



# CURRENT AGRICULTURAL STUDIES in TÜRKİYE RESEARCH and REVIEWS II

Editor

Assoc. Prof. Dr. Mehmet Arif ÖZYAZICI



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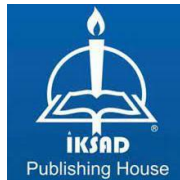
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## PREFACE

Agriculture, forestry and aquaculture are crucial for sustaining livelihoods in rural areas and ensuring food and nutrition security around the world. A significant portion of the world's population depends on agriculture and forests for many needs such as food, feed, and shelter. The fisheries and aquaculture sector plays an important role both in providing a critical portion of animal protein and in providing a source of livelihood for people living in poor and marginalized areas. For this reason, academic studies play a prominent role in providing the necessary knowledge and skills to ensure sustainable development in the agriculture, forestry and aquaculture sectors. To this end, this book provides valuable information on a wide range of topics including new strategies in legume farming, which is an important component of sustainable agriculture, new developments in forestry and aquaculture, the relationship between forage crops and animal nutrition, and the evaluation of ornamental plant diseases.

I would like to thank the valuable chapter authors who shared precious research findings and information in the fields of agriculture, forestry and aquaculture and contributed to science in these fields, and I hope that the book will be an important resource for all stakeholders.

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**CHAPTER 1**

**A STUDY ON CONFIRMED MAXIMUM SIZE RECORD OF  
BULLET TUNA (*Auxis rochei* Risso, 1810) FOR ENTIRE  
TURKISH WATERS**

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## INTRODUCTION

The family Scombridae comprises 55 species in 15 genera (Eschmeyer's Catalog of Fishes, 2024). As far as is understood, 10 of these species [*Euthynnus alletteratus* (Rafinesque, 1810), *Orcynopsis unicolor* (Geoffroy Saint-Hilaire, 1817), *Auxis rochei* (Risso, 1810), *Scomberomorus commerson* (Lacepède, 1800), *Katsuwonus pelamis* (Linnaeus, 1758), *Scomber colias* (Gmelin, 1789), *Thunnus alalunga* (Bonnaterre, 1788), *Sarda sarda* (Bloch, 1793), *Thunnus thynnus* (Linnaeus, 1758), *Scomber scombrus* (Linnaeus, 1758)] are present in Turkish seas (Fricke *et al.*, 2007). Having a yearly distribution along the shore in both tropical and temperate locations, the genus *Auxis* is epi/meso-pelagic, distributed globally in tropical and subtropical waters (Uchida, 1981; Collete *et al.*, 1986) and encapsulates only two species, *A. rochei* and *A. thazard* (Baeck *et al.*, 2014).

The smallest species of tuna in the world is known to be the bullet tuna (*Auxis rochei* Risso, 1810) (Jasmine *et al.*, 2013). Despite being regarded as a very migratory species, not much is known about its range (IOTC-WPNT08, 2008). The species' age determination, gonado-somatic index (GSI), length at first maturity and spawning time were reported by Macias *et al.* (2005; 2006) from the Spanish Mediterranean, by Plandri *et al.* (2008) from the Ligurian Sea, by Valerias *et al.* (2008) from the western Mediterranean Sea, by Bök and Oray (2001) and Karaman *et al.* (2010; 2011) from the Turkish waters. The research has also been conducted on schools' behavior patterns, spawning grounds, and fishing from various regions of the world (Sabatés and Recasens, 2001; Oray *et al.*, 2005; Oray and Karakulak, 2005; etc.).

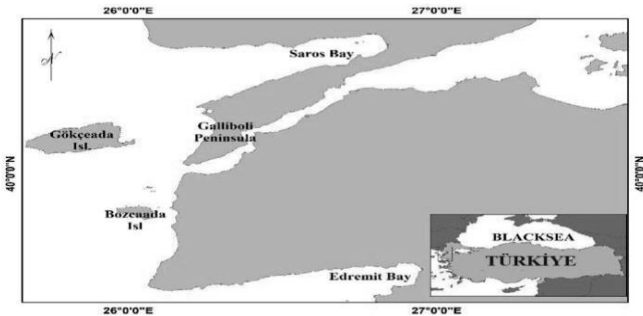
In order to monitor and conserve fish stocks, the fisheries management authorities wish to investigate some biometric data. Fish sampling programs typically yield important results, such as data on fish weight and length. Fish population dynamics require this data in order to determine length and age structures, rates of growth and other factors (Kolher *et al.*, 1995). Two very significant theoretical factors in fisheries science are maximum length and weight (Dulčić and Soldo, 2005). These measurements are incorporated, both directly and indirectly, into the majority of models used in stock evaluations (Borges, 2001). It is noteworthy that techniques for improving our comprehension of community structure and function are becoming more and more common, such as size-based assessments of fish (Jennings and Dulvy,

2005) and when primary data is scarce, it could be a useful tool for quickly evaluating growth rates (Filiz and Sevingel, 2015). These factors make it crucial to keep up-to-date data regarding the largest size of a species that could be used for recreational or commercial purposes in the future (Navarro *et al.*, 2012).

Given that ecological functions and biological rates vary with size, biologists and ecologists need to know with accuracy what the largest fish size found in a population is (Peters, 1983; Pope *et al.*, 2005). For instance, body size is positively correlated with total food consumption and negatively correlated with metabolic rate. A fish's maximum size is directly correlated with its sexual development, size at hatch, lifespan and maturation (Freedman and Noakes, 2002; Vander Veer *et al.*, 2003). This study was carried out to make a contribution to the proven maximum length of bullet tuna (*Auxis rochei* Risso, 1810), which has not been studied in the Turkish seas for more than 10 years.

## 1. MATERIALS AND METHODS

The Gallipoli Peninsula, the Gökceada and Bozcaada Islands, the Edremit Bay, and Saros Bay are the sub-regions that constitute Türkiye's northern Aegean coasts (Cengiz and Paruğ, 2020). At the point where Saros Bay opens up to the Aegean Sea, it is roughly 61 km long and 36 km wide (Eronat and Sayın, 2014). Since 2000, the bay has been off-limits to bottom trawl fishing (Cengiz *et al.*, 2014), and Sarı and Çağatay (2001) noted that nothing industrial was going on in the vicinity, therefore it may be thought of as a virgin ecosystem (Cengiz *et al.*, 2015). Due to these factors-including its scenery, geomorphology, ecology, floristic biogenetic, and tourism qualities-Saros Bay and its coastline area was granted SEPA status (Güçlüsoy, 2015) (Figure 1).



**Figure 1.** Saros Bay and Türkiye's northern Aegean coastlines

## 2. RESULTS AND DISCUSSION

A commercial fisherman captured a single *Auxis rochei* specimen on December 11, 2022, at a depth of about 15 meters. The specimen measured 45.0 cm in total length and 1200.00 g in total weight (Figure 2).



**Figure 2.** Bullet tuna (*Auxis rochei*)

As Turkish waters, 216 specimens were sampled by Karaman *et al.* (2011). They said that the species' length range was 34.0-48.0 cm (FL). However, Bök and Oray (2001) said that the highest size was 44.5 cm (FL). Froese and Pauly (2024) underlined its maximum size value was 50 cm (FL). According to this measurement, it is the world's largest individual.

As is widely known, populations subjected to a great deal of levels of fishing pressure are going to react by having fewer individuals reproduce at average ages and sizes, which could lead to a reduction in the maximum lengths that can be reached. But that kind of length could only be attained by the one individual who was not under the pressure of overfishing (Filiz, 2011). The availability of nutrients, oxygen, nourishment, lighting circumstances, temperature, pollution, current speed, nutritional concentration, salinity, density of predators, intraspecific social relationships and genetics are some of the variables that could effect growth, though. (Helfman *et al.*, 2009). These remarks imply that the ecological circumstances and pressure from overfishing determine regional variations in maximum length and weight.

### **3. CONCLUSION**

Given the relevance of the maximum length and/or weight in multiple models of fisheries, such as the Gompertz and von Bertalanffy models of growth (Quinn and Deriso, 1999), these natural habitat measures may provide crucial data that is incorporated into these computations and stock evaluations. So as to benefit fishery management and the global scientific literature, the data in this study could be considered.

### **Acknowledgments**

For their invaluable assistance in sampling specimen, the fisherman are acknowledged and appreciated by the author.

## REFERENCES

- Anderson, R. O., & Gutreuter, S. J. 1983. Length, weight, and associated structural indices. In: Nielsen, L., Johnson D. (eds.), Fisheries techniques, American Fisheries Society, Bethesda, Maryland, USA. p. 283-300.
- Baek, G. W., Quinitio, G. F., Vergara, C. J., Kim, H. J., & Jeong, J. M. (2014). Diet composition of bullet mackerel, *Auxis rochei* (Risso, 1810) in the coastal waters of Iloilo, Philippines. Korean Journal of Ichthyology, 26(4): 349-354.
- Borges, L. 2001. A new maximum length for the Snipefish *Macrohamphosus scolopax*. Cybium, 25: 191-192.
- Bök, T., & Oray I. K. 2001. Age and growth of bullet tuna *Auxis rochei* (Risso, 1010) in Turkish waters. ICCAT, Collective Volume of Scientific Papers, 52: 708-718.
- Cengiz, Ö., İşmen, A., & Özekinci, U. 2014. Reproductive biology of the spotted flounder, *Citharus linguatula* (Actinopterygii: Pleuronectiformes: Citharidae), from Saros Bay (northern Aegean Sea, Turkey). Acta Ichthyologica et Piscatoria, 44: 123-129.
- Cengiz, Ö., İşmen, A., Özekinci, U., & Öztekin, A. 2015. Some reproductive characteristics of four-spotted megrim (*Lepidorhombus boscii* Risso, 1810) from Saros Bay (Northern Aegean Sea, Turkey). Journal of Agricultural Sciences, 21: 270-278.
- Cengiz, Ö., & Paruğ, Ş. Ş. 2020. A new record of the rarely reported grey triggerfish (*Balistes capriscus* Gmelin, 1789) from Northern Aegean Sea (Turkey). Marine and Life Sciences, 2: 1-4.
- Collete, B. B. 1986. Scombridae. In: Whitehead, P. J. P., Bauchot M. L., Hureau, J. C., Nielsen, J. and Totonese, E. (Eds.), *Fishes of the Northeastern Atlantic and Mediterranean*. Unesco, Paris, 2: 981-997.
- Dulčić, J., & Soldo, A. 2005. A new maximum length for the grey triggerfish, *Balistes capriscus* Gmelin, 1789 (Pisces: Balistidae) from the Adriatic Sea. Institute of Oceanography and Fisheries-Split Croatia, 88: 1-7.
- Eronat, C., & Sayın, E. 2014. Temporal evolution of the water characteristics in the bays along the eastern coast of the Aegean Sea: Saros, İzmir, and Gökova bays. Turkish Journal of Earth Sciences, 23: 53-66.

- Eschmeyer's Catalog of Fishes. 2024. Species by family/subfamily in Eschmeyer's Catalog of Fishes (Online version-updated 09 Jul 2024). URL: <https://researcharchive.calacademy.org/research/ichthyology/catalog/SpeciesByFamily.asp#Scombridae>. (16/07/2024)
- Filiz, H. 2011. A new maximum length for the red mullet, *Mullus barbatus* Linnaeus, 1758. BIBAD - Research Journal of Biological Sciences, 4(2): 131-135.
- Filiz, H., & Sevingel, N. 2015. A new maximum length for the parrotfish, *Sparisoma cretense* (Linnaeus, 1758) in the Mediterranean Sea. Journal of Aquaculture Engineering and Fisheries Research, 1: 140-143.
- Freedman, J. A., & Noakes, D. L. G. 2002. Why are there no really big bony fishes? A point-of-view on maximum body size in teleosts and elasmobranchs. Reviews in Fish Biology and Fisheries, 12: 403-416.
- Fricke, R., Bilecenoglu, M., & Sari, H. M. 2007. Annotated checklist of fish and lamprey species of Turkey, including a red list of threatened and declining species. Stuttgarter Beitrage zur Naturkunde Serie A (Biologie), 706: 1-169.
- Froese, R., & D. Pauly. 2024. FishBase. World Wide Web electronic publication. [www.fishbase.org](http://www.fishbase.org), version (02/2024)
- Güçlüsoy, H. 2015. Marine and coastal protected areas of Turkish Aegean Coasts, 669-684 pp. In: Katağan, T., Tokaç, A., Beşiktepe, Ş., and Öztürk, B. (Eds.) (2015). The Aegean Sea Marine Biodiversity, Fisheries, Conservation and Governance. Turkish Marine Research Foundation (TUDAV), Publication No: 41, Istanbul, TURKEY.
- Helfman, G. S., Collette, B. B., Facey, D. E., & Bowen, B. W. 2009. The diversity of fishes: Biology, evolution, and ecology. Wiley-Blackwell: West Sussex, UK. 720 pp.
- IOTC-WPNT08. 2008. Report of the 8th Session of the IOTC Working Party on Neritic Tunas (Working Party Report No. IOTC-2018-WPNT08-R(E). Mahe, Seychelles.
- Jasmine, S., Rohit, P., Abdussamad, E. M., Koya, K. P., Joshi, K. K., Kemparaju, S., & Sebastine, M. 2013. Biology and fishery of the bullet tuna, *Auxis rochei* (Risso, 1810) in Indian waters. Indian Journal of Fisheries, 60(2): 13-20.

- Jennings, S., & Dulvy, N. K. 2005. Reference points and reference directions for size based indicators of community structure. *ICES Journal of Marine Sciences*, 67: 397-404.
- Kahraman, A. E., Göktürk, D., Bozkurt, E. R., Akaylı, T., & Karakulak, F.S. 2010. Some reproductive aspects of female bullet tuna, *Auxis rochei* (Risso), from the Turkish Mediterranean coasts. *African Journal of Biotechnology*, 9(40): 6813-6818
- Kahraman, A. E., Göktürk, D., & Karakulak, F. S. 2011. Age and growth of bullet tuna, *Auxis rochei* (Risso), from the Turkish Mediterranean coasts. *African Journal of Biotechnology*, 10(15): 3009-3013.
- Kolher, N., Casey, J., & Turner, P. 1995. Length-weight relationships for 13 species of sharks from the western North Atlantic. *Fishery Bulletin*, 93: 412-418.
- Macias, D., Gómez-Vives, M. J., & de la Serna, J. M. 2005. Some reproductive aspects of bullet tuna (*Auxis rochei*) from the south-western Spanish Mediterranean. *ICCAT, Collective Volume of Scientific Papers*, 58(2): 484-495.
- Macias, D., Lema, L., Gómez-Vives, M. J., & de la Serna, J. M. 2006. A preliminary approach to the bullet tuna (*Auxis rochei*). Fecundity in the Spanish Mediterranean. *Collective Volume of Scientific Papers*, 59(2): 571-578.
- Navarro, M. R., Villamor, B., Myklevoll, S., Gil, J., Abaunza, P., & Canoura, J. 2012. Maximum size of Atlantic mackerel (*Scomber scombrus*) and Atlantic chub mackerel (*Scomber colias*) in the Northeast Atlantic. *Cybiu*, 36: 406-408.
- Oray, I. K., Karakulak, F. S., Alich, Z, Ate, C., & Kahraman, A. 2005. First evidence of spawning in the eastern Mediterranean Sea: preliminary results of TUNALEV larva survey in 2004. *ICCAT, Collective Volume of Scientific Papers*, 58: 1341-1347.
- Oray, I. K., & Karakulak, F. S. 2005. Further evidence of spawning of bluefin tuna (*Thunnus thynnus* L, 1978) and the tuna species (*Auxis rochei* Ris., 1810, *Euthynnus alletteratus* Raf, 1810) in the eastern Mediterranean Sea: preliminary results of TUNALEV larval survey in 2004. *Journal of Applied Ichthyology*, 21: 236-240.



