agricultural price series with its high MAPE values despite low absolute error values. Similar findings are found in the literature [43-47]. Achieving price stability and managing uncertainties are considered important goals in the economic dimension of sustainable agricultural policies. In this context, the study findings offer both theoretical and practical implications, once again emphasizing the importance of using advanced forecasting methods.

6. Conclusions and Recommendations

The findings of the study reveal the distinct strengths of statistical and artificial intelligence-based models used in forecasting agricultural commodity prices. Accurate forecasts play a critical role, particularly in developing sustainable agricultural policies, optimizing production planning, and predicting market fluctuations. In a country like Türkiye, which holds strategic importance in agricultural production, the effective use of such models not only provides academic benefits but also enables the strengthening of decision-support mechanisms for policymakers and producers. Therefore, the study's results strongly emphasize the indispensability of scientific forecasting models in achieving sustainable agricultural goals.

This study has several limitations. First, the analysis was conducted solely on data specific to Türkiye, and the failure to consider market conditions and structural dynamics across different countries limits generalizability. Furthermore, the models used only historical price series and did not include macroeconomic and environmental variables. This partially prevents the model from reflecting all dimensions of agricultural price dynamics. Future studies can be developed to address these limitations. Using multiple variables together can increase the predictive power of models. Furthermore, comparative findings from different countries will be important for testing the effectiveness of methods in agricultural price forecasting. Furthermore, different machine learning and deep learning approaches can provide more comprehensive forecasts. Finally, conducting multidimensional assessments of price forecasts, considering not only their statistical accuracy but also their applicability to agricultural sustainability and policymakers, will be a significant contribution to future research.

It is expected that future studies will enrich the knowledge in this field with larger data sets, different methodological approaches, and the integration of climatic and economic factors, and will contribute to the development of stronger decision support systems for sustainable agricultural policies.

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CHAPTER 9

Assessing ASC certification in rainbow trout aquaculture: Implications for water quality and environmental management

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1. INTRODUCTION

Aquaculture refers to the controlled production of fish, mollusks, crustaceans, and aquatic plants through regular stocking, feeding, and protection from predators and diseases (FAO, 2011; ASC, 2019a). While aquaculture contributes to meeting the seafood demand of a growing population, it also has the potential to alleviate fishing pressure on wild stocks. Through the application of appropriate resources, species selection, and targeted investments, aquaculture now accounts for more than 50% of global seafood consumption (Bush et al., 2013). A similar trend has been observed in Turkey, where aquaculture production has even surpassed the global growth rate (TÜİK, 2023).

1.1. Need for Certification

Certification is the process by which an official or officially recognized body provides written or equivalent assurance that a product, process, or service conforms to specified requirements. It is based on a series of activities, including continuous monitoring of the production chain in accordance with defined standards (FAO, 2011; Washington and Ababouch, 2011). Aquaculture, often referred to as the "blue revolution," has necessitated addressing environmental and social concerns such as water pollution, ecosystem degradation, and poor labor standards (Bush et al., 2013). Rapid growth combined with inadequate management may lead to on-farm problems, water pollution, ecosystem degradation, and poor working conditions. As production intensifies, the potential impacts on farms and surrounding communities increase. At the same time, consumer awareness of the environmental consequences of aquaculture is rising, and farming companies are increasingly adopting third-party certification as part of their sustainability strategies (Lee, 2009; Bray, 2018). To address these

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challenges and mitigate environmental and social impacts, comprehensive and effective regulatory frameworks, standards, certification schemes, and management practices are required (Fletcher, 2021).

To this end, FAO has developed technical guidelines on aquaculture certification, outlining principles, standards, accreditation, and certification rules, and emphasizing the importance of voluntary environmental and social sustainability (FAO, 2011). These guidelines include provisions on animal health and welfare, food safety, environmental integrity, and socio-economic issues, while also specifying minimum criteria. Following their publication, several private certification schemes emerged, including the Aquaculture Stewardship Council (ASC), Aquaculture Certification Council (ACC), Best Aquaculture Practices (BAP), Friend of the Sea (FOS), GlobalG.A.P., Global Aquaculture Alliance, and the Royal Society for the Prevention of Cruelty to Animals (RSPCA) (Washington and Ababouch, 2011; Bush et al., 2013; Bray, 2018; RSPCA, 2018; Nielsen et al., 2018; FOS, 2023). These private schemes often developed in contexts where national regulations and sustainability practices were perceived as insufficient. Certification has since become an important component of international fish trade and marketing, and is increasingly applied to ensure food safety, quality, and environmental sustainability in the rapidly expanding aquaculture sector (Washington and Ababouch, 2011).

1.2. Objectives and principles of certifications

Certification schemes should encompass activities that safeguard the health and welfare of farmed animals. This objective can be achieved through the minimization of stress, reduction of disease risks, and maintenance of a healthy rearing environment throughout the production cycle. Water quality and its management are of critical importance in achieving these aims. Water used in aquaculture should meet standards suitable for human consumption and food production, and untreated wastewater must not be used. In cases where treated wastewater is utilized, the World Health Organization (WHO) guidelines on the safe use of wastewater and excreta in aquaculture should be strictly followed. Furthermore, aquatic animals, genetic materials, and other products must comply with relevant regulations to prevent the introduction or spread of diseases and infectious agents (FAO, 2011; Washington and Ababouch, 2011).

Aquaculture should be planned and implemented in an environmentally responsible manner, in compliance with relevant laws and regulations. Certification schemes are expected not only to ensure compliance but also to promote the restoration of habitats and areas degraded by previous farming activities. As aquaculture may exert environmental pressures, certification standards should require that such impacts are identified, and that adverse effects are mitigated or reduced to acceptable levels in accordance with regulatory frameworks. The use of native species should be prioritized whenever feasible, and measures should be adopted to minimize accidental releases or escapes into the wild (FAO, 2011).

The fundamental basis of aquaculture standards and certification lies in animal welfare, environmental protection, and sustainability (FAO, 2017; RSPCA, 2018; Massa et al., 2021). Certifications are increasingly adopted due to their contributions to improved product traceability, animal health and welfare, food safety, environmental performance, and working conditions, as well as by providing information that supports consumer decision-making. Nevertheless, certifications also raise concerns—among producers, regarding the burden of multiple certification requirements, and among consumers, regarding confusion created by the proliferation of eco-labels (Nielsen et al., 2018; Amundsen and Osmundsen, 2020).

1.2. Certification of Trout Farming

Rainbow trout, RT (*Oncorhynchus mykiss*) is native to the Pacific waters of North America and, since 1874, has been introduced, bred, and adapted to waters across Europe, Asia, Australia, South America, and Africa. Its adaptability has long made it one of the most important species in aquaculture. In 2018, global RT production reached approximately 850,000 tons, accounting for about 2% of total aquaculture output. Farming methods include land-based ponds, net cages in lakes and reservoirs, recirculating aquaculture systems (RAS), and marine cages. Most production occurs in freshwater, with Iran and Turkey as the largest producers, alongside significant output in several European countries and Chile (ASC, 2023b). Because RT naturally have a marine stage in their life cycle, their sea farming practices are similar to those of salmon. In Turkey, for example, freshwater trout farming is certified under freshwater standards, while marine farming is certified under salmon standards (ASC 2020; ASC 2023a, b).

The relative importance of stakeholder interests and expectations in certification depends on the species and production system. For trout farming, the highest concerns include land and water use (water quality management), feed and other resource use, nutrient enrichment and water pollution, predator control, antibiotic and chemical use, and genetic impacts. Medium-level concerns include benthic biodiversity loss, degradation of bottom habitats, and disposal of dead fish. Lower-level concerns involve disease transmission, fish escapes, invasive species, and consumer issues (Boyd et al., 2005). However, these priorities may shift depending on the production system (ponds, cages, tanks, RAS, freshwater, or marine).