- Peters, R. H. 1983. The ecological implications of body size. Cambridge University Press, New York, NY.
- Plandri, G., Lanteri, L. Garibaldi F., & Orsi, L. R. 2008. Biological parameters of bullet tuna in the Ligurian Sea. ICCAT, Collective Volume of Scientific Papers, 4: 2272-2279.
- Pope, K. L., Wilde, G. R., & Bauer, D. L. 2005. Maximum size of fish caught with standard gears and recreational angling. Nebraska Cooperative Fish & Wildlife Research Unit- Staff Publications. 201.
- Quinn II, T.J., & Deriso, R. B. 1999. Quantitative Fish Dynamics. Oxford University Press, New York.
- Sabatés, A., & Recasens, L. 2001. Seasonal distribution and spawning of small tunas (*Auxis rochei* and *Sarda sarda*) in the northwestern Mediterranean. Scientia Marina, 65(2): 95-100.
- Sarı, E., & Çağatay, M. N. 2001. Distributions of heavy metals in the surface sediments of the Gulf of Saros, NE Aegean Sea. Environment International, 26: 169-173.
- Uchida, R. N. 1981. Synopsis of biological data on frigate tuna, *Auxis thazard* and bullet tuna, *Auxis rochei*. FAO Fish. Synop., 124 pp.
- Valeiras, X., Macias, D., Gomez, M. J., Lema, L., Garcia-Barcelona, S., De Urbinqa Ortiz, J. M. & de la Serna, J. M. 2008. Age and growth of bullet tuna (*Auxis rochei*) in the western Mediterranean Sea. ICCAT, Collective Volume of Scientific Papers, 62: 1629-1637.
- Vander Veer, H. W., Kooijman, S. A. L. M., & van der Meer, J. 2003. Body size scaling relationships in flatfish as predicted by Dynamic Energy Budgets (DEB theory): implications for recruitment. Journal of Sea Research, 50(2-3): 257-272.

## CHAPTER 2

### **DIGITAL TRANSFORMATION IN LEGUME AGRICULTURE: DATA ANALYTICS AND MODELING STRATEGIES**

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## INTRODUCTION

Within the recent past, there has been a tremendous adoption of digital agricultural practices aiming at increasing productivity and sustainability in agriculture. Such technological innovation includes, among others, precision farming, smart irrigation technologies, remote sensing tools, data analysis methods, and artificial intelligence, all great factors that have significantly changed the production paradigms of agriculture (Gebbers & Adamchuk, 2010). Digital agriculture can be characterized as the use of facts and communication technologies that seek to enhance agricultural processes and give better productivity indicators (Wolfert et al., 2017). More importantly, in recent years, the incorporation of sensor technologies, together with analyses powered by artificial intelligence, has established digital agriculture as one of the main tools within the decision-making frameworks used by farmers. One of the studies by Yeo et al. (2014) showed that the adoption of precision agriculture practices could bring about 20% savings in the use of fertilizers and water. It thus gives insight into the critical role played in digital agriculture, more so in addressing concerns such as climate change and the scarcity of water resources.

Remote sensing technology is an important part of digital agriculture, which enables the full monitoring of agricultural environments and the timely evaluation of data (Zhang et al., 2019). Satellite- and drone-imaging technologies are used in different ways, including monitoring plant growth and detecting diseases and pests (Li et al., 2020). This gives the farmers more informed options regarding land management, resource utilization efficiency, and sustainable production methods.

One more important technology used in digital agriculture is IoT (Internet of Things) devices. These devices will be helpful in the continuous observance of different variables, such as soil moisture, temperature, pH, etc., in the agricultural field and instant evaluation of these data (Kumar et al., 2021). So, the farmers can provide optimum productivity by instantly intervening in field conditions. Artificial intelligence and machine learning algorithms are more prominently used due to their greater importance in the analysis of such data and in predictions for future scenarios (Jha et al., 2019).

Furthermore, big data analytics in the domain of digital agriculture has revolutionized agricultural management practices. Big data analytics allows for

the strategic planning of future agricultural activities by gleanings insights from past data, and it improves resource utilization (Wolfert et al., 2017). Such as, Devlin et al. (2020) showed that, through the use of big data analytics, the most favorable time of sowing in terms of meteorological and soil conditions was determined, leading to a 25% increase in crop yield.

### ***Importance of Legume Production***

Legumes are internationally recognized as the main source of proteins and play a key role in human nutrition and soil fertility improvement (Miller et al., 2015). These crops harbor nitrogen-fixing abilities that improve the natural composition of the soil, reduce the need for fertilization, and sustain agricultural production practices (Peoples et al., 2019). Therefore, sustainable increases in legume production relate to overall efficiency in the field of agricultural production and ecosystem health.

Leguminous crops, like lentils, chickpeas, beans, and peas, maintain the nitrogen balance in agroecosystems and are a cheap source of protein, hence improving food security (Stagnari et al., 2017). Therefore, the cultivation of legumes through sustainable means is becoming very important for improving food security, especially in developing countries. Recent studies have shown that the use of digital agriculture methods has tremendously increased in the production of legumes (Bohra et al., 2020). El-Sappagh et al. (2021) have proved that using drone-based imaging, supported with AI-enhanced data analytics, helps in early diagnosis of disease symptoms in chickpea cultivation, which reduces crop losses by 15%.

Digital agricultural practices increase the productivity of legume crops while simultaneously reducing environmental impacts. For instance, using sensor- and drone-based technologies may optimize fertilizer and pesticide applications, lowering the adverse environmental impacts caused by agricultural practices (Basso et al., 2018). Additionally, water resources can be managed in an efficient way, which becomes a great advantage when considering legume production. The function of smart irrigation systems in conserving water resources is to regulate water use according to soil moisture and plant needs (Mote et al., 2021).

Research on digital agriculture and leguminous crop production reveals that each domain has great benefits and may increase agricultural output when

combined (Tripathi et al., 2022). The application of precision agriculture techniques in the production of legumes is indispensable for the realization of both increased productivity and improvement in environmental sustainability. For instance, in the study by Pandey et al. (2023), up to 30% yield increases in chickpea and lentil production are reported using sensors and data analytics. Such applications not only increase the economic gains of farmers but also contribute much toward meeting sustainable agriculture goals.

Digital agricultural practices are increasing the importance of legumes in farming systems while maximizing the environmental benefits brought about by the plants. More precisely, Hassani et al. (2022) found that using soil moisture sensors together with drone imaging enabled better disease identification and water-stress control in legume farming, increasing yield up to 35%. Also, by using digital agricultural technologies, the potential for nitrogen fixation by legumes could be observed and enhanced, thereby increasing soil fertility and decreasing reliance on synthetic fertilizers (Peoples et al., 2019).

In legume production, digital agriculture practices have transformed the traditional agricultural process into an efficient and sustainable production process. Most of the literature has noted that technologies do not only increase yields but also reduce environmental impacts in legume agriculture. The potential use of digital agriculture in legumes is therefore great and very promising for the future of agricultural production. Integration of digital technologies throughout the production chain is expected to lead to a substantial increase in productivity and sustainability, particularly for critical crops that are of strategic importance, such as legumes.

## **DATA COLLECTION TECHNOLOGIES**

Gathering data technologies are critical to modernizing and digitizing agricultural operations. This process's technology has greatly improved the efficiency and sustainability of agricultural activities. Digital farming methods employ a variety of data collecting approaches to boost agricultural output. Sensors, remote sensing technology, and big data analytics enable agricultural decision-making that is more informed and data-driven. This section will give a thorough literature study on how these technologies are employed and the advantages they provide in agriculture.

### ***Data and Data Collection Techniques***

1. The application of data acquisition technologies plays a pivotal role in the modernization and digitalization of agricultural methodologies. The advancements in this technological domain have significantly enhanced the efficacy and sustainability of agricultural operations. Digital agricultural methodologies incorporate an array of data collection techniques aimed at augmenting agricultural productivity. The implementation of sensors, remote sensing technologies, and advanced data analytics facilitates a more informed and data-centric approach to agricultural decision-making. This section will present a comprehensive literature review regarding the application of these technologies and the benefits they confer within the agricultural sector.
  2. **Sensors:** Sensors are one of the most used data collection tools in agriculture. Sensors assist farmers in making decisions by delivering real-time data at every level of agricultural activity (Kumar et al., 2021).
  3. **Satellite and Drone Imaging:** Remote sensing technologies are used to monitor agricultural land and determine plant growth. Satellite and drone imagery provide large-scale monitoring of situations such as plant health and water stress (Zhang et al., 2019).
  4. **IoT (Internet of Things) Devices:** IoT devices are used to gather agricultural data, transport it to cloud-based systems, and analyze it. IoT technology allows for the automation of agricultural operations and increased production (Mote et al., 2021).
  5. **Meteorological Stations:** Meteorological stations are used to collect data on meteorological conditions that impact agricultural operations. These stations aid to agricultural activity planning by providing data such as temperature, humidity, and rainfall (Wolfert et al., 2017)..
  6. **Handheld Devices and Mobile Applications:** Farmers utilize handheld gadgets and smartphone apps to capture agricultural data quickly in the field. This data may be immediately linked into agriculture systems that support decisions (Tripathi et al., 2022)..
- Data collecting techniques enable agricultural operations to be managed more efficiently and sustainably. With these tools, farmers may boost

production and save expenses by making educated decisions on topics such as crop growth, fertilizer and water demands, and prevention of diseases and pests (Devlin et al., 2020).).

### ***Remote Sensing and Big Data***

The methodologies associated with remote sensing technologies are of paramount significance in the field of agriculture, as they provide a foundational framework for the monitoring, evaluation, and enhancement of agricultural methodologies. These technologies facilitate the remote surveillance of agricultural environments through various instruments, such as satellites and drones, thus enabling the observation of extensive agricultural expanses (Zhang et al., 2019). This technological advancement yields substantial advantages for agronomic specialists across multiple dimensions, encompassing the analysis of vegetative health, evaluation of soil quality, management of hydric stress, and timely identification of plant diseases. A research endeavor conducted by Li et al. (2020) revealed that yield enhancement was realized through the surveillance of plant development utilizing remote sensing technologies, which facilitated optimization in the application of fertilizers.

In addition to augmenting the productivity of agricultural endeavors, remote sensing technologies play a crucial role in the optimization of resource utilization. For instance, the continuous surveillance of soil and vegetative conditions could be accomplished through the integration of these technologies, thereby ensuring the appropriate and timely application of water and nutrients (Basso et al., 2018). Such practices are likely to not only elevate financial returns but also contribute to the sustainability of ecological systems. The concept of big data emerges as a vital instrument in the enhancement of efficiency and sustainability within agricultural production. The exploration of huge datasets in agriculture requires the thorough examination of extensive collections of data sourced from multiple avenues, including sensors, remote sensing apparatus, and other data-collection instruments, with the objective of employing the insights garnered from these evaluations in the decision-making frameworks tied to agriculture (Wolfert et al., 2017). This capability to analyze substantial datasets provides the foresight requisite for informed decision-making in agricultural planning, thereby facilitating improvements in



agricultural productivity (Devlin et al., 2020). Remote sensing technologies are instrumental in the acquisition of big data. Sensors embedded in devices such as satellites and drones are perpetually collecting data from the agricultural ecosystem and employing big data analytics for the assessment of this information (Tripathi et al., 2022). A 2020 investigation carried out by Devlin and others indicated that through the scrutiny of information acquired via remote sensing and big data analytics, the prime planting timeframe was identified in relation to existing climate conditions and soil factors, resulting in a yield increase of 25%. The integration of remote sensing technologies with big data analytics serves to enhance agricultural practices and empowers farmers to make more informed decisions. This synergy has fostered not only economic viability but also environmental responsibility in the domain of agricultural production (Wolfert et al., 2017)..

## **SENSORS AND THEIR USE IN AGRICULTURE**

Sensors are fundamentally characterized as instruments that discern variables in the physical milieu and, through a process of transduction, convert these variables into quantifiable signals. In the realm of agriculture, sensors facilitate enhanced management of agricultural practices by enabling the monitoring of critical parameters such as soil moisture, temperature, pH levels, and nutrient composition (Kumar et al., 2021). This process generates pertinent data for the judicious application of water, fertilizers, and other essential inputs required by crops, thereby augmenting productivity while simultaneously ensuring the judicious utilization of resources (Jha et al., 2019). The incorporation of sensors in agricultural practices is of paramount significance concerning the applications of precision agriculture. Precision agriculture aims to administer agricultural inputs in optimal quantities, thereby promoting more efficient and sustainable production through the application of valuable data derived from sensors for this objective (Hassani et al., 2022). Sensors empower farmers to observe field conditions in real time, thus facilitating prompt interventions when necessary. Certain sensors, such as soil moisture sensors, ascertain the necessity for irrigation, consequently conserving water while also upholding favorable growth conditions for crops (Mote et al., 2021).

### ***Sensor Types and Usage Areas***

There are different types of sensors used in agriculture and each is used for different purposes:

**1. Soil Moisture Sensors:** These sensors detect the quantity of moisture in the soil and estimate watering requirements. This allows plants to be irrigated optimally while avoiding needless water stress (Mote et al., 2021).

**2. Temperature Sensors:** Plant growth and development are temperature dependent. Temperature sensors monitor ambient and soil temperatures, ensuring that plants develop at an appropriate temperature (Kumar et al., 2021)..

**3. pH Sensors:** The pH of the soil influences how plants take up nutrients. pH sensors detect soil acidity or alkalinity and enable for soil conditioner treatments as needed (Li et al., 2020).

**4. Electrical Conductivity (EC) Sensors:** These sensors assist farmers in optimizing fertilization decisions by detecting the concentration of nutrients in the soil (Hassani et al., 2022)..

**5. Air Quality and Gas Sensors:** These sensors measure the levels of carbon dioxide and other gases to offer information on plant photosynthesis and air quality (Jha et al., 2019)..

Sensors in agriculture boost production and product quality while also helping to preserve the environment. Sensors allow agricultural inputs (water, fertilizers, insecticides, etc.) to be administered at the optimal amount and timing, lowering costs while also reducing negative environmental consequences.

### **AGRICULTURAL MODELING AND USES**

Approaches such as modeling and decision support give farmers tools to make better data-driven decisions in agricultural production. Agricultural modeling is one of the strategies used in agriculture to improve the efficiency and sustainability of production processes. These models combine climate data, soil properties, water and crop data to make predictions on how the agricultural production processes can be optimized (Jones et al., 2017). The use of Ag

modeling helps optimize ag-related activities like cropping planning, irrigation management, fertilization and pest control. So, it helps farmers to take better decisions and handles agronomical processes in an enhanced way; as risk reduces. Models like DSSAT (Decision Support System for Agrotechnology Transfer) and APSIM (Agricultural Production Systems sIMulator) have gained widespread usage in (Jones et al., 2003). What it is: Agronomic modeling can also be applied for investigation of responses in crops to environmental stresses due to climate change. This is a crucial aspect of sustainability production planning with particular reference to the agricultural sector, which has been struggling to support rapid population expansion while simultaneously dealing with limited resources. Such as simulation of agricultural plant growth, moisture and nutrient cycling processes in the various production systems to improve agricultural productivity through APSIM model (Holzworth et al., 2014).

Legumes have unique features and production processes that can be studied during agricultural modeling. Legumes are essential crops that enhance soil fertility by increasing nitrogen content of the soils. We model these kinds of crops to better understand processes like nitrogen fixation, and water + nutrient use. In a study by Ahmed et al. Abstract (209 characters): The APSIM model is accurate for simulating the water and nutrition use of legumes with improvements in the productivity of legumes simulated due to high potential returns on investment. Abstract With the current scenario of climate change, gaining insights about how crops like legumes can adapt to environmental stress conditions, in particular with respect to drought response both at plant as well as soil-root systems levels are a must for cultivation of these crops more sustainably. DSSAT model has also employed to understand legume growth processes and responses. In one such study, the DSSAT model was used to assess the water and nitrogen needs of legumes for a number of climate scenarios and determined rational planting time and fertilization strategies (Boote et al. 2013). This allows farmers to model resource usage for increased yielding while supporting environmental sustainability.

Studying leguminous crops in agricultural research is important for revealing how shifting climate conditions influence these species, along with crafting fitting adaptation strategies. By employing agricultural modeling methodologies, researchers can gain enhanced insights into the adaptive

mechanisms of legumes in response to diverse climatic variables and the management of these adaptive processes. This knowledge enables legume cultivators to mitigate risks and secure sustainable agricultural practices. Moreover, such models are exceptionally beneficial for the design and administration of agricultural systems that exhibit increased resilience to the challenges posed by climate change (Lobell et al., 2008). The integration of agricultural modeling and investigations pertaining to legumes is crucial for fostering sustainable agricultural practices, optimizing the utilization of natural resources, and minimizing ecological repercussions. These inquiries capitalize on the nitrogen-fixing capabilities and soil-enhancing attributes of legumes to bolster soil health and promote crop yield.

### ***Artificial Intelligence and Machine Learning***

Artificial intelligence (AI) and machine learning (ML) are widely used technologies to increase yields and optimize farming systems in agriculture AI and ML analyze large amounts of data and extract meaningful information, and inform farmers allow for better decision making (by Kamilaris & Prenafeta - Boldú, 2018). For example, machine learning algorithms are used to rapidly detect and classify plant diseases, thereby reducing crop losses (Singh et al., 2018). By analyzing sensor data, machine learning can optimize the use of water and fertilizers, and contribute to more efficient use of resources (Sharma et al., 2020). Furthermore, AI can be used for tasks such as harvesting, irrigation and pest management in agricultural robotic applications (Aravind et al., 2021). These technologies can make agriculture more predictable and efficient. AI and ML technologies reduce uncertainty in agricultural production, reduce risks and provide farmers with flexibility to adapt to climate change and other external factors (Liakos et al., 2018). The application of this technology has great potential to increase seed production and environmental sustainability in agricultural production.

### ***Decision Support Systems***

The decision support system (DSS) enhances the ability of farmers to make rational decisions based on collected data in relation to agricultural production. The systems aid in the better management of agricultural processes through the integration of various sources such as sensors, remote sensing and big data (Choudhary et al., 2015). A CDS assists farmers to implement the

suitable measures at the appropriate time and in the most cost-effective way. In agribusiness, however, an effective decision support system concentrates on production as well as resources management. For instance, if farmers are advised through CDS about the timing of irrigation and rates of fertilizer applications, they are likely to attain higher and quality yields (Jones et al., 2003). DSSAT (Decision Support System for Agrotechnology Transfer) is a type of CDS that allows the user to design the growth processes of various crops and gives information on fertilization, irrigation, and harvest planning for farmers. In such scenarios, these systems allow for less uncertainty in the agricultural processes enhancing better management decisions by the farmers. Support of decisions is also needed for climate change and for reaching goals of sustainable development of the environment. Such systems ensure that improved and precise decisions can be made on agricultural processes, which are variable with respect to climate change and the environment (Thorburn et al., 2011). Also the use of CDS allows farmers to respond quickly and appropriately to issues such as pest and diseases (Dutta et al., 2015).

Currently, given practicing digital agriculture, CDSs are gaining popularity in the agricultural sector. Moreover, these systems are beneficial for economical profitability and environmental reasons in addition to raising production efficiency in agriculture (Thorburn et al., 2011). For instance integrated decision support systems are a complete management that covers aspects such as soil, water, air and crops data. Such systems facilitate optimization of resource use and therefore reduce costs of production as well as minimizing the effect that agricultural activities have on the environment (Jones et al., 2017). With regard to risk management and crisis response in agriculture, it is also noteworthy to find out that CDSs have particular importance. For instance, CDSs bonded with early systems of warning against disasters such as storms enable farmers to protect crops as they anticipate possible impacts of such disasters. This makes the production in agricultural sustainable and plays a big role in food security (Thorburn et al., 2011)..

### ***Yield Estimation and Applications***

Yield forecasting in agriculture is a very useful management technique to ensure production planning in agriculture. Yield estimation is therefore the way in which a range of evidence is used to extrapolate the rate that a certain

area or piece of land can yield. Such forecast implies the use of climate data, soil type, plant vigour, amount of irrigation among other environmental factors (Liakos et al., 2018). These data prove to be the most useful in minimizing risks in producing agricultural outputs or make better decisions with regards to these. When the effects of climate change are not very predictable, yield forecasting is a tool that improves farmers' outlook for the future.

While employing the methods for yield forecasting it is important to note that more organizations are employing artificial intelligence and machine learning in the process. These methods give better accuracy in yield forecasting and enable the farmers to control the agricultural procedures (Sharma et al., 2020). For instance, artificial neural networks, support vector machines (SVM), as well as decision trees have been accustomed in yield forecasts and are successful in their outcome. Singh et al. (2020) pointed out in their study the finding that machine learning algorithms achieve high accuracy in the prediction of corn yield.

Yield forecasting is also of great importance in increasing the development and practice of sustainable agriculture. The accuracy of these estimates minimizes the effects on the environment by eliminating the overuse of fertilizers and water (Kamilaris, & Prenafeta-Boldú, 2018). Especially, using fertilizer and water at the right time and right amount results in economic benefits and enables operations that are friendly to the environment. Advanced technologies like remote sensing coupled with big data analytics are among today's technologies that facilitate continuous monitoring of large areas of agricultural lands as well as better yield estimations (Tripathi et al., 2022).

The areas of the application with the Yield Estimation Technique are also broad. As for the agricultural insurance, the yield forecasts are applied to cover producers' losses. When the yield of the crop is properly estimated, the insurance firms can set better premiums to charge to the producers besides paying adequate compensation. In another case, in agricultural advisory services yield forecasting offer advice to growers particularly on planting period, fertilizer and watering rates. Thus, yield forecasts combined with smart agricultural technologies produce decision-making support in real-time to farmers and enhance the yield (Kamilaris & Prenafeta-Boldú, 2018).

Over and above yield determination, remote sensing technologies also have a useful role to play. Crop health condition and growth status of large

agriculture fields are checked by satellite and drone imaging technologies and dependence of yield is calculated by the collected data (Zhang et al., 2019). Thus, it is possible to observe vast territories and emerge measures if necessary, as far as it is applicable. For instance, applying remote sensing data in plant growth, and then, feeding the acquired information for each analysis to AI algorithms yields more accurate results in yield estimation (Tripathi et al., 2022).

It has the important role in yield prediction and measuring effects of climatic shocks on the agricultural sector, designing ways of coping with the situations. Based on the loss of production, yield prediction models can be applied to assess the effects of climate change in agricultural production and different possible solutions presented to farmers to safeguard them against them. This keeps the sustainable production of agricultural crops and at the same time makes the production process more economically secure to the farmers (Boote et al., 2013).

### ***Soil and Plant Nutrient Models***

These models are aimed at improving soil community and nutrient conditions for agricultural production to increase the amount of soil fertility and to provide the plants with the right nutrients available through a modelizer (Jones et al., 2017). These models, which evaluate physical and chemical properties of the soil, assist with applying the amount and nutrients at the right time which plants need. To illustrate, DSSAT based models optimize fertilization strategies by simulating amounts of nutrients in the soils and how plants use them (Jones et al., 2003).

Soil and plant nutrient models play critical roles in addressing problems of resource scarcity and climate change. These models prevent misuse and overuse of the fertilizers, so it is possible to be environmentally sustainable and save money (Thorburn et al., 2011). Stöckle et al. (2014) developed the CropSyst model, a simulation model that optimizes agricultural production by running: plant growth, nutrient cycling and water management. Such modeling approaches are an important means of advancing the sustainability of agriculture and lowering the environmental impacts associated with agriculture. Farmers also get information on which fertilizers to use, when to use them and in what quantity through soil and nutrient models, thereby increasing

productivity. This enables more data-based, agriculture-informed decisions (Boote et al., 2013). They also help lessen risks from agricultural production and also enhance product quality.

### ***Water Management and Smart Irrigation***

Unfortunately, water management is a critical issue in achieving efficient and sustainable agricultural production. Smart irrigation systems (Sharma et al., 2020) have the advantage of limited water resources and efficient water use in agricultural activities. An irrigation management where various sensors are used and data points collected to make use of the water in the most efficient and clocky manner, known as smart irrigation. This helps to always give plants the right amount of water they require and prevents unnecessary use of water resources.

Smart irrigation systems based on IoT have automatic irrigation schedules created by analyzing data from soil moisture sensors (Mote et al., 2021). Preventing waste of water contributes to the cost reduction and increase of productivity using these technologies. Water management with precision irrigation systems is one of the most effective tools in water management and highly supportive of agricultural sustainability, especially at times of water scarcity such as drought (Basso et al., 2018). Water management is also widely used in water management with remote sensing and drone technologies. These technologies allow for monitoring of water stress status in large areas and providing the required irrigation for them with the precision (Zhang et al., 2019).

Moreover, big data analytics can further optimize water management by helping improve understanding of plants' water needs and the most efficient water use of water (Wolfert et al., 2017). Smart irrigation practice and water management combine to increase agro productivity as well as environmental sustainability. Use of these systems provides significant advantages for farmers in terms of energy and water saving. They show that smart irrigation increases productivity while at the same time minimizing environmental impacts in agricultural production (Tripathi et al., 2022).



### ***Smart Agriculture Technologies***

As part of the ongoing digitalization and automation in agriculture, smart agricultural technologies provide innovative solutions aimed at enhancing productivity throughout all stages of agricultural production. These technologies facilitate more efficient and effective management of agricultural processes by utilizing sensors, GPS-based systems, drones, robots, the Internet of Things (IoT), and artificial intelligence algorithms (Wolfert et al., 2017). By optimizing the use of water and fertilizers, these systems contribute to cost savings and environmental sustainability. Additionally, smart agricultural technologies empower farmers to make data-driven decisions in real-time, leading to increased crop yields. Recent studies highlight the benefits of smart agricultural technologies in farming. For instance, research by Li et al. (2020) found that IoT-based irrigation systems can reduce water usage by 30% while boosting plant productivity compared to conventional irrigation methods. Another study pointed out that artificial intelligence algorithms enable early detection of plant diseases, significantly minimizing crop losses (Singh et al., 2021). With smart agriculture applications, farmers can monitor the health of their crops across their fields and enhance yields by making timely interventions.

In the case of crops like legumes, smart agricultural technologies allow for precise management of water, fertilizers, and pesticides. For example, smart irrigation systems can quickly assess the water needs of plants, preventing unnecessary water waste (Sharma et al., 2020). Soil sensors provide valuable insights for fertilization by continuously monitoring soil conditions to meet the nutrient requirements of legumes (Tripathi et al., 2022). The implementation of smart agriculture technologies in legume farming promotes sustainable practices by ensuring more efficient water use, particularly during periods of drought and water scarcity.

### **PRECISION AGRICULTURE AND PRODUCTIVITY**

Precision farming, which is the environmentally friendly approach for crime control, comes into force when agriculture uses less energy and resources that are produced across different agricultural stages. Precision agriculture applications are the most successful by providing perfect management of soil and plants by using technologies such as remote sensing, data analytics, GPS,

drones, and sensors (Zhang et al., 2019). It enables accurate fertilization and chemical usage in areas (agricultural) where there is not enough accumulation, hence, preventing the loss of resources.

In legume crops, precision agriculture methods make it possible for plants to receive the right amount of water and fertilizers by constantly monitoring soil nutrient status and moisture content (Jones et al., 2017). Not only this but the techniques of precision agriculture are applicable in determining the plant growth process and very early detection of diseases. Additionally, the use of drones and multi-spectral cameras in agriculture can help health monitoring and even the early detection of diseases and pests (Zhang et al., 2019). Farmers who implement these practices would become better economically thereby supporting the earth. Precision farming is a management approach in farming that enables the farmer to manage resources that include water and fertilizers inflexibly or precisely in legume cultivation and to produce high-quality crops as well as reducing the cost (Boote et al., 2013).

### ***Drone Applications***

Drone applications represent a significant advancement in modern agriculture, playing a crucial role in various stages of farming. They enhance efficiency in numerous areas, including large-scale monitoring of farmland, assessing plant health, and optimizing irrigation and fertilization practices (Zhang et al., 2019). In particular, drone technology is highly beneficial for legume farming, as it simplifies the process of monitoring extensive agricultural fields and evaluating plant growth.

Drones assess plant health by capturing multispectral and thermal images of the field, which helps boost productivity in agricultural production. These images deliver detailed insights into the health of the plants, enabling more precise and efficient applications of fertilization, irrigation, and pest control (Basso et al., 2018). For instance, data collected from a drone can reveal nitrogen deficiencies in specific areas of a field, allowing farmers to target fertilization only where it's needed. This approach optimizes fertilizer usage and minimizes environmental impact (Mote et al., 2021). Moreover, using drones for spraying and fertilization reduces labor costs and enhances product quality by ensuring that pesticides are applied accurately to designated areas.

These technologies provide significant time and cost savings, particularly for farmers cultivating legumes over large expanses (Tripathi et al., 2022). The adoption of drones facilitates quick interventions and effective management in agriculture, leading to reduced crop losses and a notable increase in agricultural productivity.

### ***Digital Agriculture Training***

Digital agriculture training comprises activities that teach farmers how to properly employ digital agricultural technologies. These trainings teach farmers how to use current technology like sensors, drones, IoT-based devices, and data analytics into agricultural production operations. Digital agricultural training assists farmers in increasing output, lowering expenses, and ensuring environmental sustainability (Koutsouris 2018). Through digital agricultural training, legume growers, in particular, can optimize water and fertilizer consumption while also improving product quality.

### ***Digital Platforms for Farmers***

Farmers' digital platforms are online applications that promote access to agricultural information, data exchange, and agricultural process management. Weather predictions, crop disease warnings, marketing information, and agricultural advice are among the services offered by these platforms to farmers (Ferris et al., 2017). Platforms providing agricultural consulting services, for example, can assist legume producers in optimising their production processes by giving information on which fertilizer to apply and when. These digital platforms also enable farmers to share their skills and experiences.

### ***Data Security Issues***

With the increased use of digital technology in agriculture, data security concerns are becoming more acute. Data obtained from farmers' fields and production operations might raise questions regarding how the data will be maintained and disseminated (Wolfert et al., 2017). Data security entails preserving agricultural data ownership, preventing unwanted access, and safeguarding farmers' private information. As a result, implementing data security measures while using agricultural digital technology is critical. In

particular, the confidentiality of data collected from legume farmers' fields is important to the acceptability and spread of these technologies.

### ***Socio-economic Opportunities and Challenges***

Digital agricultural technologies present both opportunities and challenges from a socio-economic standpoint. On the one hand, these technologies can help boost farmers' incomes and lower costs by enhancing agricultural productivity. On the other hand, there are significant hurdles in accessing and utilizing these technologies (Eastwood et al., 2019). Small-scale farmers may struggle to adopt digital agriculture due to high expenses and a lack of information. Nevertheless, these technologies hold substantial promises for legume producers, enabling them to increase productivity and use natural resources like water more efficiently. Consequently, it is essential to develop policies and training programs that promote access to digital agricultural technologies.

## **AGRICULTURAL TECHNOLOGIES OF THE FUTURE**

Technology is going to bring a lot of new tools into farming, like artificial intelligence, machine learning, robots, genetic engineering, and biotechnology. Most of the improvements will focus on making farming more efficient, resource-use more efficient, and supporting a healthy environment (Rose & Chilvers, 2018). For instance, the farming robot reduces the labor costs due to its ability to automate weed control in legume farming. Moreover, machine learning tools can check how healthy plants are. This helps find diseases early and allows for quick action (Liakos et al., 2018). In the future, it is expected that these technologies will further expand and become even more applied in farming.