High suspended solid matter (SSM) in effluents of land-based farms can increase sedimentation near outlets, harming benthic organisms. Concerns about benthic impacts are even greater in cage culture. Sedimentation beneath seacages can be 2–20 folds higher than reference sites, while in freshwater lakes it can reach 100–200 folds higher. Sediment accumulation is typically limited to within 50 m of the cage center (Boyd et al., 2005). Such accumulation negatively affects aquaculture (by reducing DO, producing toxic gases, turbidity) and the surrounding environment (through eutrophication, benthic damage, biodiversity loss, and algal blooms).

1.4. Aquaculture Stewardship Council (ASC)

The Aquaculture Stewardship Council (ASC) was established in 2009 with support from WWF as an initiative to address challenges arising of rapid expansion of aquaculture (Bush et al., 2013; Nielsen et al., 2018). It operates as an independent, not-for-profit, third-party certification/ labeling program based on scientifically robust standards. These standards were developed in line with FAO guidelines (FAO, 2011) to promote environmental sustainability and social responsibility, and to support best practices in aquaculture (ASC, 2023b). ASC is the only full member of ISEAL, the Alliance for Social and Environmental Standards, recognized in the aquaculture certification category (Nielsen et al., 2018; ASC, 2019a, b).

The ASC standards aim to improve the management of fish farming, minimize negative environmental and social impacts, and contribute to meeting the growing demand for seafood. The certification framework focuses on compliance with national legislation, protection of habitats, biodiversity, and ecosystem integrity, maintaining the health and genetic diversity of wild populations, responsible resource use, and environmentally sound disease management. Social dimensions include ensuring fair and responsible farm operations, maintaining good community relations, and applying standards to suppliers of juvenile fish (ASC, 2023b). Particular emphasis is placed on mitigating benthic impacts, protecting water quality, managing nutrient discharges, and minimizing interactions with sensitive habitats, species, and wildlife (ASC, 2019a, b).

Water quality and environmental management are central to aquaculture sustainability. A quaculture plays a key role in reducing pressure on overexploited wild stocks while supporting food security, employment, and economic development. For Mediterranean-Black Sea region, where Turkey holds a central position, FAO (2017) identified 3strategic goals. The second of these calls for aquaculture to: (a) integrate fully with the ecological environment while protecting ecosystem services; (b) ensure adequate health and welfare of farmed aquatic animals; and (c) promote collaborative research and technological development on aquaculture–environment interactions, guided by industry and farmer needs (FAO, 2017; Massa et al., 2021). ASC certification of RT farming in Turkey began with a pilot audit in 2013, followed by applications for RT and other species in 2014. Prior to certification, several studies assessed the environmental impacts of trout farms in the region under national water pollution control legislation and EU directives on freshwater quality for fish life (EC, 2006). These investigations reported a number of negative impacts (Yıldırım and Pulatsü, 2011; Bulut et al., 2011, 2012; Sasi et al., 2017). Further research addressed the selection of effective water quality parameters and the development of water quality indices for farm inflows and outflows (Koçer and Sevgili, 2014). More recently, the introduction and implementation of aquaculture certification programs in Turkey—particularly in Southwestern Anatolia—have been examined by Hazırbulan and Çetinkaya (2023) and Hazırbulan (2024). This study evaluates the development, effectiveness, and shortcomings of the ASC freshwater trout standard and certification process, with particular attention to water quality and environmental management in aquaculture farms of the study area.

2. MATERIAL AND METHODS

2.1. Study Area

A list of aquaculture farms in Southwestern Anatolia (Muğla, Denizli, Burdur, and Aydın) producing RT (*O. mykiss*) under ASC "Freshwater Trout" certification was compiled from the records of the Ministry of Agriculture and Forestry of Turkey (MoAF) (ASC, 2020; MoAF, 2023). Following consultations with the owner companies and management bodies, and considering transportation, accessibility, and permission constraints, six farms were selected for site visits, surveys, and observations:(i) Abalıoğlu Lezita Balıkçılık Seydikemer Tesisi (Muğla), (ii) Selina Balıkçılık Seydikemer Tesisi (Muğla), (iii) Gümüşdoğa Su Ürünleri Sahilceylan Tesisi (Muğla), (iv) Özpekler Su Ürünleri Fethiye Tesisi (Muğla), (v) Özpekler Su Ürünleri Gölhisar Yapraklı Barajı Kafes Tesisi (Burdur), and(vi) Kılıç Deniz Ürünleri Bafa-1 Gölü Kafes Tesisi (Muğla–Aydın) (Figure 1; Table 1).

After preliminary interviews and planning, the selected farms and relevant administrative bodies were visited. Face-to-face surveys were conducted with facility managers and employees, direct observations were made on site, and photographs were taken—with permission from farm managers—focusing on features relevant to water quality and environmental management.

2.2. Survey design, implementation, observations, and interviews

Water quality and environmental management within aquaculture certification is a relatively new field of study in Turkey. To date, no standardized surveys or published research tools exist to evaluate certification practices. Therefore, the survey used in this study was designed by the authors in accordance with general principles of survey preparation (Hoston, 2002). In developing the questions, the following sources were considered: the basic principles and objectives of certification, the ASC Freshwater Trout Standard (AFT v1.2) (ASC, 2019b), national aquaculture regulations, official audits and inspections carried out in Turkey (MoAF, 2006, 2018, 2023a), and personal field observations.

The final survey comprised 31 open-ended, pre-informed questions (SQs), which were administered to targeted participants. Responses were collected in written form. The full set of questions, along with their purposes and justifications, are provided in Hazırbulan (2024, Appendix C). Data obtained from the surveys were entered into Excel spreadsheets for organization and analysis. Ethics approval for the survey was obtained from the Ethics Committee of Isparta University of Applied Sciences (Hazırbulan, 2024, Appendix D).

Survey responses were grouped into three main categories: i) survey participants and farm information, ii) ASC certification applications—successes, challenges, and prevalence, and iii) water quality, environmental management, and impact assessment. In addition, developments in ASC AFT versions (v1.0, v1.1, v1.2) and in the ASC Salmon Standard (SS v1.4) were reviewed. Complementary information and opinions were also collected from local ASC certification bodies.

Figure 1. ASC certificed RT farms in South-western Anatolia (◎ surveyed and examined; ▲ other farms)

3. RESULTS

3.1. Development of the ASC Freshwater Trout Standard

The ASC Freshwater Trout Standard (AFT) has undergone successive revisions since its initial release.

AFT v1.0. The first version of the standard (AFT v1.0) was completed following scientific studies and stakeholder consultations, approved by the Freshwater Trout Aquaculture Dialogue Steering Committee, and formally adopted by ASC. It was published in January 2013 and entered into force immediately (ASC, 2013). The aim of AFT v1.0 was to provide a framework for measurably reducing or eliminating negative environmental and social impacts of trout farming. It outlined best practices in environmental management, social responsibility, fish health, and feed composition.

In terms of ***environmental impacts***, the standard introduced criteria for water quality, effluent management, and habitat protection, offering basic guidelines to minimize the ecological footprint of freshwater trout farming. For ***feed sustainability***, it emphasized responsible sourcing of feed ingredients, reducing reliance on wild fish (fishmeal), and promoting sustainable feed practices. With respect to ***fish health and welfare***, it established general standards for disease management, humane treatment, and welfare monitoring. Finally, for ***social responsibility***, the standard set initial criteria for worker rights, fair treatment, and community engagement.