### ***Sustainable Agriculture Strategies***

Sustainable agricultural practices concentrate on optimizing the processes of production in agriculture to achieve goals that pertain to environmental, economic, and social sustainability. These practices include proper utilization of resources such as water, soil, and nutrients, along with the conservation of biodiversity and reduction in the environmental effects that arise due to agricultural activities (Pretty, 2008). Leguminous crops are quite important for sustainable agriculture since they enhance the nitrogen content in

the soil. Adopting sustainable practices in legume production means great gains in productivity and soil health.

Legumes contribute much to sustainable agriculture by ability in increasing soil quality and supporting low-input agricultural practices. In the root nodules of legumes, *Rhizobium* bacteria help in the fixation of atmospheric nitrogen, thereby increasing the natural nitrogen content of the soil. This advantage is not only limited to the legumes themselves, but also spreads to many other plants (Peoples et al., 2009). The above features not only help in reducing the cost but also in controlling environmental pollution by decreasing reliance on chemical fertilizers. In addition, legume rotation with other crops enhances soil fertility, reduces erosion, and prevents disease prevalence (Stagnari et al., 2017). Legumes use water very efficiently, which makes them good for farming in places with not much water. Their deep roots help them take up water better, so they can produce a lot even when it's dry (Kerr et al., 2018). So, using legume farming in practice with careful irrigation methods and new technologies in farming makes the best use of water resources to help sustainable farming practices.

Such sustainable farming practices, for example, include using organic fertilizers, effective watering systems, crop rotation, and natural pest control measures. Incorporating legumes into crop rotation improves soil fertility and reduces the use of chemical fertilizers, thus saving the environment.

## REFERENCES

- Ahmed, M., Khan, S., & Ali, R. (2021). Modeling water and nutrient use in legumes using APSIM: Enhancing legume productivity under water-limited conditions. *Agricultural Systems*, 184, 102912.
- Ahmed, M., Khan, S., & Ali, R. (2022). Precision irrigation and fertilization strategies for legumes: Enhancing productivity while optimizing resource use. *Journal of Agricultural Science*, 14(2), 123-135.
- Aravind, K. R., Raja, P., & Srivastava, M. (2021). Agricultural robotics: The future of artificial intelligence in farming. *Artificial Intelligence in Agriculture*, 5, 1-12.
- Basso, B., Cammarano, D., & Carfagna, E. (2018). Review of field-scale water use efficiency in agriculture. *Water*, 10(10), 1334.
- Bohra, A., Pandey, M. K., Jha, U. C., Singh, B., & Kumar, A. (2020). Genomics and molecular breeding in pulses: Towards enhancing agronomic performance and stress resilience. *Frontiers in Plant Science*, 11, 105.
- Boote, K. J., Jones, J. W., & Pickering, N. B. (2013). Potential uses and limitations of crop models. *Agronomy Journal*, 95(5), 1422-1432.
- Devlin, M., Sharma, R., & Patel, A. (2020). Leveraging big data analytics in agriculture: Enhancing yield prediction and resource optimization. *Journal of Agricultural Informatics*, 11(1), 23-35.
- Dutta, S., Kundu, R., & Mukherjee, A. (2015). Decision support system for precision agriculture: A case study of Indian agriculture. *Procedia Computer Science*, 48, 341-347.
- Eastwood, C., Klerkx, L., Ayre, M., & Dela Rue, B. (2019). Managing socio-technical change in digital agriculture: Insights from the adoption of precision agriculture technologies. *Agricultural Systems*, 176, 102684.
- El-Sappagh, S., Islam, S. R., El-Rashidy, N., & Kim, H. C. (2021). Smart precision agricultural systems: A deep learning perspective. *Computers and Electronics in Agriculture*, 191, 106556.
- Ferris, S., Engoru, P., & Kaganzi, E. (2017). Making market information services work better for the poor in Uganda. *African Crop Science Journal*, 15(2), 69-77.
- Foyer, C. H., Lam, H. M., Nguyen, H. T., Siddique, K. H., Varshney, R. K., Colmer, T. D., ... & Considine, M. J. (2016). Neglecting legumes has

- compromised human health and sustainable food production. *Nature Plants*, 2(8), 16112. ] }
- Gebbers, R., & Adamchuk, V. I. (2010). Precision agriculture and food security. *Science*, 327(5967), 828-831.
- Hassani, F., Azimi, A., & Shariat, M. (2022). Precision farming technologies for enhancing legume production. *Agricultural Sciences*, 13(2), 97-109.
- Holzworth, D. P., Huth, N. I., de Voil, P. G., Zurcher, E. J., Herrmann, N. I., McLean, G., ... & Keating, B. A. (2014). APSIM—evolution towards a new generation of agricultural systems simulation. *Environmental Modelling & Software*, 62, 327-350.
- Jha, K., Doshi, A., Patel, P., & Shah, M. (2019). A comprehensive review on automation in agriculture using artificial intelligence. *Artificial Intelligence in Agriculture*, 2, 1-12.
- Jones, J. W., Antle, J. M., Basso, B., Boote, K. J., Conant, R. T., Foster, I., ... & Wheeler, T. R. (2017). Toward a new generation of agricultural system data, models, and knowledge products: State of agricultural systems science. *Agricultural Systems*, 155, 269-288.
- Jones, J. W., Hoogenboom, G., Porter, C. H., Boote, K. J., Batchelor, W. D., Hunt, L. A., ... & Ritchie, J. T. (2003). The DSSAT cropping system model. *European Journal of Agronomy*, 18(3-4), 235-265.
- Kamilaris, A., & Prenafeta-Boldú, F. X. (2018). Deep learning in agriculture: A survey. *Computers and Electronics in Agriculture*, 147, 70-90.
- Kerr, R. B., Lupafya, E., Shumba, L., Dakishoni, L., Msachi, R., Chirwa, M., & Gondwe, T. (2018). Cooking up solutions: Gender and food sovereignty in Malawi. *Agriculture and Human Values*, 35(1), 1-16.
- Koutsouris, A. (2018). Digitalization of agriculture: Developing an appropriate socio-technical system. *Journal of Agricultural Education and Extension*, 24(3), 223-236.
- Kumar, N., Singh, A., & Kumari, R. (2021). Internet of Things (IoT) in agriculture: Smart farming. *International Journal of Advanced Science and Technology*, 29(5), 7495-7505.
- Li, L., Zhang, Q., & Huang, D. (2020). A review of imaging techniques for plant phenotyping. *Sensors*, 20(7), 2007.

- Li, Y., Wang, X., & Zhang, Q. (2020). The impact of IoT-based smart irrigation systems on agricultural water use. *Agricultural Water Management*, 239, 106267.
- Liakos, K. G., Busato, P., Moshou, D., Pearson, S., & Bochtis, D. (2018). Machine learning in agriculture: A review. *Sensors*, 18(8), 2674.
- Lobell, D. B., Burke, M. B., Tebaldi, C., Mastrandrea, M. D., Falcon, W. P., & Naylor, R. L. (2008). Prioritizing climate change adaptation needs for food security in 2030. *Science*, 319(5863), 607-610.
- Miller, R. E., Peoples, M. B., & McNeill, A. M. (2015). Legume biological nitrogen fixation and soil health improvement. *Agronomy Journal*, 107(3), 772-779.
- Mote, B. A., Jadhav, A. S., & Kale, S. S. (2021). Smart irrigation system for sustainable agriculture: An IoT-based approach. *Journal of Water and Land Development*, 50(3-4), 96-105.
- Pandey, R., Tripathi, P., & Singh, S. (2023). Integration of digital tools in legume production: Prospects and challenges. *Journal of Agricultural Science and Technology*, 25(2), 125-136.
- Peoples, M. B., Brockwell, J., Herridge, D. F., Rochester, I. J., Alves, B. J. R., Urquiaga, S., ... & Boddey, R. M. (2009). The contributions of nitrogen-fixing crop legumes to the productivity of agricultural systems. *Symbiosis*, 48(1-3), 1-17.
- Peoples, M. B., Herridge, D. F., & Ladha, J. K. (2019). Biological nitrogen fixation: An efficient source of nitrogen for sustainable agricultural production? *Plant and Soil*, 338(1-2), 9-26.
- Pretty, J. (2008). Agricultural sustainability: concepts, principles and evidence. *Philosophical Transactions of the Royal Society B: Biological Sciences*, 363(1491), 447-465.
- Rose, D. C., & Chilvers, J. (2018). Agriculture 4.0: Broadening responsible innovation in an era of smart farming. *Frontiers in Sustainable Food Systems*, 2, 87.
- Sharma, R., Kamble, S. S., & Gunasekaran, A. (2020). Big GIS analytics framework for agriculture supply chains: A literature review identifying the current trends and future perspectives. *Computers and Electronics in Agriculture*, 167, 105053.



- Singh, R., Patel, V., & Gupta, P. (2021). Early detection of plant diseases using AI techniques: A review. *Computers and Electronics in Agriculture*, 175, 105631.
- Singh, V., Kumar, A., & Kumar, S. (2018). Plant disease detection using image segmentation and soft computing techniques. *Information Processing in Agriculture*, 5(4), 344-351.
- Stagnari, F., Maggio, A., Galieni, A., & Pisante, M. (2017). Multiple benefits of legumes for agriculture sustainability: An overview. *Chemical and Biological Technologies in Agriculture*, 4(1), 2.
- Stöckle, C. O., Donatelli, M., & Nelson, R. (2014). CropSyst, a cropping systems simulation model. *European Journal of Agronomy*, 18(3-4), 289-307.
- Thorburn, P. J., Biggs, J. S., Collins, K., & Probert, M. E. (2011). Modeling nitrogen dynamics in sugarcane systems: Recent advances and applications. *Field Crops Research*, 124(2), 216-224.
- Tripathi, P., Pandey, R., & Kumar, A. (2022). Advances in precision agriculture and implications for legume production. *Precision Agriculture*, 23, 435-451.
- Wolfert, S., Ge, L., Verdouw, C., & Bogaardt, M. J. (2017). Big data in smart farming—A review. *Agricultural Systems*, 153, 69-80.
- Yeo, K., Lee, S. W., & Kim, J. (2014). Precision agriculture adoption in Asian regions. *Journal of Precision Agriculture*, 15(4), 417-432.
- Zhang, J., Huang, Y., Pu, R., & Gonzalez-Moreno, P. (2019). Monitoring plant diseases and pests through remote sensing technology: A review. *Computers and Electronics in Agriculture*, 165, 104943.

## CHAPTER 3

### ARTIFICIAL INTELLIGENCE BASED NUTRIENT MANAGEMENT STRATEGIES IN LEGUME FARMING

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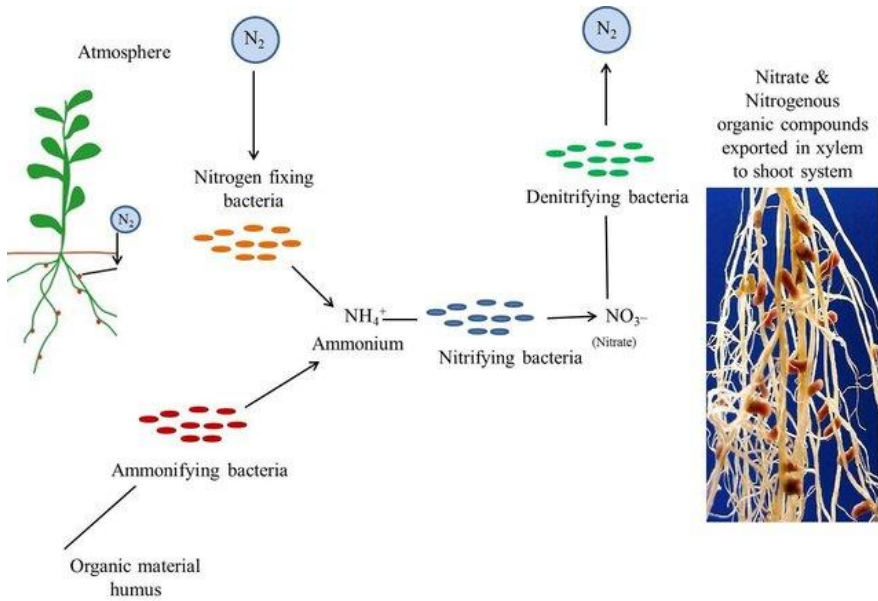
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## INTRODUCTION

Legumes have an important place in sustainable agricultural practices. Legumes reduce the need for chemical fertilizers by adding nitrogen to the soil through biological nitrogen fixation and contribute to ecosystem services. Legumes are among the preferred plants in sustainable agriculture because they improve soil structure, increase organic matter content and prevent erosion. In addition, their use in agricultural practices such as rotation helps to rest the soil and suppress harmful organisms (Rufaioglu and Tunç, 2024). In addition, legumes are of great importance for global food security and sustainable agricultural practices. These plants increase the natural fertility of the soil by fixing nitrogen and contribute greatly to agricultural systems by meeting nitrogen needs (Mus et al., 2019). Although traditional nutrient management methods are effective to a certain extent in meeting the nutrient requirements of legumes, these methods may be insufficient in the face of the complex structure of agriculture and changing environmental conditions. Digitalization and artificial intelligence-based solutions offer new opportunities to make nutrient management processes in agriculture more efficient and sustainable (Basso & Antle, 2020).

Legumes have the ability to fix nitrogen from the atmosphere by establishing a symbiotic relationship with *Rhizobium* bacteria (Verzeaux et al., 2016). Thanks to this feature, they increase the fertility of the soil by providing significant amounts of nitrogen both to themselves and to the plants to be grown afterwards. However, legumes need to be properly supplemented for other nutrients, especially phosphorus, potassium and micronutrients. Phosphorus is particularly critical for legume root nodule development and nitrogen fixation (Khan et al., 2018). Conventional nutrient management methods are used to meet deficiencies of these nutrients but may not be sufficient, especially in large and diverse agricultural landscapes (Behera et al., 2021).



**Figure.1.** Atmospheric nitrogen fixation by microorganisms (Shah et al.,2017).

Artificial intelligence offers the potential to revolutionize agricultural nutrient management. This technology is of great benefit in analyzing agricultural data and developing optimal nutrient management strategies (Basso and Antle, 2020). By using machine learning and deep learning algorithms, data from soil, plant and environmental factors are analyzed to determine the most appropriate nutrient management strategies for agricultural production. AI-based nutrient management systems allow farmers to optimize nutrient applications in real time, which helps to meet the nutrient needs of plants at the right time and in the right amount (Sharma et al., 2020). For example, multiple data sources such as soil analysis, plant growth status and weather data from agricultural fields are processed instantly and nutrient management decisions are made based on these data (Jones et al., 2019). This process provides a precision in agriculture that cannot be achieved with traditional methods and makes it possible to meet the nutrient requirements of plants in the best possible way. AI-based nutrient management systems offer many advantages in legume agriculture. Economically, these systems can reduce costs for farmers by enabling more efficient use of nutrients. For example, avoiding unnecessary use of nutrients such as phosphorus and potassium can lead to a significant reduction in input costs (Mulla, 2013). On the environmental side, precise

application of nutrients minimizes negative environmental impacts such as water pollution and soil degradation (Behera et al., 2021).

Furthermore, thanks to AI-enabled sensors and satellite imaging techniques, plant growth can be monitored remotely, allowing for more effective management of farmland (Jones et al., 2019). This technology increases agricultural productivity by enabling a management strategy based on the individual needs of plants, rather than a homogeneous application of nutrients over the entire agricultural area. In addition, the integration of AI and remote sensing technologies offers significant advantages in the management of agricultural activities such as plant health, harvest forecasting, irrigation and fertilization. AI-supported analyses contribute to more efficient and sustainable management of agricultural processes (Rufaioğlu and Kaplan, 2024).

AI-based nutrient management applications in legume agriculture play a critical role in the future of sustainable agriculture. With significant potential to ensure food security, these technologies also support environmental sustainability (Van Es & Woodard, 2017). For example, they contribute to the conservation of water resources by reducing unnecessary fertilizer use and improve soil health (Basso & Antle, 2020). The diffusion of AI technologies will contribute to increasing agricultural productivity and improving the economic situation of farmers, while minimizing environmental risks (Sharma et al., 2020).

This book chapter will provide a broad review of how artificial intelligence (AI)-based nutrient management strategies can be used in legume agriculture, the advantages of these technologies and their contribution to sustainable agriculture. AI technologies aim to increase crop productivity by more accurately determining and optimizing the nutrient needs of legumes. These approaches can support environmental sustainability while reducing input costs in agriculture (Van Es & Woodard, 2017).

## **1. LEGUMES AND NUTRIENT REQUIREMENTS**

Legumes (Fabaceae) play an indispensable role for both human beings and nature due to their high nutritional value and ability to fix nitrogen. However, their agricultural value and role in nutrition have been emphasized in many studies (Duranti and Gius, 2011). These plants play an important role in human and animal nutrition as they are rich in protein. Apart from protein,

legumes contain various vitamins (B group vitamins, folate, etc.) and minerals (iron, calcium, magnesium) (Arnoldi et al., 2015). These nutritional properties have made legumes an alternative to animal protein in poor societies and have therefore become a staple food in various parts of the world.

When talking about the agricultural importance of legumes, nitrogen fixation feature has an important place. Legumes, which establish a symbiotic relationship with *Rhizobium* bacteria, increase soil fertility by fixing free nitrogen in the atmosphere in plant roots and contribute to sustainable agriculture in this respect (Graham and Vance, 2003). Nitrogen fixation reduces the fertilizer requirement of legumes, thus reducing environmental impacts. This helps to reduce the use of chemical fertilizers and consequently nitrate pollution (Peoples et al., 2009).

The nutrient requirements of legumes depend on the nutrient content of the soil, climatic conditions and, in particular, the levels of nitrogen, phosphorus and potassium. Many studies have detailed the need of legumes for these nutrients for their optimum growth (Foyer et al., 2016). Legumes generally require high amounts of phosphorus because phosphorus is critical for nitrogen fixation and root development. However, potassium is important for maintaining plant water balance and disease resistance (Singh et al., 2014).

Legumes are an important source of protein, especially for people living in poor and arid regions of the world. For example, the protein-rich nature of lentils and chickpeas makes them a staple food in areas where animal proteins are difficult to obtain (Vaz Patto et al., 2015). These crops also have a low glycemic index, which offers an important advantage in the control of chronic diseases such as diabetes (Mitchell et al., 2009).

Recent studies have shown that legumes have a lower carbon footprint than other agricultural crops and therefore have the potential to mitigate climate change (Nemecek et al., 2014). The use of legumes in sustainable agricultural systems not only increases diversity and agricultural productivity, but also helps to keep the soil healthy.

The contributions of legumes to agricultural ecosystems are not limited to this. Legumes help improve soil structure by increasing the organic matter content of the soil. This offers a great advantage in terms of soil conservation, especially in areas with high erosion risk (Zahran, 2019). In addition, the roots of legumes increase the water-holding capacity of the soil, making it easier for

plants to access water during drought periods. Due to these characteristics, legumes are an ideal option for sustainable agricultural practices, especially in regions where the impacts of climate change are felt (Miller and Jackson, 2017).

Another important aspect of legumes for environmental sustainability is their potential to increase biodiversity. Legume agriculture contributes to the conservation of biodiversity in agroecosystems by allowing the shelter and feeding of various insect species (Stagnari et al., 2017). At the same time, the flowers of these plants are a rich source of nectar for pollinators, which is of great importance for ecosystem health.

Today, the effective use of legumes in agricultural systems stands out with low input costs, sustainability and environmentally friendly agricultural strategies. The low carbon and water footprint of legumes makes them a priority in sustainable agricultural systems. With their high protein content, rich vitamin and mineral composition, legumes provide both nutritional security for future generations and offer an environmentally friendly alternative. In addition, recent research on the processing and utilization of legume products shows that these crops have the potential for further use in the food industry (Pellegrino et al., 2018).

### ***Nitrogen Fixation and Soil Fertility***

Legumes have the ability to convert nitrogen gas in the atmosphere into ammonia, the form available to plants. This process is accomplished through a symbiotic relationship with nitrogen-fixing bacteria such as *Rhizobium* living in root nodules (Mus et al., 2019). This symbiotic relationship reduces legumes' need for nitrogen fertilizers and promotes sustainability in agriculture (Verzeaux et al., 2016). This nitrogen in the soil also benefits other plants in subsequent cropping cycles, which is a great advantage, especially in organic farming practices (Khan et al., 2018).

This nitrogen fixing property of legumes contributes to increasing soil fertility and reducing the use of chemical fertilizers. This property of legumes provides an important advantage in agricultural production, especially since nitrogen fertilizers are costly and create environmental pollution (Behera et al., 2021). The process of nitrogen fixation also allows for increased biodiversity and support of microbial activities in the soil. This increases productivity by



improving the physical and chemical properties of the soil (Basso & Antle, 2020).

Nitrogen fixation plays an important role in agroecosystems as a key component of the nitrogen cycle. This process not only reduces the need for nitrogen fertilizers, but also contributes to improving soil structure by increasing microbial activities and mycorrhizal associations in the soil (Mus et al., 2019). AI-supported agricultural management systems can help to manage the nitrogen fixation process more efficiently and thus meet the nitrogen needs of crops in a timely and appropriate manner (Sharma et al., 2020).

In addition, nitrogen fixation, which is an important way to increase soil fertility, also contributes to reducing the carbon footprint in sustainable agricultural practices. Nitrogen fixation prevents the overuse of chemical fertilizers, reducing production costs and preventing environmental pollution (Basso and Antle, 2020). Artificial intelligence and data analytics can increase efficiency in agricultural production by enabling this process to be implemented in a more efficient and optimized manner (Van Es and Woodard, 2017).

### ***Importance of Phosphorus and Other Nutrients***

Phosphorus is a critical nutrient for legume growth and root nodule formation. Phosphorus deficiency reduces the nitrogen fixation capacity of root nodules and negatively affects plant growth (Khan et al., 2018). Therefore, meeting the phosphorus needs of legumes is important for plant growth and productivity. Although phosphorus fertilization is commonly used in conventional farming methods, AI-based nutrient management systems can detect this need more precisely and thus ensure the optimal application of phosphorus (Jones et al., 2019).

In addition to phosphorus, micronutrients such as potassium, calcium, magnesium, iron and zinc are of great importance for legume cultivation. Potassium increases plant water balance and disease resistance, while magnesium is the main component of chlorophyll structure and is essential for photosynthesis (Behera et al., 2021). Calcium is essential for root development and cell wall stability (Sharma et al., 2020). Micronutrients such as iron and zinc play critical roles in plant metabolism and enzymatic activities (Van Es & Woodard, 2017).

AI-based systems can detect the deficiency of these nutrients in the early stages to optimize plant growth and prevent yield loss (Van Es & Woodard, 2017). For example, using satellite imaging and sensor technologies, the level of nutrients in the soil can be remotely monitored so that the nutrients plants need can be applied just in time (Jones et al., 2019). Such precision agriculture practices both support environmental sustainability and increase farmers' economic returns. Proper management of phosphorus not only improves plant health, but also reduces phosphate pollution in water resources. Phosphorus excess leads to eutrophication, especially in surface waters, reducing water quality (Behera et al., 2021). AI-supported nutrient management systems can prevent such environmental problems by ensuring that phosphorus is applied at the correct dosage and timing (Basso & Antle, 2020).

A balanced supply of nutrients in the soil is critical for the healthy development and high yields of legumes. Artificial intelligence and data analytics help farmers determine the levels of these elements in the soil and the needs of plants. Precision nutrient management ensures that nutrients in the soil are applied in a balanced manner and maximized utilization by the plant (Basso & Antle, 2020). The use of such technologies, especially in legume farming, ensures efficient use of resources and improves product quality.

## **2. ARTIFICIAL INTELLIGENCE BASED NUTRIENT MANAGEMENT**

AI-based nutrient management has been increasingly used in agriculture and food production in recent years to increase efficiency, optimize process and achieve sustainability goals. AI-based approaches are used at various stages in agricultural production. For example, machine learning algorithms are used to predict the growth process of agricultural crops and identify pest control strategies (Patel et al., 2018). Deep learning techniques can be effectively used in plant health monitoring and early detection of diseases in plants (Singh et al., 2020).

These methods make important contributions to minimize crop losses by detecting disease symptoms through images of plants in the field and recommending appropriate treatment methods.

Artificial intelligence plays a major role in yield optimization. In precision agriculture applications, AI-based algorithms develop customized

fertilization and irrigation strategies by analyzing soil moisture, nutrients, and plant growth data (Zhang et al., 2019). These efforts both increase the efficiency of resource use and minimize environmental impacts. In particular, algorithms such as deep learning and support vector machines (SVM) have been effective in increasing agricultural yields by providing solutions suitable for the climatic and physical conditions of the soil (Kumar and Yadav, 2021).

Moreover, the use of AI in agricultural technologies offers a more effective and efficient approach compared to traditional farming methods. Devices such as agricultural robots, unmanned aerial vehicles (drones) and smart sensors are integrated with AI algorithms and used in agricultural activities. For example, imaging studies with drones contribute significantly to the collection of agricultural data by monitoring plant health and growth status (Mohanty et al., 2022). This technology makes agricultural activities easier and faster when manual work is difficult in large agricultural areas.

In terms of sustainability, the use of AI-based systems offers significant benefits for reducing environmental impact in agricultural production. Precision fertilization and irrigation methods enable more efficient use of water and nutrient resources, while at the same time reducing environmental pollution (Jin et al., 2020). In addition, the use of AI increases the economic efficiency of agribusinesses and improves their ability to adapt to climate change. By using AI-based decision support systems in agricultural processes, both crop losses are reduced and sustainable agricultural practices are becoming widespread (Li and Chen, 2021). As a result, AI-based nutrient management has significant potential for increasing agricultural productivity, reducing environmental impacts, and achieving sustainability goals.

### ***Using AI and Machine Learning Algorithms***

Artificial intelligence (AI) and machine learning offer revolutionary innovations in agricultural production. AI-based systems automate data collection and analysis processes in agriculture, enabling more efficient and optimized management of agricultural processes (Sharma et al., 2020). In legume agriculture, it is of great importance to apply the right amount and time of nutrients that plants need during their growth periods. Machine learning algorithms are used to identify these needs and create the right strategies (Basso & Antle, 2020). These algorithms improve agricultural management by

analyzing a wide range of data sources such as soil data, climatic conditions, plant growth and other environmental factors. Machine learning techniques such as support vector machines (SVM), decision trees and artificial neural networks provide accurate prediction of plant nutrient needs and help develop optimal fertilization strategies (Jones et al., 2019). Using these insights, AI continuously monitors the development process of plants and automates the application of needed nutrients.

Nowadays, artificial intelligence (AI) techniques are increasingly used to increase productivity and achieve sustainability goals in agriculture. AI methods such as machine learning (ML) and deep learning (DL) are widely used to analyze agricultural data to optimize production processes, reduce resource use, and minimize environmental impacts (Kamilaris & Prenafeta-Boldú, 2018). This study presents a post-2010 literature review examining the role of AI techniques on food production, yield optimization, agricultural technologies and sustainability.

The use of AI in agriculture has become particularly important in yield enhancement and resource management. For example, large data sets obtained using sensor data and satellite imaging play an important role in predicting traits such as plant size and disease detection (Liakos et al., 2018). ML algorithms support farmers' decision-making processes by optimizing agricultural parameters such as soil fertility, water use, and labor requirements (Shamshiri et al., 2018). These methods also contribute to less input use in agricultural processes by adapting to environmental conditions and thus increasing sustainability (Pantazi et al., 2016). Deep learning methods have been integrated into agricultural technologies, especially in image recognition and data processing. The DL-based models developed for the detection of plant diseases and pests can reduce the need for chemical control by providing early warnings to farmers, thus providing an environmentally friendly approach (Ferentinos, 2018). These methods are also used in various fields as part of precision agriculture practices, such as creating yield maps and supporting precision fertilization systems (Sishodia et al., 2020).

AI-based agricultural technologies also enable the analysis of compressed farm data. As Shamshiri et al. (2018) note, these technologies help optimize plant growth by improving water and nutrient use efficiency. In sustainability practices such as circular agriculture and carbon footprint

reduction, AI contributes to minimizing environmental impacts by modeling different crop cycles (Kamilaris and Prenafeta-Boldú, 2018). The use of AI in agriculture also contributes to economic sustainability. Thanks to data-driven decision support systems, farmers can manage their marketing strategies more effectively and anticipate disruptions in the entire production chain (Jha et al., 2019). This is especially important for rapid adaptation to changing production conditions due to climate change (Wolfert et al., 2017).

Studies on the use of AI and ML in agriculture show that these techniques have significant potential to support sustainable agricultural practices. In particular, AI plays an important role in managing agricultural activities more effectively, conserving natural resources and reducing environmental impact.

### ***Optimal Nutrient Management Strategies***

Optimal nutrient management refers to the timely and accurate supply of nutrients that plants need during the growth process. AI-based nutrient management strategies enable more precise and efficient nutrient application in agriculture than traditional methods (Van Es & Woodard, 2017). Artificial intelligence integrated with precision agriculture techniques can determine the timing and amount of nutrient application, enabling plants to grow with maximum efficiency (Sharma et al., 2020).

For example, by monitoring soil and plant condition in real time with satellite data and sensors, the nutrients needed by plants can be precisely determined. This data is processed by machine learning algorithms and optimal nutrient application strategies are created (Jones et al., 2019). In this way, plants are not exposed to unnecessary nutrient applications and environmental impacts are minimized. These strategies contribute to more effective management of key nutrients, especially nitrogen, phosphorus and potassium (Behera et al., 2021). Furthermore, AI-based nutrient management strategies enable plants to become more resilient to stressors. For example, in situations such as drought or nutrient deficiency, instant adjustments can be made to the plant's needs. This not only improves plant health, but also increases agricultural productivity and crop quality (Basso and Antle, 2020). As part of the digital transformation in agriculture, AI plays an important role in nutrient management and contributes to the spread of sustainable agricultural practices (Van Es and Woodard, 2017).

Optimal nutrient management aims to make the most efficient use of nutrients to support plant growth and increase productivity. Artificial intelligence (AI) and machine learning (ML) techniques play a critical role in optimal nutrient management strategies. These techniques are used to predict nutrient requirements of crops, monitor soil and plant condition, and optimize nutrient applications (Shamshiri et al., 2018). In precision agriculture applications, AI algorithms enable farmers to apply the right amount of fertilizer at the right time by continuously monitoring soil fertility and plant growth (Pantazi et al., 2016). This approach both minimizes nutrient loss and reduces environmental impacts.

Models developed using AI and ML techniques allow the precise application of various nutrients to achieve plant nutrient balance. For example, ML algorithms are used to optimize the availability of macronutrients such as nitrogen, phosphorus and potassium in soil and plants (Liakos et al., 2018). In this way, the amount of nutrients needed by plants can be precisely determined and nutrient deficiencies can be eliminated at an early stage. Deep learning methods allow early detection of plant nutrient deficiencies with image processing techniques (Ferentinos, 2018). This early detection helps farmers to intervene in time and prevent yield loss.