AFT v1.1. In 2019, AFT was revised to incorporate new knowledge, stakeholder feedback, and advances in aquaculture practices. Although finalized, version 1.1 was not published (ASC, 2019a). This version was organized under ***seven principles*** addressing key environmental and social concerns in trout farming: (i) compliance with all national regulations, (ii) protection of habitat and biodiversity, (iii) minimization of impacts on aquatic resources, (iv) reduction of disease transmission risks and proactive monitoring of fish health, (v) environmentally responsible use of resources, (vi) maintenance of social responsibility, and (vii) requirements for suppliers of fingerlings and eyed eggs. Compared to v1.0, ***environmental requirements were strengthened***, with stricter criteria for water quality and effluent management, and enhanced guidance for habitat protection and biodiversity conservation. ***Feed sustainability standards*** were also expanded, requiring updated sourcing practices aligned with newer sustainability benchmarks, improved traceability of feed ingredients, and reduced environmental impacts of feed production.

AFT v1.2. The most recent revision, AFT v1.2, was published in July 2019 and came into force in December 2019 (ASC, 2019b). Building on v1.1, this version introduced ***specific application criteria for freshwater net-cage trout farming in lakes and reservoirs***, thereby broadening the standard's scope to reflect production practices increasingly used in many regions. The full Turkish translation of AFT v1.2 is provided in Hazırbulan (2024, Appendix A). In line with ASC policy, the standard is subject to ***periodic review every 3–5 years*** to ensure its continued effectiveness, incorporating the latest scientific knowledge and best practices. AFT v1.2 has been applied in inland waters across Turkey, providing the regulatory and certification framework for ASC-approved freshwater trout farming.

ASC Salmon Standard v1.4 (SS v1.4) was first developed by the Salmon Aquaculture Dialogue Steering Committee and formally adopted by ASC as version 1.0 in July 2012. Since then, the standard has undergone several revisions and updates to reflect evolving scientific knowledge, production practices, and stakeholder expectations. The current version, SS v1.4, was published in September 2022 and became mandatory in February 2023 (ASC, 2022). It defines the latest requirements for responsible salmon farming. In Turkey, RT (*O. mykiss*) is also produced in marine net cages, particularly in the Black Sea. The product is marketed as "***Turkish salmon***," and ASC certification for these farms follows the SS v1.4 framework. SS v1.4 establishes detailed requirements across several domains:

- ***Water quality and waste management*****:** includes limits for nitrogen and phosphorus discharges, requirements for monitoring and minimizing impacts on recipient waters, and preparation of solid waste and sludge management plans.

- ***Chemical use and escapes*****:** emphasizes restrictions on chemical inputs, fish escape prevention/ monitoring, reporting obligations, and maintaining impacts within acceptable limits.

- ***Environmental management*****:** requires environmental impact assessments (EIA), reduction of potential environmental effects through monitoring programs, habitat protection, site selection principles, and mitigation of benthic zone impacts.

- ***Biodiversity protection*****:** addresses risks related to escapes, genetic interactions, predator management, and minimization of adverse effects on native species and ecosystems.

The standard prioritizes ***practices that are both stringent and monitorable***, enabling stronger control over water quality, environmental management, and biodiversity conservation (ASC, 2022). In addition, *several annexes* were introduced with SS v1.4:

- ***Annex 1*** provides detailed methodologies water pollution assessing, water quality, environmental impacts. It specifies indicators such "fauna indices, macrofaunal taxa, biotic indices, sulfide and redox potential, Cu, DO, dissolved organic substances (DOS), and nutrient sampling methods, alongside biodiversity-focused impact assessments.

- ***Annex 8*** outlines water quality management in juvenile fish production, including calculation of TP per ton of fish produced, data-sharing protocols, and monitoring methods for land-based facilities. It also describes benthic macroinvertebrate sampling procedures, waste and sludge management practices for closed and semi-closed fingerling farms, and carrying-capacity evaluation methods for net-cage operations (ASC, 2022).

By these updates, SS v1.4 represents a significant step toward stricter, measurable, and science-based certification of salmonid aquaculture, including Turkey's marine-farmed RT.

New ASC Farm Standard

Currently, ASC operates with 12 species-specific standards. To enhance coherence across species and production systems, ASC has initiated the development of a unified ***Farm Standard***. This process involves broad stakeholder consultation and integration of the latest scientific data, aiming to establish a single framework applicable to all aquaculture farms (ASC, 2024a,b,c). The new Farm Standard is structured around four core principles: ***Farm management; Environmental responsibility; Social responsibility and Fish welfare.***

Among these, ***fish welfare is positioned at the center of the initiative***, with emphasis placed on the characteristics of the water source (e.g., hydrological flow, morphology, bathymetry) and the type of farming system employed. This represents a shift toward a more holistic and welfare-oriented perspective, ensuring that production practices are aligned not only with environmental and social criteria but also with the physiological and behavioral needs of the farmed species (ASC, 2024a,b,c).

3.2. ASC Trout Certification in Turkey

Following the publication of AFT v1.1, pilot audits were conducted in a trout farm located in Kahramanmaraş, Turkey, in 2013. Subsequently, certification applications expanded to RT farms in Southwestern Anatolia in 2015. The first certified farm in Turkey was Özpekler Karaçam land-based farm in Köyceğiz, Muğla in 2016. As of April 2024, a total of 20 farms hold ASC certification for RT production. Of these, twelve (60%) operate as net cage farms (11 in dam lakes and natural lakes, 1 in the Black Sea), while eight (40%) are land-based farms established on rivers (Table 1). Farm numbers, types, production data, and certification validity periods are subject to change; for up-to-date information, ASC's official database can be accessed at https://asc-aqua.org/find-a-farm/.

The study area represents one of the key RT farming regions of Turkey (Figure 1). Within this area, 11 ASC-certified RT farms are located in the provinces of Muğla, Aydın, Denizli, and Burdur. Among them, eight are land-based farms and three are net cage farms. Six of these farms, which were observed and surveyed for the present study, account for 55% of ASC-certified farms in the region. Ministry of Agriculture and Forestry (MoAF, 2023) records, farm distribution in the study region is as follows: 51 farms (17 RT) in Aydın, 100 farms (100 RT) in Denizli, 300 farms (157 RT) in Muğla, 82 farms (79 RT) in Isparta, 50 farms (49 RT) in Burdur, and 87 farms (73 RT) in Antalya, totaling 670 facilities, of which 475 (70.8%) produce RT. Within this regional context, the share of ASC-certified RT farms (11 farms) is 2.32%, whereas at the national scale (20 farms) the certification rate remains below 1%.

Table 1. ASC certificated RT farms in Turkey (https://asc-aqua.org/find-a-farm/)

Company	**Certificate type Nr.**	**Farm(s)**	**Species**	**Cert. date**	**Expry date**	**ASC Standards**
Özpekler Su Ürünleri	Multi site- 4 ASC-00203	Özpekler su Ürünleri -	RT *O. mykiss*	05.09.2021	04.09.2024	AFT v1.2
Karaçam land farm, Karaçam Köyceğiz Muğla 2) Gölhisar net cage farm and Asmalı hatchery, Burdur (*) 3) Fethiye land farm Fethiye, Muğla(*) 4) Özpekler-2 trout farm Çameli, Denizli						
Gümüsdoğa Su Ürünleri Üretim İhr. İth. A.Ş.	Multi site- 2 ASC-00206	Ballica farm	RT *O. mykiss*	19.06.2023	18.06.2026	AFT v1.2
Çırçır Alabalık-1 Karakaya DL 10th sec. 2) Keban trout-5 Karakaya DL 10th sec.						
Gümüsdoğa Su Ürünleri Üretim İhr. İth. A.Ş.	Single site ASC-00208	Geyiktasi Karakaya DL 9th sec.	RT *O. mykiss*	19.06.2023	18.06. 2026	AFTv1.2
Gümüsdğa Su Ürünleri Üretim İhr. İth. A.S.	Multi site - 3 ASC-01870	Hakan Keban Area	RT *O. mykiss*	23.10.2020	18.06. 2023	AFT v1.2