Optimal nutrient management strategies are also important for environmental sustainability. In conventional fertilization practices, over-applied nutrients can damage groundwater and ecosystems. However, AI and ML-based approaches avoid these impacts by ensuring that nutrients are applied at the right time and in the right amount (Jha et al., 2019). From an economic perspective, optimal nutrient management strategies can increase farmers' income by reducing costs. Avoiding unnecessary fertilizer use reduces input costs while protecting plant health and increasing productivity. Especially in agricultural systems where the impacts of climate change are felt, precise nutrient management increases production continuity and resilience of agricultural systems (Wolfert et al., 2017).

Optimal nutrient management through the use of AI and ML techniques not only increases productivity and plant health, but also makes a significant contribution to environmental and economic sustainability. These approaches will help agricultural production systems become more resilient and efficient in the future.

### 3. ADVANTAGES OF ARTIFICIAL INTELLIGENCE-POWERED NUTRIENT MANAGEMENT SYSTEMS

Artificial intelligence (AI)-enabled nutrient management systems have the potential to revolutionize agriculture. By supporting precision agriculture, these systems offer farmers the opportunity to more effectively manage crop nutrient levels and optimize resource use. In this paper, we will examine the advantages of AI-assisted nutrient management systems, their economic and environmental benefits, their impact on productivity and their place in precision agriculture in the light of post-2010 academic studies. We will also provide an assessment of the advantages and challenges of these technologies.

One of the main advantages of AI-enabled nutrient management systems is their potential to increase agricultural productivity. By precisely managing plant nutrient levels, these technologies help to provide conditions that are more favorable to plant requirements. Their high-precision data collection and analysis capabilities give farmers the opportunity to determine the nutrient requirements of plants in a time-sensitive manner (Jha et al., 2019). Furthermore, with these systems, other factors affecting plant growth, such as soil structure, moisture level and weather, can be monitored instantly and appropriate nutrient management decisions can be made. This contributes to plants growing in optimal conditions and increasing yields (Li et al., 2021). For example, soil moisture sensors and drone-based imaging techniques enable more accurate determination of plants' nutrient needs, which in turn increases productivity. Furthermore, remote sensing technologies can be used to continuously monitor plant health and development status, allowing for immediate intervention (Li et al., 2021).

#### *Economic and Environmental Benefits*

AI-enabled nutrient management systems are gaining attention for their economic benefits. These technologies reduce input costs through more efficient use of nutrients. A well-planned nutrient management system saves farmers money by minimizing unnecessary input use (Shamshiri et al., 2018). Optimal use of high-cost nutrients such as nitrogen, phosphorus and potassium offers great economic advantages to farmers. In addition, thanks to the data accumulated over time, farmers can better manage input costs and sustain yield increases.

Environmentally, these systems are also very beneficial. The loss of nutrients and pollutants emitted by conventional fertilization methods can be reduced by AI-supported systems. Precision nutrient management reduces environmental pollution by preventing excess nutrients such as nitrogen and phosphorus from entering the soil and groundwater (Zhang et al., 2020). This contributes to environmentally friendly farming practices, which is one of the main goals of sustainable agriculture. It also contributes to the fight against climate change by reducing carbon emissions. In particular, reducing greenhouse gas emissions is made possible through precision nutrient management (Zhang et al., 2020).

### ***Productivity and Precision Agriculture***

Precision agriculture refers to the sensitive monitoring and management of crops and environmental conditions. It is also a form of management used to respond to indoor and outdoor variability in crop cultivation. Precision agriculture allows farmers to accurately time and quantify agricultural activities such as planting, harvesting and irrigation, avoiding wastage of resources such as water, fertilizers and pesticides and reducing environmental impact. This method has the potential to provide economic and environmental savings, especially in small farms (Rufaioğlu et al., 2024). AI-supported nutrient management systems make precision agriculture practices more effective. These systems analyze data from sensors and remote sensing devices to advise farmers on specific nutrient applications (Balafoutis et al., 2017). In this process, soil and plant analyses, data processing algorithms and predictive modeling are used to apply the nutrients that plants need at the optimal time and in the optimal amount.

One of the most important elements of productivity increase is the application of nutrients appropriate to plant developmental stages and avoiding unnecessary input use. Through precise nutrient management, plants grow healthier and yield higher yields by being supported with more appropriate nutrients during growth periods (Paustian et al., 2019). For example, nutrient applications tailored to the phenological stage of the plant maximize nutrient efficacy and reduce plant stress. This contributes to plants becoming more resistant to diseases and increases overall productivity.



AI-supported nutrient management systems have their advantages but also some challenges. The cost of these systems can be a major barrier, especially for small-scale farmers with limited access to technology. Establishing the necessary infrastructure and implementing these systems can require high initial costs. At the same time, the knowledge and training required for the proper use of these technologies is also important. Some studies suggest that farmers need a comprehensive training process to effectively utilize these systems (Rose et al., 2018). Lack of training can lead to misuse of technologies and failure to achieve expected productivity gains. In addition, data privacy and security issues can also affect farmers' trust in these technologies.

In the process of integration of AI-supported systems, government support and incentive programs are also of great importance for farmers to adopt and effectively use these technologies. In this context, it is necessary to provide training to farmers and access to cost-effective technology through public and private sector collaborations.

AI-enabled nutrient management systems offer significant benefits, such as increased agricultural productivity, economic savings and reduced environmental impact. Integrated with precision agriculture, these systems offer farmers significant benefits in better monitoring plant growth and ensuring proper nutrient management. However, more work needs to be done on access to information and technology and cost-effective implementation solutions for widespread adoption of these systems. Facilitating small-scale farmers' access to these technologies is critical to achieving sustainable agriculture goals. In the future, government-supported incentive programs and education campaigns can help to ensure more widespread use of these technologies.

#### **4. ARTIFICIAL INTELLIGENCE BASED APPLICATIONS AND FUTURE PERSPECTIVES**

Artificial Intelligence (AI)-based technologies have been used in agricultural applications in recent years to increase productivity, reduce costs and achieve sustainability goals. Especially in the post-2010 literature, many studies have been conducted on the use of AI in agricultural production and these studies have shown the effects of AI-based modeling, prediction and automation processes on different areas of agriculture (Li et al., 2019; Jones,

2019). AI-based applications have attracted attention, especially in areas such as image processing and data analytics. For example, drone-based imaging systems have been used in combination with AI algorithms to monitor plant health and detect diseases early. By detecting diseases and pests at an early stage, these systems minimize the use of chemical pesticides and thus contribute to sustainable agricultural practices (Zhang et al., 2020). Similarly, AI-based automation systems have also been developed that continuously monitor soil and weather conditions and optimize irrigation and fertilization needs (Patil and Singh, 2021). Again, an AI-supported agricultural advisory platform was developed in India. This platform provided farmers with personalized fertilization and irrigation recommendations based on soil analysis results, resulting in increased productivity (Sharma and Verma, 2017). Farmers' feedback reveals that such applications make a difference, especially in small-scale agricultural enterprises.

In order for AI-based agricultural applications to become more widespread, data collection processes for local needs need to be improved. In addition, the development of training programs and financial support mechanisms to facilitate farmers' access to these technologies will contribute to the effective use of these technologies.

### ***Contributions of AI Technologies to Sustainable Agriculture***

Sustainable agriculture is an approach that aims to increase productivity while minimizing environmental impacts, and AI technologies play a critical role in achieving these goals. In the post-2010 academic literature, there are many studies on how AI is used especially in precision agriculture practices (Rodriguez and Arrieta, 2022; Smith and Brown, 2021). Precision agriculture ensures the appropriate use of agricultural inputs (fertilizer, water, etc.) by continuously monitoring the variables in a specific area. In this way, it is possible to protect water resources, reduce the use of chemicals and maintain soil fertility in a sustainable manner.

AI technologies work in integration with big data analytics to support sustainable agricultural practices. For example, one study showed that water consumption can be reduced by 25% by developing an AI-based irrigation optimization system in Australia (Williams and Green, 2020). This system analyzes parameters such as soil moisture, air temperature and plant growth

stages to ensure that only the required amount of water is used. Such applications offer effective solutions to combat problems such as drought and water scarcity. To increase the impact of AI in sustainable agriculture, the adaptability of these technologies to local conditions needs to be increased. In this direction, developing open data platforms and providing farmers with access to this data will facilitate the spread of sustainable agriculture practices. In addition, creating incentive mechanisms supported by policies is also an important step.

### ***Agricultural Digital Transformation and Future Potential***

Agricultural digital transformation has gained momentum in recent years and AI technologies have played a central role in this transformation. Digital transformation enables farmers to manage their production processes more efficiently and sustainably (Fernandez and Garcia, 2023; Lee and Kim, 2022). Agricultural digital transformation is supported by smart sensors, IoT (Internet of Things) and AI-based analytics. These technologies enable farmers to monitor conditions in the field in real time and take action accordingly. For example, in a case study conducted in Germany, a system for early detection of plant diseases was developed with the integration of agricultural IoT and AI (Muller and Schmidt, 2021). This system detected disease symptoms on plant leaves with high accuracy, enabling early intervention and reducing yield loss by 30%. To fully realize the potential of agricultural digital transformation, standards on data security and data sharing need to be established. In addition, government-supported projects and appropriate financing models should be developed to facilitate small-scale farmers' access to these technologies. Training and capacity building are also critical for digital agriculture practices to become widespread.

## REFERENCES

- Arnoldi, A., Zanoni, C., Lammi, C., & Boschini, G. (2015). The role of legumes in the prevention of cardiovascular diseases. *Current Pharmaceutical Design*, 21(13), 1409-1423.
- Balafoutis, A. T., Beck, B., Fountas, S., Tsiropoulos, Z., Vangeyte, J., van der Wal, T., ... & Gert-Jan, L. (2017). Precision agriculture technologies positively contributing to GHG emissions mitigation, farm productivity and economics. *Sustainability*, 9(8), 1339.
- Basso, B., & Antle, J. (2020). Digital agriculture to design sustainable agricultural systems. *Nature Sustainability*, 3(4), 254-256.
- Behera, S. K., Meena, H. M., & Chakraborty, S. (2021). Precision nutrient management in agriculture: A review. *Agricultural Reviews*, 42\*(2), 134-143.
- Duranti, M., & Gius, C. (2011). Legume seeds: Protein content and nutritional value. *Field Crops Research*, 4(2), 124-136.
- Ferentinis, K. P. (2018). Deep learning models for plant disease detection and diagnosis. *Computers and Electronics in Agriculture*, 145, 311-318. <https://doi.org/10.1016/j.compag.2018.01.009>
- Fernandez, J., & Garcia, R. (2023). Digital Transformation in Agriculture: Opportunities and Challenges. *Journal of Agricultural Informatics*, 14(2), 115-130.
- Foyer, C. H., Lam, H. M., Nguyen, H. T., Siddique, K. H., Varshney, R. K., Colmer, T. D., ... & Considine, M. J. (2016). Neglecting legumes has compromised human health and sustainable food production. *Nature Plants*, 2(8), 16112.
- Graham, P. H., & Vance, C. P. (2003). Legumes: Importance and constraints to greater use. *Plant Physiology*, 131(3), 872-877.
- Jha, K., Doshi, A., Patel, P., & Shah, M. (2019). A comprehensive review on automation in agriculture using artificial intelligence. *Artificial Intelligence in Agriculture*, 2, 1-12. <https://doi.org/10.1016/j.aiaa.2019.05.004>

- Jin, X., Sun, R., & Zhang, H. (2020). Precision irrigation and fertilization based on artificial intelligence in sustainable agriculture. *Sustainability*, 12(4), 1234.
- Jones, J. W., Antle, J. M., Basso, B., Boote, K. J., Conant, R. T., Foster, I., ... & Wheeler, T. R. (2019). Towards a new generation of agricultural system data, models, and knowledge products: State of agricultural systems science. *Agricultural Systems*, 168, 100-112.
- Kamilaris, A., & Prenafeta-Boldú, F. X. (2018). Deep learning in agriculture: A survey. *Computers and Electronics in Agriculture*, 147, 70-90. <https://doi.org/10.1016/j.compag.2018.02.016>
- Khan, S., Afzal, S., Iqbal, Z., & Mirza, M. S. (2018). Phosphorus and potassium management for legume production under various soil conditions. *Journal of Plant Nutrition*, 41(12), 1500-1515.
- Kumar, R., & Yadav, A. (2021). Machine learning approaches for yield prediction and optimization in agriculture. *Journal of Agricultural Science*, 159(6), 789-802.
- Lee, S., & Kim, H. (2022). The Role of Artificial Intelligence in Enhancing Agricultural Productivity. *Computers and Electronics in Agriculture*, 197, 106331.
- Li, M., Wang, X., & Zhang, Y. (2021). Intelligent agriculture based on machine learning and IoT. *Journal of Sensors*, 2021.
- Li, Y., et al. (2019). Machine Learning Applications in Precision Agriculture: A Review. *Computers and Electronics in Agriculture*, 156, 12-19.
- Liakos, K. G., Busato, P., Moshou, D., Pearson, S., & Bochtis, D. (2018). Machine learning in agriculture: A review. *Sensors*, 18(8), 2674. <https://doi.org/10.3390/s18082674>
- Miller, P. R., & Jackson, G. D. (2017). Cropping sequence, tillage, and nitrogen influence dry pea production. *Agronomy Journal*, 99(6), 1442-1449.
- Mitchell, D. C., Marinangeli, C. P., & Jones, P. J. (2009). Pulse consumption improves diet quality in adults. *British Journal of Nutrition*, 102(2), 181-186.
- Mohanty, S., Sahu, R., & Pattnaik, P. (2022). Drone-based monitoring and precision farming: Applications and implications. *Agricultural Technology Research*, 45(3), 233-245.

- Mulla, D. J. (2013). Twenty five years of remote sensing in precision agriculture: Key advances and remaining knowledge gaps. *Biosystems Engineering*, 114(4), 358-371.
- Muller, H., & Schmidt, K. (2021). Integration of IoT and AI for Disease Detection in Agriculture: A Case Study. *Precision Agriculture*, 22(4), 945-960.
- Mus, F., Crook, M. B., Garcia, K., Garcia Costas, A., Geddes, B. A., Kouri, E. D., ... & Peters, J. W. (2019). Symbiotic nitrogen fixation and the challenges to its extension to nonlegumes. *Applied and Environmental Microbiology*, 85(3), e01412-18.
- Nemecek, T., Hayer, F., & Bonnin, E. (2014). Assessing environmental impacts of contrasting farming systems with a special focus on greenhouse gas emissions. *Agriculture, Ecosystems & Environment*, 180, 114-126.
- Pantazi, X. E., Moshou, D., & Bochtis, D. (2016). Precision agriculture: Challenges in sensors and data fusion. *Procedia Engineering*, 153, 52-59. <https://doi.org/10.1016/j.proeng.2016.08.087>
- Patel, N., Shah, J., & Desai, C. (2018). Machine learning in agriculture: A review. *Journal of Innovative Research in Computer and Communication Engineering*, 6(5), 1020-1028.
- Patil, A., & Singh, R. (2021). Automated Irrigation Management Using AI-Based Systems. *Agricultural Water Management*, 251, 106870.
- Paustian, K., Larson, E., Kent, J., Marx, E., & Swan, A. (2019). Soil C sequestration as a biological negative emission strategy. *Frontiers in Climate*, 1, 8.
- Pellegrino, E., Bedini, S., Avio, L., Bonari, E., & Giovannetti, M. (2018). Impact of legumes on soil biological fertility in rotation: A review. *International Journal of Plant Production*, 7(1), 1-18.
- Peoples, M. B., Herridge, D. F., & Ladha, J. K. (2009). Biological nitrogen fixation: An efficient source of nitrogen for sustainable agricultural production? *Plant and Soil*, 315(1-2), 1-8.
- Rodriguez, A., & Arrieta, L. (2022). Artificial Intelligence and Sustainable Agriculture: A Literature Review. *Sustainability*, 14(1), 389.
- Rose, D. C., Wheeler, R., Winter, M., Lobley, M., & Chivers, C. A. (2018). Agriculture 4.0: Making it work for people, production, and the planet. *Land Use Policy*, 79, 344-357.

- Rufaioğlu, S.B., & Kaplan, F. (2024). The Role of Artificial Intelligence in Smart Agriculture Applications. In *Impact of Climate Change on Agriculture and Ecosystems*, Chapter 5. DOI:
- Rufaioğlu, S.B., & Tunç, M. (2024). Sustainable Agriculture Approaches in Legumes. *ISPEC Journal of Science Institute*, 3(1), 38-52.
- Rufaioğlu, S.B., Kaplan, F., & Bilgili, A.V. (2024). Precision Agriculture and Applications. *Focus on Agricultural Sciences*, Chapter 6.
- Shah, I., Prasad, M., Brar, B., Lambe, U. P., Jyothi, M., Ranjan, K., Deepika, V., & Sikka, G. (2017). Promiscuous rhizobia: A potential tool to enhance agricultural crops productivity. In S. Bhore, K. Marimuthu, & M. Ravichandran (Eds.), *Biotechnology for sustainability: Achievements, challenges and perspectives* (pp. 358-375). AIMST University
- Shamshiri, R. R., Kalantari, F., Ting, K. C., Thorp, K. R., Hameed, I. A., Weltzien, C., ... & Ahmad, D. (2018). Advances in greenhouse automation and controlled environment agriculture: A transition to plant factories and urban agriculture. *International Journal of Agricultural and Biological Engineering*, 11(1), 1-22. <https://doi.org/10.25165/j.ijabe.20181101.3185>
- Sharma, N., Singh, V., & Sehgal, V. K. (2020). Role of artificial intelligence in agriculture: A comprehensive review. *Journal of Plant Growth Regulation*, 39(2), 1-20.
- Sharma, P., & Verma, R. (2017). AI-Driven Agricultural Advisory Systems: Impact on Smallholder Farms. *Agricultural Systems*, 159, 9-18.
- Singh, A., Gupta, R., & Sharma, V. (2020). Deep learning for plant disease detection. *Agricultural Systems*, 177, 102695.
- Singh, B. P., Pathak, K. A., & Singh, M. (2014). Phosphorus and potassium nutrition in legumes for sustainable food production. *Agronomy Journal*, 106(1), 103-109.
- Sishodia, R. P., Ray, R. L., & Singh, S. K. (2020). Applications of remote sensing in precision agriculture: A review. *Remote Sensing*, 12(19), 3136. <https://doi.org/10.3390/rs12193136>
- Smith, J., & Brown, T. (2021). Precision Farming with AI: An Emerging Tool for Sustainable Agriculture. *Journal of Environmental Management*, 299, 113662.

- Stagnari, F., Maggio, A., Galieni, A., & Pisante, M. (2017). Multiple benefits of legumes for agriculture sustainability: An overview. *Chemical and Biological Technologies in Agriculture*, 4(2), 1-13.
- Van Es, H. M., & Woodard, J. D. (2017). Innovation in agriculture and food systems in the digital age. *Choices*, 32(1), 1-6.
- Vaz Patto, M. C., Amarowicz, R., Aryee, A. N. A., Boye, J. I., Chung, H. J., & Martin-Cabrejas, M. A. (2015). Achievements and challenges in improving the nutritional quality of food legumes. *Critical Reviews in Plant Sciences*, 34(1-3), 105-143.
- Verzeaux, J., Hirel, B., Dubois, F., Lea, P. J., & Tetu, T. (2016). Agricultural practices to improve nitrogen use efficiency through the use of arbuscular mycorrhizae: Basic and agronomic aspects. *Plant Science*, 264, 48-56.
- Williams, D., & Green, S. (2020). Optimizing Water Usage in Agriculture Through AI Technology. *Water Resources Management*, 34(9), 2875-2890.
- Wolfert, S., Ge, L., Verdouw, C., & Bogaardt, M. J. (2017). Big data in smart farming—a review. *Agricultural Systems*, 153, 69-80. <https://doi.org/10.1016/j.agsy.2017.01.023>
- Zahran, H. H. (2019). Rhizobium-Legume Symbiosis and Nitrogen Fixation under Severe Conditions and in an Arid Climate. *Microbiology and Molecular Biology Reviews*, 63(4), 968-989.
- Zhang, Q., Wang, X., & Huang, J. (2019). Optimizing resource use in agriculture with artificial intelligence techniques. *Computers and Electronics in Agriculture*, 162, 184-192.
- Zhang, X., Davidson, E. A., Mauzerall, D. L., Searchinger, T. D., Dumas, P., & Shen, Y. (2020). Managing nitrogen for sustainable development. *Nature*, 583(7817), 51-59.
- Zhang, X., et al. (2020). Early Detection of Crop Diseases Using AI and UAV Imaging. *Field Crops Research*, 249, 107762.





## **CHAPTER 4**

### **TANNINS in SOME FORAGE PLANTS and THEIR EFFECTS on RUMINANTS**

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## INTRODUCTION

Tannins are phenolic compounds naturally found in the structure of plants and produced by plants to defend themselves against pathogenic microorganisms and viruses (Kuloglu, 2007; Unver et al., 2014; Boga et al., 2021). The functions of tannins differ depending on the tissue in which they are present. For instance, tannins in the bud shield the plant from freezing, while those in the leaf tissue protect the plant from being eaten by insects, birds, and herbivorous animals due to tannins' bitter taste. However, the tannins found in the seed preserve it by having a bactericidal effect and thus ensure the plant's survival and sustainability (Unver et al., 2014). For grazing ruminants, tannins are essential in two ways. One of these is the prevention of bloating. Pasture bloat occurs when a significant amount of fresh, high-protein feed, such as alfalfa, is rapidly digested. It subsequently causes a rapid increase in rumen protein content, leading to an elevation in the rate of microbial fermentation in the rumen and rapid accumulation of carbon dioxide and methane gases. Microbial slime, plant cell membranes, and proteins combine with fermentation gases to form stable foam swallowed as a liquid in the valve leading from the rumen to the esophagus, causing it to remain closed. The gradually accumulated and trapped gasses cause swelling in the rumen and thus hinder blood flow and breathing. Untreated bloat might lead to death by cardiac arrest or asphyxiation. Yet, tannin-containing feeds do not induce bloating since tannins bind excess plant proteins, precipitate them in the rumen fluid, and avoid the formation of the stable foam, which is typical of pasture bloat. Another effect of tannins is that they suppress internal parasites (especially against numerous species of nematodes). The impact of tannins on nematodes largely depends on their concentrations, chemical structures, and the type of nematode species. The effectiveness of tannins also varies depending on the developing stage of the nematode and the location in the gastrointestinal tract where the tannin is active (MacAdam et al., 2013).

Tannins are found in numerous and various plant species especially forage legumes, acacia, oak, carob, tea, pomegranate, and grape (Boga et al., 2021). Table 1 lists the tannin concentrations found in some forage plants. Tannins are divided into two groups: hydrolyzed tannins and condensed tannins. Hydrolyzed tannins consist of polyphenol nuclei with molecular weights ranging from 500 to 3,000 Daltons (Da). However, condensed tannins

are polyphenolic compounds that are found abundantly in many plants and have proven effectiveness in minimizing methane emissions among ruminant animals and preventing pasture bloat (McMahon et al., 2000; Roldan et al., 2022). Condensed tannins are also secondary products of plants, primarily present in dicotyledonous plant cell walls or stored in vacuoles, stems, bark, leaves, flowers, or seeds. They are also water-soluble organic compounds. Condensed tannins are oligomeric or polymeric flavonoids consisting of flavone-3-ols, including catechin, epicatechin, galocatechin, and epigallocatechin. Their molecular weights range from 1,000 to 20,000 Da. They are depolymerized only by strong oxidation and acid and are highly resistant to degradation by anaerobic enzymes (Tong et al., 2022). Hydrolyzed tannins directly affect methane-gas-synthesizing microorganisms and hydrogen-molecule-releasing bacteria (Ece and Avci, 2018). Condensed tannins constitute up to 20% of the dry matter in legume forage plants used as ruminant feed (Mueller-Harvey et al., 2019). Furthermore, they lower greenhouse gas emissions derived from animals by inhibiting some hydrogen-releasing protozoa in the rumen and methane-synthesizing organisms that directly use hydrogen (Ozturk and Gulumser, 2023). Desirably, the condensed tannins in forage plants should not exceed 3% (Kaymak Bayram et al., 2023).

**Table 1.** Tannin concentrations in some forage plants

Forage Plants	Tannin type	Plant part	Stage	Tannin contents (%)
<i>Medicago sativa</i>	TT	Whole plant	% 10-20 flowering stage	0.59-0.95% toplam tanen (Vieira et al., 2001)
<i>Medicago sativa</i>	CT	Whole plant	Late bud stage	1.8 g kg <sup>-1</sup> DM (Lagrange and Villalba, 2019)
<i>Medicago species</i>	TT	Seed		0.27-1.23% (Kokten et al., 2011)
<i>Moringa Oleifera</i>	TT	leaf	-	1.4% (Ibrahima ve Kirkpınar, 2019)
<i>Lathyrus sativus</i> L.	CT	Whole plant	Flowering stage	1.03-1.37% (Sezer, 2024)
<i>Lathyrus sativus</i> L.	TT	Seed	-	324.47-856.45 mg 100 g <sup>-1</sup> (Yerra and Kilari, 2018)
<i>Lotus corniculatus</i> (var. japonicus)	CT	Flower Petal	-	15 g kg <sup>-1</sup> fresh weight 8 g kg <sup>-1</sup> fresh weight

		Petioles, stem, roots		< 5 g kg <sup>-1</sup> fresh weight (Morris et al., 1993)
<i>Lotus corniculatus</i>	CT	Whole plant	Full flowering	4.7 - 8.7 % (Acuña et al., 2008)
<i>Lotus corniculatus</i> <i>L.</i>	TT	Leaf	Flowering	8.5-58.8 mg g <sup>-1</sup> Dry Weight (Marshall et al., 2005)
<i>Onobrychis sativa</i>	CT	Whole plant	Flowering	2.07-4.70% (Ulger and Kaplan, 2016)
<i>Onobrychis viciifolia</i>	CT	Whole plant	50-75% flowering stage.	6.81-7.64 mg g <sup>-1</sup> DM (Abebe et al., 2024)
<i>Onobrychis viciifolia</i>	CT	Whole plant	Regrowth	58.7 g kg <sup>-1</sup> DM (Berard et al., 2011)
<i>Lotus corniculatus</i>	CT	Whole plant	Late bud stage	13.0 g kg <sup>-1</sup> DM(Lagrange and Villalba, 2019)
<i>Lotus corniculatus</i>	CT	Whole plant	Begin of flowering	24.2 g kg <sup>-1</sup> DM (Uzun ve Ocak, 2018)
<i>Lotus corniculatus</i>	CT	Whole plant	Regrowth	9.4 g kg <sup>-1</sup> DM
			Flowering/full bloom	18.6 g kg <sup>-1</sup> DM (Berard et al., 2011)
<i>Lotus tenuis</i>	CT	Whole plant	Begin of flowering	24.1 g kg <sup>-1</sup> DM (Uzun ve Ocak, 2018)
<i>Trifolium hybridum</i>	CT	Whole plant	Flowering/full bloom	11.6 g kg <sup>-1</sup> DM (Berard et al., 2011)
<i>Trifolium repens</i>	CT	Whole plant	Flowering/full bloom	6.9 g kg <sup>-1</sup> DM (Berard et al., 2011)
<i>Trifolium pratense</i>	CT	Whole plant	Regrowth (after harvest)	0.2 g kg <sup>-1</sup> DM
			Flowering/full bloom	8.1 g kg <sup>-1</sup> DM (Berard et al., 2011)
<i>Onobrychis viciifolia</i>	CT	Whole plant	Late flowering stage	27.1 g kg <sup>-1</sup> DM (Lagrange and Villalba, 2019)
<i>Trifolium meneghinianum</i> Clem.	CT	Whole plant	Budding	1.06 %
			Flowering	1.32 %
			Pod setting periods	1.93 % (Kaymak Bayram et al., 2023)

TT: total tannins, CT: condensed tannins, Regrowth: after harvest

## 1. FACTORS AFFECTING TANNIN CONTENT

Tannin content varies within and among plant species depending on genetics, habitat, and developmental stages of plants (Yerra and Klari, 2018; Molnar et al., 2024). Air temperature and soil fertility are the most significant environmental parameters affecting the condensed tannin concentration (Acuña et al., 2008). Lees et al. (1994) reported growing *Lotus uliginosus* clones at two different temperatures (20°C and 30°C) and accordingly found that plants grown at 30°C had higher condensed tannin contents than plants grown at 20°C. They also remarked that high-temperature stress might lead to more condensed tannin synthesis in leaves. Additionally, Miller and Ehlke (1995) documented a positive correlation between lignin concentration and condensed tannin content. Berard et al. (2011) found that condensed tannin amounts considerably varied depending on the plant's developmental stages. They reported that the condensed tannin concentrations during the vegetative and flowering stages were 0.1 g kg<sup>-1</sup> DM and 4.1 g kg<sup>-1</sup> DM in *Trifolium ambiguum*, 0.2 g kg<sup>-1</sup> DM and 8.1 g kg<sup>-1</sup> DM in *Trifolium 66retense*, 9.4 g kg<sup>-1</sup> DM and 18.6 g kg<sup>-1</sup> DM in *Lotus corniculatus*, 0.0 g kg<sup>-1</sup> DM and 6.9 g kg<sup>-1</sup> DM in *Trifolium repens*, and 0.0 g kg<sup>-1</sup> DM and 11.6 g kg<sup>-1</sup> DM in *Trifolium hybridum*, respectively. Contrary to other plants, the condensed tannin content in *Onobrychis viciifolia* reportedly decreased from 58.7 g kg<sup>-1</sup> DM to 33.7 g kg<sup>-1</sup> DM with ripening. Several studies indicated that the observed declines in condensed tannin concentrations in *Onobrychis viciifolia* might originate from an increase in the leaf-stalk/leaf ratio with ripening and a decrease in enzyme activities responsible for condensed tannin production with ripening (Lees 1993; Lees et al., 1995; Taylor and Quesenberry, 1996; Singh et al., 1997; Joseph et al., 1998). Finally, Gardhouse (2020) also reported that condensed tannin content decreased with ripening in sainfoin (trefoil) cultivars.

## 2. THE SIGNIFICANCE of TANNINS for RUMINANTS

Tannins are polyphenolic chemicals with varying molecular weights that plants can synthesize during secondary metabolism. They can bind to proteins and interfere with ruminal fermentations (Vasta et al., 2008; Besharati et al., 2022). Tannins (hydrolyzed and condensed tannins) are present at different concentrations in various animal feed sources. Condensed tannins are the most typical tannin types found in forage legumes, shrubs, and tree leaves (Min et

al., 2003). Many of these plants are alternative feed sources as part of ruminant feeding strategies to replace part of the grain ratio in animal diets to minimize production costs and maximize the quality of animal products in ruminant nutrition (Vasta and Luciano, 2011). However, it is acknowledged that they potentially cause toxic and/or anti-nutritional effects on animals (Mueller-Harvey 2006). The anti-nutritional effects of tannins reside in their digestion-delaying effects when they interact with dietary proteins and polymers, such as cellulose, hemicellulose, and pectin (McSweeney et al., 2001). The ability of tannins to bind and generate such complex molecules depends on the structure of the polyphenols and the availability of the necessary macromolecules (Besharati et al., 2022). These insoluble chemical complexes formed by the binding of tannins to proteins display a characteristic that can inhibit animals' nitrogen uptake, lead to a decrease in feed palatability, and result in a perception of astringency orally (Mueller-Harvey et al., 2019; Zeller 2019).