Hakan yem 950 t/y trout project, Karakaya DL 9th sec. 2) Net cage 450 t/y trout farm project Keban DL 3th sec. 3) Öz-Bet trout Karakaya DL 10th sec.						
Gümüsdoğa Su Ürünleri Üretim İhr. İth. A.Ş.	Single site ASC-00210	Sahilceylan farm (*)	RT *O. mykiss*	014.02.2023	13.02.2026	AFT v1.2
Selina Fish Su Ürünleri Ltd.Sti.	Single site ASC-00211	Selina Fish Alabalik Ürt. Tes. Rev. Prj.(*)	RT *O. mykiss*	05.08.2023	04.08.2026	AFT v1.2
Gümüsdoğa Su Ürünleri Üretim İhr. İth. A.Ş.	Single site ASC-00212	Yaniklar Can alabalık Farm	RT *O. mykiss*)	26.02.2023	15.02.2026	AFT v1.2
Abalıoğlu (Lezita Balık) A.Ş	Single site ASC-00207	Fethiye Land farm (*)	RT *O. mykiss*	13.03.2024	12.03.2027	AFT v1.2
Kılıç Deniz Ürünleri Üretim İhr.İth. Tic. A.Ş.	Single site ASC-F-0149	Bafa-1 Net cage trout farm Project (*)	RT *O. mykiss*	18.09.2023	17.09.2026	AFT v1.2
Kemer Su Ürünleri Üret. Tic. A.Ş.	Multi site-2 ASC-F-0028	Kemer DL. Amasya Köyü	RT *O. mykiss*	05.03.2024	15.03.2027	AFT v1.2
Bağcı Amasya Köyü 100. Yıl Revize Alabalık Prj. 2) Kemer DL kafeste Alabalık rev prj.						
Gümüsdoğa Su Ürünleri Üretim İhr. İth. A.Ş.	Single site ASC 01570	İskele Su ür. cage Derbent DL	RT *O. mykiss*)	17.06.2021	16.06.2024	AFT v1.2
Gümüsdoğa Su Ürünleri Üretim İhr. İth. A.Ş.	Single site ASC 01850	Hakan Sinop projesi, cage Blacksea	RT *O. mykiss*	23.05.2022	22.05.2025	SS v1.4.
Liman Entegre Balıkçılık san. Tic. Ltd. Şti	Single site ASC 01912	Liman Entegre Farm	RT *O. mykiss*	01.09.2022	31.08.2025	AFT v1.2

(*)The farms visited, surveyed and observed in this study

a **b**

c

d

e

f

Figure 2. The observed and survey conducted farms and their facilities a) Abalıoğlu-Lezita's concrete ponds (b) Özpekler Gölhisar Yapraklı's net cages c) Gümüşdoğa Sahilceylan farm's ozone generator d) Selina Fish Seydikemer's concrete ponds e) Gümüşdoğa Sahilceylan farm's drum filters f) Özpekler Fethiye-Eşen farm's ponds (Photo by S.Hazırbulan)

3.3. Survey Results

Participants completed 31 survey questions (SQs) (Hazırbulan, 2024, Appendix C) independently of one another. The survey addressed professional background, responsibilities, work experience, farm production characteristics, ASC certification, water quality and environmental management, environmental impact assessment, and associated analyses and audits. Key issues related to ASC certification, achievements, shortcomings, water quality, and environmental management are summarized below. In accordance with ethical principles, responses are not presented at the individual farm level.

3.3.1. Survey participants and farms

Among the 14 survey participants, 9 were engineers (64.29%), 3 were quality managers/engineers (21.43%), 1 was a manager/regulator (7.14%), and 1 was a worker/foreman (7.14%). Their work experience on farms ranged from 1–5 years, 5–10 years, 10–15 years, to more than 15 years. The majority of participants (n = 9) were employed at farms located along the Eşen River (Seydikemer, Muğla), while 3 were from the Bafa-1 net-cage facility and 2 from the Yapraklı Dam Lake (DL) net-cage farm in Gölhisar, Burdur. Four of the surveyed farms were land-based and utilized water from the Eşen River. Two farms operated net-cage facilities, one in Lake Bafa (a natural freshwater/brackish lake) and the other in Yapraklı Dam Lake.

Market-size production capacities ranged from 250 to 2,500 tons per year, whereas fry/fingerling production capacities varied between 7×10^6 and 57×10^6 per year. In addition to meeting their own demand for fingerlings, farms in the study region also supplied a substantial proportion of the fingerling requirements of net-cage farms in other regions of Turkey. While RT represented the principal species produced, some companies also cultured European sea bass (*Dicentrarchus labrax*), gilthead sea bream (*Sparus aurata*), and meagre (*Argyrosomus regius*) in marine net-cage systems.

With the exception of one farm, certifications were obtained under AFT v1.2 in Turkey. One farm producing RT smolts in net cages off the Sinop coast in the Black Sea was certified under SS v1.4 (Table 1). All ASC-certified farms also held GlobalG.A.P. Aqua certification. Additionally, four farms held BRC certification, two held IFS certification, two held Halal certification, and one held ISO 22000, ISO 9001, SEDEX, and BFC certifications.

3.3.2. Application, achievements, challenges and prevalence of ASC certification

• *Is any restrictions in repeated monitoring and audits? What are the most important of them?* (SQ.14) yes (12), no (2); high costs (10), bureaucratic obstacles and difficulties (4), insufficient monitoring/audits expertise (1) are reported as restrictions.

• *Were there any errors in site selection and farm construction? If yes, what are they and their negative consequences?* (SQ.19) no (8) yes (6); experienced problems are listed as not appropriate pond shape, depth and wall thickness (5), old and impractical buildings (4), built close to/next to residential areas (3), built in a place open to waves/storms and have security risk (2), elevation difference, water intake and discharge problem (1).

• *Is there a certification and audit folder file in farm? Which files and information are stored in this folder?* All participants (14) answered yes to the question (Q.23), and regarding the folder content, veterinary health plan (12), production records (11), waste management plan (11), water quality analysis reports (11), drug and vaccine applications (9), audit reports (7), feed analyses (7), MoAF provincial/district directorate documents (6), licenses (5), certification documents (4), instructions and guidelines (3), training records (2), no knovledge (1).

• *Is certification useful and effective? Can it be dispensed with?* (SQ.25); yes (12), no (2); no, it should be continued (12), yes, it can be dispensed with (2), *What are the benefits*? It provides a quality product and traceable production (7), increases market share (6), increases exports (4), but they pointed out that scertification creates high costs for farm.

• *Is certification effective and widespread in Turkey?* (SQ.28) effective (10), not effective (2) no knowledge (2); There is no evaluation regarding prevalence. While providing market opportunity (6), providing customer/consumer confidence (4), increasing exports (4), traceable production (4) and quality fish production (2) are emphasized as evidence of effectiveness and advantages; the need for certification training and implementation (12), high cost of certification (11), multitude of bureaucratic procedures (2) are listed as disadvantages.

• *How can training be provided for certification, implementation and audits?* (SQ.29); should be provided by certification body (10), a course should be included in the undergraduate curriculum (6), be provided by MoAF units (3), Turkish versions of standard and certification documents should be provided (3), and no idea (1) about the training method.

• *Is easily accessible to ASC? In what ways?* (SQ.30), yes (10), no/I don't know (4); and by tools such internet, telephone, fax (9), accredited consultancy companies (3).

• *What are the successes, challenges, deficiencies and prevalence of ASC certifications (SQ.31),* traceable sustainable, quality fish production (9), providing appropriate working conditions (4), exportation, employment and foreign exchange input (5), giving importance to water quality and environmental management (2), customer satisfaction, giving importance to personnel training and health (1); as deficiencies/challenges, high water quality analysis costs (6), lack of a Turkish version of the certification and standard (3), certification aims foreign markets (1), lack of university-private sector collaboration in certification, inadequacy of private and public auditors in certification (1), and no opinion was expressed on prevalence.

3.3.3. Water Quality and Management

- *What analyses and audits are conducted by certification bodies or MoAF offices in farms? (SQ.6)* Reported activities include water quality analyses (12), benthic mud analyses (2), fish analyses (2), as well as solid waste control, feed analysis, and checks for dioxins, pesticides, drug residues, and other contaminants (1).

- *Which national legislation is followed in aquaculture activities, fish health, water quality, and environmental management? (SQ.7)* Aquaculture Regulation (13), Fisheries Law No. 1380 (7), MoAF circulars and local offices' recommendations (7), Food Law (2), and Safety Law (1).

- *What kinds of analyses/measurements are conducted by MoAF local units and accredited laboratories in farms on water quality, environment, and environmental impact assessment? (SQ.8)* BOD, COD, TP, TN (11), TSS (10), temperature and DO (9), pH (8), cyanide (5), benthic monitoring (4), turbidity, conductivity, salinity (4), TRIX index (2) were reported. One respondent reported no information (1).

- *What measures does the certification body require for farming, water quality, environmental management, and environmental impact reduction? (SQ.9)* Reported measures include protection and improvement of water quality (8), chemical and solid waste management (6), implementation of Veterinary Health Plan (6), control of stock density (5), clarification of causes of fish deaths

(4), control of phosphorus ratio in feed (4), compliance with hygiene rules (3), reduction of phosphorus ratio in bottom mud (2), ensuring high feed digestion and low FCR ratio, monitoring feed raw fat ratio, and protection of fish health and welfare (1). One respondent stated "I don't know" (1).

- *Is there a need for additional sampling, measurement, and analysis of water quality in farms? (SQ.10)* Responses: yes (12), no (2). Suggested additional needs include monitoring water quality at inlet and outlet points (11), benthic fauna analysis at sources before water intake and after effluent discharge (10), and pollution monitoring within and around the farm (4).

- *Does the certification body perform water quality measurements and analyses? Which laboratories are employed? (SQ.11)* Responses: yes (13), don't know (1). Analyses are carried out by accredited laboratories (12), MoAF provincial directorates (1), and the Ministry of Environment (1).

- *Are all the analyses and measurements necessary? Should they be reduced? What are the five most important ones? (SQ.16)* Responses: yes, necessary (11); no, not necessary (3). Should not be reduced (8); may be reduced (6). The most important parameters identified were DO (10), TN (10), temperature (9), pH (9), TSS (9), TP (8), benthic fauna analysis (7), COD/BOD (6), heavy metals (4), hygiene and disease control (4), antibiotic analysis (3), sediment analysis (2), and other (1).

- *Are any methods applied in farms to protect and improve water quality? Which methods, and how successful are they? (SQ.17)* Responses: yes (13), no (1). Reported methods include drum filters (8), oxygen tubes (5), natural aeration (4), aerators of different types (4), and ozone generators (3). Reported success: successful (10), very successful (2), unsuccessful (1), cannot be measured (1).

- *What are the common water quantity and quality problems in farms? (SQ.18)* Reported problems include high water temperature (12), decreased water flow rates (12), low DO (8), decreased water levels (6), persistent turbidity (3), gas bubble emergence (CH_4, H_2S, CO_2) (2), and other issues such as high TSS and uneaten feed accumulation (3).

- *What actions are taken when a water quality or environmental problem occurs in a farm? What technical assistance can the facility receive? (SQ.20)* Reported responses: warnings from the certification body regarding insufficient analysis (5), contacting MoAF local units (5), use of oxygen tubes (4), conducting additional water quality analyses (4), stopping feeding and leaving fish unfed (4), emptying and disinfecting problematic ponds (2), taking precautions against algal blooms (2). Some reported no such problems to date (2), no information (2), or that farms were fined by officials (1).

- *How is water quality monitoring carried out in farms? Is there an automation system? (SQ.24)* Monitoring methods: manual device measurements (9), camera-based pond and fish monitoring (3), water quality early warning devices (3), visual observation (2). Regarding automation: yes (7), no (7).

3.3.4. Environmental Management and Environmental Impact Assessment (EIA)

- *Are ecological quality standards applied in the farm's receiving waters (stream, lake, dam lake)? If so, what is the source of the standards? (SQ.12*) Responses: yes (7), no (7). Reported sources include national regulatory legislation (6), ASC standards (5), and accredited laboratories (2).

- *Do amateur fishermen catch trout in the stream, lake, or dam lake used by the farm? If so, to what extent? Are other species also caught? (SQ.13)*Responses: yes (11), no (3). Reported frequencies: occasionally (5), medium (3), a lot (3). Other species mentioned include *Capoeta* sp. (5), common carp (4), eel (3), and others (2).

- *Are there negative effects of birds, reptiles, and rodents on the farm? If so, how are these effects prevented or reduced? (SQ.15)* Responses: yes (13), no (1). Prevention methods include regular pesticide application by contracted companies (8), protective nets over ponds/cages (4), cage roof systems (3), use of sound bombs (3), daily net checks (2), mouse traps (2), and camera monitoring (2).

- *What measures are taken to protect effluent quality and reduce pollution in receiving waters? How effective are these measures? (SQ.21)*Reported measures include drum filters (12), settling ponds (8), inlet–outlet water quality monitoring (4), applying correct stock density (2), compliance with solid waste management rules (2), and SSM value monitoring (1). taking no specific precautions (1), no clear opinions were expressed on measure effectiveness.

- *Does the farm have a solid waste management plan? How are solid wastes disposed of? (SQ.22)* Responses: yes (13), no (1). Disposal methods: delivery to the municipal's solid waste storage and disposal facility (10), delivery to accredited recycling companies (10), no answer (2), unknown (1).

- *What are the negative environmental interactions and problems related to the farm? (SQ.26)* Reported issues include disease and parasite spreading (7), decrease in water quality and water pollution (6), negative impacts on benthic fauna and sediment quality (6), algal blooms and eutrophication (5), impacts of escaped fish (4), use of prohibited drugs (2), uncertainty stocking material origins (1), visual pollution (1), no environmental interactions (1).

- *How can these interactions and problems be reduced? (Q.27)* Suggested measures: preventing fish escapes (5), controlling eutrophication/algal blooms (5), reducing water pollution (5), minimizing negative impacts on benthic fauna/sediment (5). Mentioned specific methods; use of good quality water-resistant materials (feed, medicine, chemicals) (4), regular benthic fauna monitoring (4), construction of escape-prevention structures (4), reducing stock density (4), establishment of water treatment plants (4), drum filter use (3), aeration–oxygenation systems (3), proper adjustment of harvest times (2), reducing feeding rates (2), compliance with licensed capacity (1), regular removal of dead fish (1), improving hygiene conditions (1), adoption closed-system RAS farming (1), and separation of facility sewage (1).

3.4. The local ASC office opinions and proposed solutions to emerged problems

- ***Water quality monitoring and improvement***: Water quality is a fundamental factor for the success of farms, and ASC certification requires continuous monitoring and compliance with standards as a primary obligation. The ASC Freshwater Trout Standard (AFT) mandates regular monitoring of parameters such as DO, DOS, pH, NH_3, and NO_2, along with documented proof of compliance. However, regular monitoring process and correcting problems are time-consuming and costly for farms. In addition, inadequate monitoring mechanisms and inconsistencies in water quality standards create further challenges. To reduce or overcome these problems, ASC encourages the establishment of more effective water quality monitoring systems, continual improvement of existing practices, and strict measures to prevent weaknesses in monitoring and reporting.

- ***Farm sites and environmental impacts****:* Aquaculture activities can affect local ecosystems depending on farm location and design. In land-based systems, inappropriate site selection, poorly planned facility design, incorrect placement of concrete ponds relative to the streambed, and improper slope management can disrupt environmental balance, potentially causing floods, landslides, inundations, damage to water intake facilities, and fish escapes into streams. In net cage farms, insufficient depths between cage bottoms and the lake or reservoir floor, as well as weak bottom currents at some sites, result in organic sediment accumulation and turbidity, which negatively impact aquaculture operations and surrounding ecosystems.

- ***Water pollution:***Some land-based and net cage farms are located very close to agricultural and livestock production areas. N, P and pesticides from agricultural runoff enter the farm sites, leading to water pollution and the spread of pathogens, this reduces production efficiency and increases management challenges. Such problems can be minimized by strict compliance with ASC's requirements for disease and parasite control, environmental management, and water quality standards.

- ***Compliance with national regulations:***Aquaculture is subject to evolving national level environmental regulations. Certification bodies and farms face difficulties in keeping up with renewed legal requirements, frequent regulatory changes complicate the preparation of necessary analyses and documents, and create challenges in transferring updated practices to farm personnel.

- ***Fertilizer, pesticide, and chemical use:***Fertilizers and pesticides used in nearby agricultural areas negatively affect farm water quality and effluent. While ASC certification requires the controlled and sustainable use of these substances, compliance is often costly for farms. Within farms, the use of chemicals and veterinary drugs must be strictly controlled. ASC certification prioritizes environmentally friendly practices, strictly regulates chemical applications, prohibits their use by untrained personnel, and closely supervises their impacts to prevent harm to both the environment and fish health.

- ***Water resources and waste management:*** It is necessary that source water enter to farms continuously at a certain flow rate, this is monitored as a primary requirement. However, in some areas farms face to problems limited water flow rate due to water scarcity by low precipitation or excessive source water use in upstream. It can be frequently observed in certification audits. It is mandatory to treat the effluent whose quality decreases due to aquaculture before discharging it into the receiving water, and to remove the solid waste properly generated by farming activities. Waste management is important in environmental sustainability and compliance with certification requirements. In audits, with/without notice, solid waste management are monitored as a primary requirement. However, wastewater treatment and elimination of solid wastes are costly for farms.

- ***Environmental protection, wild species, fish escapes:*** ASC has established "*primary compliance requirements*" to minimize the impacts of aquaculture to wetlands within the scope of the Ramsar Convention. Aquaculture can affect sensitive habitats, the implementation and monitoring of habitat protection measures require attention in certification process. By the requrements, important contributions are made to environmental protection by implementing strict rules. Local wild species may enter the net cages, certification compliance rules require meticulous and accurate recording of wild species passage into the net cage. In land farms, measures taken to prevent weir blockages, collapses, floods, and net ruptures in net cages and accidental escapes into the environment are strictly monitored, reports are requested and the information is entered into the facility's ASC web data screens. ASC supports and strictly enforces on-site habitat protection and compliance with national regulations. However, differences in national aquaculture and environmental regulations can create confusion in implementation. Therefore, ASC collaborates with local regulators to establish primary guidelines for on-site habitat protection.

- ***Sustainability:*** ASC promotes sustainable aquaculture by strictly monitoring water quality, environmental management, and habitat protection, encouraging farms to operate in environmentally responsible ways. However, these requirements increase operational costs and create additional resource management challenges. Additional water analyses, waste disposal measures, and increased use of vehicles and electricity may be needed to ensure sustainability, all of which raise farm operating costs. ASC collaborates with local regulatory authorities, scientists, and producers to share best practices and organize educational programs aimed at improving water quality monitoring, regulating chemical use, reducing environmental impacts, and promoting sustainable aquaculture. Continuous review and updating of certification programs is essential, as environmental conditions and regulations evolve over time; only with regular updates can sustainability goals be fully achieved. Climate change in farm areas also affects aquaculture, and ASC provides guidance on principles to mitigate these effects and promote resilience.

- ***Training and capacity building***: For effective certification, technical staff-including accredited laboratory personnel, veterinarians, aquaculture engineers, and farm workers-must receive ongoing training in sustainable and traceable aquaculture practices. Training is required for new certification applications, adoption of primary compliance requirements, and monitoring of water quality and environmental management practices. During farm audits, gaps are often observed, such as incomplete training records, missing Turkish versions of standards and certification documents, or inaccessibility of these resources. Training needs can be addressed through additional completion periods, but some farms face difficulties accessing trainings, updated information, or Turkish-language resources.

- ***Access to information and communication***: Data collection, monitoring, and communication can be challenging in some farms. Accurate and up-to-date data are required for audits and regular monitoring, but maintaining comprehensive records is time-consuming and may increase costs. Some facilities consider their data proprietary and keep it confidential. ASC ensures the confidentiality of critical farm-specific information, with audit screens including a note stating that "only the farm can grant the necessary disclosure permissions."

- ***Technological deficiencies and investment needs***:

Implementation of ASC certification requires adequate technological infrastructure. Especially smaller farms, lack essential equipments (pH, DO meters, oxygen and ozone tubes, sampling containers, camera monitoring systems, and computerized feeding mechanisms). These deficiencies make measurements, data collection, and information sharing difficult, highlighting the need for targeted investments in technology to meet certification requirements.

3.5. Observations in farms

The farm infrastructure and technical personnel are considered sufficient in ASC certified farms. The personal are interested in certifications and care taken for Certification requirements.

• Farms carefully set visual signs and flags indicating the certifications in places visible to everyone.

• In net cage farms fish movements are monitored by camera system, fish behaviors are examined and behavioral changes are tried to be evaluated. The fish thought to be sick are determined, taken to quarantine net cages or ponds, efforts are made to prevent disease and parasite transmission between ponds, and the fish's feed intake is monitored.

• In land-based farms have high production capacity, before descharging the effluents kept in sedimentation ponds and try to reduce the SSM with drum filters (Figure 2e). In some farms drum filters do not operate continuously due to possible failure or high energy costs.

• Solid wastes (dead fish residues, feed bags, plastic, and medicine boxes) can accumulate in farms. Farm employees collect solid wastes daily and put in containers placed by the municipality within the farm, and the wastes are periodically collected by municiality or solid waste collection companies. All frams have a “solid waste management plan” that kept in folders to be shown during audits.

- The obstacles such as traps, barriers, cages, and nets are placed in appropriate places of the farm against wild animal that can enter the facility from the natural environment, to prevention contact between wild animals and farm area.

- Daily morning and evning records are kept in farms, forms and minutes are prepared, and relevant files are kept for audit and MoAF inspections, and production management. The records contain temperature, DO, DOS, tearing of net cages, repair and maintenance operations, control of predators caught in nets, daily feed given to cages, of dead fish number collected from ponds and cages, causes of death, and fish losses of unknown cause (escapes, bird and rodent predation, etc.).

- DO levels decrease at night in net cages. Farms install and operate oxygenation equipment (aerators, ozone generators.) and use oxygen tubes to supply DO needs of fish, improve water quality, prevent asphaxia risks and increase fish growth, and comply certification requirements.

- The flow rates of farm inlets decrease in summer and autumn in land-based farms. Significant water level drops seen in dam lakes, threfore water depth in the cage areas are insufficient. No equipment has been found to measure the flow rate farm water inlets. Additionally, since the flow rate is not known in the source water and shows significant seasonal fluctuations, it is not known whether the facilities comply with the “*environmental flow rate*” rule in farm site, and, whether the flow rate stated in the farm’s license can be provided in all periods of the year.

- The farms use the same stream’s water (eg.. Eşen river), and they located closer to each other (Figure 1) have water quality and environmental problems, the farms located in upstream section experience fewer water quantity and quality problems; but those located in downstream experience various problems.

4. DISCUSSION AND CONCLUSION

4.1. ASC certification standards

ASC has been developing trout certification standards since 2010. Its vision is to create a world where aquaculture provides food and social benefits to humanity while minimizing negative environmental impacts. The ASC seeks to lead aquaculture toward environmental sustainability and social responsibility through effective market mechanisms that generate value throughout the supply chain. A central focus of ASC standards is the impact of farms on biodiversity, particularly with respect to site selection and habitat protection (ASC, 2019a,b). ASC promotes best practices to minimize the environmental and social footprint of aquaculture while ensuring that certified products reaching consumers are safely and responsibly produced (ASC, 2022). To support continuous improvement and flexibility, ASC standards undergo regular updates (Amundsen and Osmundsen, 2020; ASC, 2023b; ASC, 2024a). Planned developments include the preparation of a unified farm standard for all species, digital transfer of monitoring and analysis data, faster auditing procedures, and reduced bureaucracy (ASC, 2023b).

Although production structures and farmed species vary across regions, ASC-certified farms are now widespread worldwide. By 2017, ASC-certified products exceeded 1 million tons, and by 2020, the number of certified farm sites surpassed 1,000. Currently, ASC certification involves 2,073 producers with a combined production volume of 1,899,907 tons/year, covering 49 certified species and 24,446 ASC-labeled products. Specifically for RT, there are 28 ASC-certified farms in Asia, 58 in Europe, 19 in North America, 9 in South America, and farms in 42 countries worldwide hold ASC certification (ASC, 2023b). However, as the ASC Freshwater Trout (AFT) standards evolve, they may become increasingly complex, with stricter measures and expanded requirements. Consequently, ASC-certified trout farms number could be limited by the added costs of certification, audits, and analyses, along with broader financial challenges.

4.2. Success, prevalence, and problems

The diversity and density of responses in this study indicate that farm employees generally understand the objectives of certification. ASC-certified farms in the study region demonstrate adequate technical, administrative, and personnel capacity; however, additional training is needed for effective implementation and auditing. The development of aquaculture standards for all stakeholders must address both the environmental and social impacts of culture methods, and standards should be tailored to the species level. Certification standards must be grounded in science and focused on key impacts (Boyd et al., 2005).

ASC aquaculture standards are integrated into general farm requirements. Under ASC's new approach, species-based standards are combined into a unified farm standard applicable to all aquaculture systems and environments. Certification requirements are grouped into *major* and *minor* categories, reflecting their relative importance, and the standards are in constant development and refinement (Boyd et al., 2005; ASC, 2013, 2019, 2022).

Fish farms must comply with national regulations governing land/water use, legal ownership of sites, fish health and welfare, effluents, benthic impacts, biodiversity, predator control, and the use of antibiotics and chemicals (MoAF, 2006, 2018, 2023a). However, certification schemes must be stricter than national regulations to be effective (Boyd et al., 2005). National legislation often prioritizes economic growth over environmental protection, leading to inadequate enforcement. Consequently, demand-driven policies are needed to promote sustainable aquaculture (Howes et al., 2017). So, non-governmental actors have developed eco-certification systems that function as voluntary sustainability standards, using market mechanisms to enforce safety, traceability, and transparency in production processes. This governance style has been widely adopted in regions such as Eastern Europe (Washington and Ababouch, 2011) and by Turkish producers aiming to access EU markets.

Despite these advantages, ASC certification remains relatively uncommon in Turkey, the study region, and globally (Bush et al., 2013). Source waters and effluents pollution continues despite certification rules, while technical difficulties, insufficient audits, high water analysis and certification costs, and inadequate training remain major challenges. Nevertheless, ASC's certification of 12 commercially significant species, the large production capacities of certified farms, and the resulting foreign trade advantages represent important strengths for expanding certification in the future. At present, objective and practical methods to measure the success of certification are still lacking. One approach is to evaluate behavioral changes within certified companies. The effectiveness of certification depends on whether farms internalize new principles and adjust their daily practices accordingly. Interviews and surveys with farm managers and employees confirm that many certification-related practices have been integrated into daily operations (Amundsen and Osmundsen, 2020).

High certification, analysis, and audit costs remain a shared concern for certification bodies, farm owners, and employees. These costs are unevenly distributed: farms in the upper basin, which use high-quality water with fewer environmental problems, bear similar financial burdens as those in the lower basin, where environmental pressures are greater. This raises questions about whether costs reflect the actual workload of certification bodies and laboratories, and whether redistribution mechanisms could be developed (Washington and Ababouch, 2011). Ultimately, high costs pose a significant barrier to the wider adoption of certification (Bush et al., 2013). Survey participants emphasized that

ASC certification contributes to foreign money earnings through exports, while also protecting water quality, biodiversity, and the broader environment. However, they also noted that expensive water analyses and the training required for implementation and auditing increase production costs.

Although ASC aquaculture certification is relatively new, it has already demonstrated positive environmental outcomes by reducing global warming potential, acidification, and eutrophication through more efficient N management (Nhu et al., 2016). Despite these benefits, widespread adoption among medium- and small-scale farms is unlikely due to limited technical capacity, high certification and audit costs, and the burden of documentation. Growth in certification rates is more likely among larger farms that can absorb these costs and benefit by export opportunities (Marschke and Wilkings, 2014). In Turkey, farms with higher capacity and stronger organizational structures are renewing their ASC certifications on a three-year cycle (www.asc-aquaculture.org) (Table 1).

3.5. Water Quality (WQ) and Management

WQ analyses and audits attract the most attention among farm personnel. Managers and employees generally have sufficient knowledge of legislation and key WQ parameters, and they recognize their importance for production and certification. Good WQ is essential for the health and welfare of RT. It ensures adequate DO, removes metabolic wastes (CO_2, NH_3), and dilutes uneaten feed and feces (CIWF, 2018; RSPCA, 2018). Poor WQ, by contrast, causes stress, increases disease susceptibility, leads to organ damage (e.g., fin deformities), and results in higher mortality rates. Fin deformities are widely regarded as a clear indicator of WQ deterioration and overstocking (CIWF, 2018).

Fish welfare is becoming a decisive factor in responsible aquaculture and in the social acceptability of aquaculture products (ASC, 2024a). WQ is therefore in central not only to fish welfare but also to environmental protection and certification. While RT is considered a robust and versatile species, its health and welfare depend on consistently good WQ. For ASC certification, farms are required to measure specific parameters at defined intervals, maintain values within set limits, dispose of biological and non-biological waste appropriately, and minimize adverse environmental impacts (ASC, 2019b; ASC, 2023b).

The EU Freshwater Fish Directive (FWFD, 2006/44/EC), integrated into the Water Framework Directive in 2013, establishes minimum standards and sampling protocols to support and protect fish life (salmonids, cyprinids). Turkish aquaculture legislation makes frequent reference to this directive, applying its criteria to natural waters, land-based farms, and net cage systems (EC, 2006). Surveyed farms included 4 land-based (66.7%) and 2 net cage farms (33.3%). Currently 12 net cages and 8 land-based ASC-certified farms in Turkey (Table 1).

Water source characteristics strongly influence farm performance. In land-based farms, water temperature and flow rate determine both stocking capacity and waste removal efficiency. In summer and autumn, high temperatures and low DO pose major risks, which are further exacerbated when multiple farms share the same source, as seen in the Eşen Stream. In net cages, inappropriate site selection (e.g., shallow placement or insufficient currents) can lead to organic sediment accumulation, turbidity, and ecosystem damage.

In Turkey, effluent monitoring for land-based farms is under the jurisdiction of the Ministry of Environment, Urbanization and Climate Change. However, criteria for which farms require discharge permits (by type, size, or water use) have not yet been established. A regulatory emphasis on effluent quality, rather than source WQ, may inadvertently understate fish welfare concerns and complicate compliance with ASC standards. Critical issues include temperature rises in net cages (causing DO declines), salinity fluctuations in marine sites, and nutrient releases (TP, TN, SSM) that drive turbidity, eutrophication, and algal blooms. Because these parameters vary spatially (e.g., depth, site) and temporally (e.g., monthly, daily), audits, monitoring, and analyses are often challenging. ASC Freshwater Trout Standard v1.2 sets the following limits for WQ and flow: Land-farm water temperature: 12–16 °C; pH: 6.5–8.0; Turbidity: ≤10 NTU; Un-ionized NH_3: 0.1–0.02 mg/L, and 0.005 mg/L for fry; NO_2^-: ≤0.1 mg/L in soft waters, <0.2 mg/L in hard waters; Flow: max 50% of the natural stream flow may be diverted, and returned without significant quality loss, ensuring ecological flows are maintained. Additionally, the min dissolved oxygen saturation (DOS) at farm effluent must be 60%, measured monthly. If a single measurement falls below this threshold, farms must conduct continuous monitoring with electronic probes for at least one week and demonstrate recovery to ≥60%. Where DOS is insufficient, farms must supply oxygen using oxygen or ozone tubes, paddle aerators, vertical pumps, spray pumps, bottom air distributors, or gravity aerators, depending on their technical capacity (ASC, 2019a,b). Compliance with these requirements may be particularly challenging during droughts or dry seasons.

At temperatures between 19–24 °C, RT tolerance to hypoxia decreases sharply (CIWF, 2018). This seasonal stress was reported in the visited farms, especially in summer and autumn. According to ASC (2019b), DO in rearing waters must remain above 5 mg/L (>60% saturation). At lower DO levels, trout display avoidance behavior, crowding near water inlets or cage surfaces, which may trigger aggression, dominance hierarchies, and greater vulnerability to bird predation. By comparison, the RSPCA (2018) sets a stricter min of 7 mg/L (>80% saturation). Natural and mechanical oxygenation methods are widely used, including oxygen tubes, ozone generators, and aeration systems (Figure 2c). These practices are indispensable for production efficiency, certification compliance, and environmental protection. Settling ponds further support water quality: those at farm inlets enhance DO and reduce turbidity, while those at outlets mitigate effluent impacts. Current AFT v1.2 DO requirements are considered achievable under the hydrological and climatic conditions of south-western Anatolia and Türkiye.

Most WQ parameters (temperature, DO, DOS, NH_3, NO_2, NO_3, pH, turbidity, salinity, CO_2) can be measured manually or automatically on site, while others (BOD, TP, TN, SSM, benthic indicators) require laboratory analyses. Some farms operate automatic monitoring and alarm systems, which offer advantages but also demand substantial investment in technology, trained personnel, and financial resources. The high frequency of analyses, combined with laboratory costs, was widely noted as a burden by survey participants and the local ASC unit.

Climate change represents an emerging challenge. Rising temperatures, declining stream flows, and lower lake levels may increase harmful algal blooms and reduce farming opportunities. At the same time, high-altitude, cold-water habitats may provide new opportunities for sustainable trout production (Waite et al., 2014). These dynamics must be considered in the future development of certification standards.

Stocking density is another critical parameter affecting fish welfare, WQ, and environmental protection. Densities fluctuate over time with growth and size grading, making the determination of "*ideal*" rates complex. Reported stocking densities in Europe and North America range from 2–80 kg/m^3, with most farms operating at 15–40 kg/m^3 and an upper limit of 60 kg/m^3. Densities above 36 kg/m^3 negatively impact growth, FCR, and welfare, while also degrading WQ through elevated CO_2, NH_3, and organic wastes (North et al., 2006; CIWF, 2018). In the surveyed farms, stocking densities were not provided, and it was unclear whether records are maintained. Some participants stated that "*production should not exceed licensed capacity,*" suggesting possible overstocking in certain ponds/cages.

4.4. Environmental Protection and Management

- ***Farm Infrastructure and Escape Prevention*:** To protect the environment and ensure responsible management, farm water inlets and outlets must be controlled to prevent fish escapes and the entry of wild fish, other aquatic/terrestrial animals, and foreign materials (stones, rubble, plastic waste, etc.) from outside the facilities. Security measures such as doors, wire or metal fences, and protective nets (RSPCA, 2020; ASC, 2019b) should be accessible for regular cleaning and repaired when necessary. Solid wastes generated during production must be delivered to authorized institutions. Escapes of RT from ponds or cages into receiving waters/lakes/reservoirs are considered a low priority in certification schemes (Boyd et al., 2005). However, escaped fish can cause ecological impacts such as predation, disease transmission, and biodiversity loss. Unnoticed escapes due to cage tears, net punctures, or outlet failures not only cause fish losses and raise production costs but also pose environmental risks. Survey participants reported varying levels of RT catch by sport fishers. Yet, since uncertified farms also operate in the same water bodies, it is difficult to identify the exact source of escapes. Farms have also reported significant unidentified losses on their websites. Transparency and trust are critical: ASC-certified farms are expected to count fish regularly and provide public information on escapes (ASC, 2023b). All reasonable precautions must be taken to prevent escapes.

- ***Effluent Quality and Filtration Systems*:** WQ reports (inlets/outlets) of drum filters (Figure 2e) and land-based farms are inaccessible, making it difficult to assess whether conditions defined in AFT v1.2 for effluents are met. For effective environmental management, the continuous operation of drum filters is essential. All surveyed farms, as well as most others in Türkiye, have renewed their certifications, indicating general compliance with standards.

According to AFT v1.2 (ASC, 2019b), DO in RT ponds must not fall below 5 mg/L (DOS >60%). In some cases, source water already has low DO, which decreases further during culture. To maintain fish health and effluent quality, oxygen tubes and ozone generators are used. SSM in effluents can increase more than tenfold (Boyd et al., 2005). To mitigate SSM, turbidity, TN, and TP loads, sedimentation ponds and drum filters are actively used. These systems are required both by AFT v1.2 and national regulations (MoAF, 2006, 2018, 2023a). All ASC-certified land-based farms in Türkiye have sedimentation ponds and drum filters, though they are occasionally left idle due to high energy costs or technical failures.

- ***Environmental Challenges in Cage Facilities:*** Low water levels in cage systems (e.g., Yapraklı) may lead to increased temperature and salinity (e.g., Bafa Lake), algal blooms, sudden fish kills, and reduced biodiversity (Sasi et al., 2017; Ülker et al., 2021). One of the main environmental impacts of RT net cages is organic sediment accumulation beneath cages and within a 50 m radius, which reduces benthic biodiversity (Boyd et al., 2005). Most survey participants recognized this issue and supported mandatory benthic analyses. Sediment accumulation not only harms benthic fauna but also promotes turbidity and eutrophication. It has been noted that some certified farms suffer from poor site selection, particularly where depth and bottom currents are inadequate, increasing the risk of sediment buildup and complicating certification and audits.

- ***Interactions with Protected Areas*:** Currently, no ASC-certified RT farms in Türkiye are located near national parks. However, one net cage farm is situated in Lake Bafa, which is adjacent to the Aydın-Bafa Lake Nature Park. In future certifications, the potential interactions between RT aquaculture and protected areas may impose additional constraints.

Acknowledgements

This study was prepared from the doctoral dissertation titled "***Water Quality and Environmental Management in Aquaculture Certifications***" conducted by Dr. Servet Hazırbulan under the supervision of Prof. Dr. Osman Çetinkaya.

The authors would like to thank the farm owners who allowed the farm visits and surveys, the technical staff and employees who participated in the survey, the Isparta University of Applied Sciences Ethics Committee for providing the ethics report for the surveys, the central and local units of the Ministry of Agriculture, the Central Union of Aquaculture Producers, and the local units of the ASC.

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