Min and Solaiman (2018) reported that the positive results of tannins primarily depend on their effects on gut microbiome diversity and their capacity to generate fermentation end products (short-chain fatty acids) with various biological roles. Fonseca et al. (2023) documented that condensed tannins in ruminant diets are useful for rumen fermentation and rumen protein degradation per unit of dry matter. They also decrease enteric methane production and increase weight gain. However, tannins contribute to ruminant productivity and health (Ramírez-Restrepo et al., 2005; Hoste et al., 2006). As a result, tannins may either remain neutral or favorably or adversely affect animal nutrition depending on some factors, including their chemical structure, molecular weight, their concentration in the diet, plant origin and composition of the diet, animal species, and physiological status of the animal fed (Makkar 2003). Such contrary tannin effects may arise from different chemical compositions or types, the amount of the tannins, the animal species fed, and the diet to which tannins are mixed (Patra and Saxena, 2011). Therefore, the chemical structures of tannins vary greatly (Rodríguez et al., 2014). Besides their chemical structure, tannins may generate either positive or negative effects on animal performance and production quality-both factors are intrinsically linked to animal physiology-depending on their ratio in the diet (Waghorn 2008). Using proper ratios and mixing tannins into the diet will improve the intestinal microbial ecosystem and intestinal health in ruminants; accordingly, it will



positively affect animal production (Besharati et al., 2022). Some other contributions of tannins are the increase of protein that cannot be degraded in the rumen, the availability of feed protein for production purposes after the rumen, the increment in microbial protein synthesis efficiency, and the prevention of bloating in ruminants. Several tannins seemingly possess potent antioxidant and anti-carcinogenic properties (Riedl et al., 2002). Some studies also report that using tannin-rich plants in animal diets enriches the fatty acid profile of meat and milk, increases the healthy fatty acid concentrations, and improves the oxidative stability of the products (Benchaar and Chouinard, 2009; Dschaak et al., 2011). Thus, there is growing interest each year in using tannin-rich plants and plant extracts in ruminant diets to improve the quality of animal products. However, using tannin-rich feeds in animal diets requires extreme caution due to their possible detrimental effects on animal performance and induction of metabolic disorders. Several factors, including temperature, light intensity, water, stress, soil nutrients, soil quality, topography, and even variations within a single plant over the year, could affect a plant's tannin concentrations and bioactivity (Patra and Saxena, 2011). As a result, the subject-related literature indicates widely disparate and seemingly contradictory findings for tannins.

### **3. INTERACTIONS between TANNINS and RUMEN MICROORGANISMS**

Ruminal metabolism adapts to the anti-nutritional effects of tannins in feeds by providing microbial degradation of these compounds. Accordingly, plant phenolics are subject to varying degrees of microbial transformation and degradation while ingested in the gastrointestinal tract of ruminants. Several species have been identified as ruminal microorganisms that can tolerate high concentrations of hydrolyzed and condensed tannins, including *S. gallolyticus*, *S. bovis*, and strains closely related to *S. gallolyticus*, in addition to *Clostridium* sp. and a gram-negative rod from the class *Proteobacteria* (McSweeney et al., 2001). Tannins can hinder ruminal nitrogen metabolism by reducing proteolytic bacteria (Herremans et al., 2020). They can also increase the amount of conjugated linoleic acid in meat and milk production by altering the ruminal bio-hydrogenation process through selective activity on ruminal bacteria; however, this effect is dose-dependent (Kamel et al., 2018). In the presence of

tannins, a higher propionate molar ratio in the fermentation system and lower protozoal numbers produced by tannins result in a higher efficiency of microbial protein synthesis (Wang et al., 1996). Cipriano-Salazar et al. (2018) reported that animals potentially tolerated 2% tannin added to ruminant diets depending on the presence of microorganisms that tolerate or degrade tannin in rumen fluid; however, the increment in the ratio completely inhibited ruminal bacteria functions.

#### **4. EFFECTS of TANNINS on PROTEIN PROTECTION**

Protein protection is crucial for high-yielding ruminants whose protein requirements cannot be satisfied by microbial protein synthesis. Hence, adding condensed tannins (CT) in animal diets is a prominent process to reduce ruminal protein destruction, i.e., as protein preservatives. Tannins are a heterogeneous group of high molecular weight phenolic compounds. The presence of many phenolic groups is the primary reason for tannins' high affinity for proteins (Bunglavan and Dutta, 2013). The tannin-protein complex is pH-dependent and stable in the rumen, where the pH varies between 5.0 and 7.0. However, condensed tannins and proanthocyanidins are decomposed in the abomasum and anterior duodenum, where the pH is much lower (below pH 3.5) (Grazziotin et al., 2020). Complexification increases the protein availability in the feed for digestion by protecting them from microbial hydrolysis and deamination in the rumen, thus allowing the absorption of more amino acids in the small intestine (Min et al., 2003). Hence, it increases the efficiency of nitrogen utilization and milk protein content by retaining more nitrogen in the body (Aguerre et al., 2020; Grazziotin et al., 2020; Herremans et al., 2020). Bhatta et al. (2000) reported that adding 7.5% tamarind (*Tamarindus indica*, Linn) seed hulls to a concentrated diet (0.75% tannin content in the diet) increased milk production and development rate, which they attributed to the protection of dietary protein against degradation in the rumen. Yet, McSweeney et al. (2001) revealed that, in some cases, protecting rumen protein with tannins potentially reduces rumen ammonia concentrations below critical levels for efficient digestion of forage diets. Hence, under these conditions, rumen populations better adapted (tolerant) to tannin-containing diets may be more efficient in protein and carbohydrate digestion. Dschaak et al. (2011) found that cows fed a diet supplemented with condensed tannin extract had lower amounts

of milk urea nitrogen and ruminal ammonia nitrogen without any decrease in milk protein yield. This data potentially suggests that supplementing with condensed tannin extract may lessen the amount of nitrogen lost by the rumen as ammonia since rumen bacteria are less likely to degrade crude protein. Therefore, as organic protein preservatives, tannins can be utilized at safe concentrations in livestock farming to support better production and health of ruminants (Bunglavan and Dutta, 2013).

## **5. EFFECTS of TANNINS on GRAZING BEHAVIOR**

Voluntary feed intake and digestibility typically decline among ruminants grazing on tannin-rich vegetation, and body weight and wool growth ratios decrease accordingly (Min et al., 2003). Animals have also developed various mechanisms to mitigate the adverse effects of plants and increase intake. For instance, while eating plants, grazing animals behave selectively in pastures based on the perceptual integration of taste, odor, and sensation in chemosensory cells in the oral cavity. As a result, they prefer eating some plants yet avoid consuming others (Beauchamp and Mennella, 2009). Physical and chemical properties determine the palatability of the feed. The integration effects of toxins during digestion are another factor that affects palatability (Atwood et al. 2001). Saliva also plays a critical role in the perception of taste and texture sensations (Engelen et al., 2007). Saliva, rich in tannin-binding salivary proteins, is one of the primary adaptive mechanisms, especially in small ruminants. Thus, saliva is the first defensive mechanism developed by mammalian species against tannins (Mueller-Harvey, 2006; Shimada, 2006). Proline-rich proteins and histatin peptides are among these tannin-binding salivary proteins, which have a strong affinity for tannins (Shimada 2006). Animals feeding high tannin-containing diets may produce more tannin-binding salivary proteins to regulate their adverse effects. In essence, salivary tannin-binding proteins are an inducible system that adapts to the nutritional availability of tannins in the diet (Clauss et al., 2005; Costa et al., 2008), since prolonged consumption of tannin-containing diets results in salivary gland enlargement (Van Soest 1994). However, not all animals salivate proline-rich proteins in their saliva. Bueno et al. (2015) reported that small ruminants are less affected by the harmful effects of tannin-rich diets than big ruminants. For instance, goats display a high tolerance to tannins since tannin-binding salivary

proteins hinder adverse tannin effects on ruminal digestibility and stimulate the growth of tannin-tolerant bacteria (Min and Solaiman, 2018; Schmitt et al., 2020). Sorensen et al. (2005) indicated that experienced animals grazing tannin-rich pastures expectedly ingest more tannins, lose less body mass, experience fewer toxicity symptoms, and maintain a more positive energy balance in their favored plant.

## **6. EFFECTS of TANNINS on ANIMAL PRODUCTS and PERFORMANCE**

Tannin-like polyphenolic compounds in plants are considered the primary source of natural antioxidants. Antioxidants are compounds that can donate hydrogen ( $H^{\cdot}$ ) radicals to pair with other available free radicals to prevent the spread of reactions during oxidation. Hence, this process reportedly minimizes rancidity in meat and delays lipid oxidation without impairing sensory or nutritional properties, thus preserving the quality and shelf life of the meat products (Kumar et al., 2015). Studies also reported that tannins lessen the harmful effects induced by mutagens and display a protective effect against DNA damage, facilitate rumen fermentation by modulating plasma metabolites and antioxidant capacity, and alter the body's fatty acid profile by generating a beneficial change in the rumen bio-hydrogenation process (Unver et al., 2014; Gao et al., 2024). Tannins alter the fatty acid profile by shortening the ruminal bio-hydrogenation process of unsaturated fatty acids and increasing their flow to the duodenum. This alteration also ensues changes in the unsaturated fatty acid profile of the meat and milk, presumably due to changes in the composition of rumen microbial populations. Khiaosa-Ard et al. (2009) reported that tannin-added lamb diets elevated the amount of saturated fatty acids in lamb meat by reducing the bio-hydrogenation of polyunsaturated fatty acids in the rumen. Dogan and Gunal (2020) documented that a  $75 \text{ g DM}^{-1}$  tannin-added diet adversely affected the production of total volatile fatty acids, recommending that the tannin concentration in the diet should not exceed  $50 \text{ g kg}^{-1} \text{ DM}$ . Boga et al. (2021) emphasized the criticality of knowing the range of positive effects of ruminant diets and recommended using tannins in animal ratios, indicating that a 1-4% DM or  $20\text{-}45 \text{ g day}^{-1}$  tannin-added diet could provide substantial advantages. Accordingly, it is reasonable to conclude that feeding ruminants with tannin-supplemented diets is a robust strategy to improve the health

properties of meat and milk (Vasta et al., 2008). However, Kushwaha et al. (2012) reported that condensed tannin had no favorable effect on ewes grazing *Lotus corniculatus* in early lactation but increased milk yield by 2 liters in mid- and late lactation. Wang et al. (1996) observed slightly lower voluntary feed intake and higher live weight gain, carcass weight gain, carcass dressing-out percentage, and wool growth in lambs grazing *Lotus corniculatus* compared to lambs grazing alfalfa (*Medicago sativa* L.). They reported that the primary outcome of CT in lambs grazing *Lotus corniculatus* was to increase fleece wool growth without affecting voluntary feed intake, thus increasing the productivity of fleece wool production. They also noted that CT did not affect the rumen fermentation of carbohydrate-heavy volatile fatty acids. However, Girard et al. (2016) found that lambs fed condensed tannin derived from *Lotus corniculatus* and *Onobrychis viciifolia* had lower carcass yield, and they related this lower yield to lower weight gain rate, lower slaughter weight, and lower carcass weight. Dos Santos et al. (2022) reported that using tannins up to 1% in dry matter intake in ruminant diets induced no adverse effect on animal performance; however, they suggested extreme caution for usages over 1% rates due to the possibility of detrimental effects on DM intake, performance, and carcass characteristics of growing lambs. Zulfiqar et al. (2024) found that dietary tannin supplementation had no substantial difference in growth performance and nutrient digestibility in lambs; however, it increased protein bypass value since it considerably reduced blood urea nitrogen levels. Studying the effects of tannins on reproduction, Banchero et al. (2012) reported that 1.5% condensed tannin-supplemented soybean cosette on days -8 to -4 before ovulation increased the ovulation rate among sheep grazing on pasture. However, they noted that using a 2.5% tannin rate decreased their dry matter consumption and energy intake accordingly, and no increase in ovulation rate was observed in response to the protection of proteins by tannins. As a result, they concluded that the primary factor affecting the ovulation rate in very short-term tannin-supplemented feeding was not only the protein but also where the protein was used in the digestive system.

## 7. EFFECTS of TANNINS on ANIMAL HEALTH

Parasites in the digestive system of grazing animals are one of the factors that cause substantial losses in ruminant animals. These parasites reduce feed

intake and live weight, negatively affecting animals' growth, milk yield, fleece wool yield, and reproduction. Anthelmintic drugs are ideal for controlling parasites in the digestive system; however, consumers consider their residues disturbing in animal products (Parkins and Holmes, 1989). It is widely known that tannins potentially reduce the number of internal parasites in different ways (Amesa and Asfaw, 2018). Firstly, tannins form non-biodegradable complexes with proteins in the rumen, and these complexes dissociate at low pH in the abomasum, releasing more proteins for metabolism in the small intestine of ruminants. In other words, tannins indirectly bind to proteins in the rumen and prevent microbial degradation by ensuring an anti-parasitic effect; as a result, it elevates the resistance and durability of the animal against nematode parasitic infections. Secondly, tannins may cause a direct anthelmintic effect by hindering the larval development of parasites in the animal digestive system (Waghorn et al., 1994). Min et al. (2003) reported that tannins-containing diet consumption among parasite-infected lambs and sheep gained live weight, and the parasite eggs in fecal matter dropped by roughly 20-50%. Similarly, Atiba et al. (2021) observed higher feed consumption and live weight increase among parasitized sheep and goats fed with condensed tannin-containing diets due to higher protein and amino acid availability. They also indicated that condensed tannin-containing feeds produced meat with lighter colors and higher levels of antioxidant activity. Alonso-Díaz et al. (2010) reported that small ruminants retain saliva rich in tannin-binding salivary proteins; hence, they potentially ingest higher amounts of tannin-rich plants, which in turn have more tannin in their gastrointestinal systems acting as an anthelmintic against gastrointestinal nematodes. Thus, it is possible to state that the tannins consumed by animals grazing on tannin-rich pastures act as natural anthelmintics against gastrointestinal nematodes. Besides improving protein nutrition, condensed tannins can also modulate the activity of host immune cells through eosinophil cells. A higher quantity of eosinophil cells, a type of white blood cell made in the bone marrow that is involved in the body's immune response, is the most significant factor in the body's response to parasitic infection and is typically associated with the expression of host resistance to parasites (Alba-Hurtado and Muñoz-Guzmán, 2013). Several studies also reported that condensed tannin-containing feedings improve feed intake in parasitized small ruminants (Lisonbee et al., 2009; Moore et al., 2008; Sokerya et al., 2009; Amit et al.,

2013; Merera et al., 2013). Accordingly, feeding small ruminants with condensed tannin-containing diets has been considered an alternative to anthelmintic drugs to control parasitic nematodes and improve their productivity. However, bloat, vastly observed in ruminants, is a disease caused by flatulence in the rumen and reticulum and impairs the functions of the gastrointestinal and respiratory systems (Wang et al., 2012). Rumen bloat occurs due to the high solubility of feed proteins and is very common in cattle fed with legumes, especially in the spring period (Amesa and Asfaw, 2018). It is widely known that grazing animals with tannin-containing legumes eliminates bloating due to their protein complex formation properties. The recommended safe CT concentration in forage legumes to avoid bloating is 1-5 mg CT g<sup>-1</sup> DM (Li et al., 1996). Despite the high growth rates, bloating is a considerable deterrent factor among ruminant animals grazing in alfalfa (*Medicago sativa* L.) pastures. Accordingly, adding sainfoin (*Onobrychis viciifolia* Scop.), a legume retaining condensed tannins; in the feed vastly controls minimizing alfalfa pasture bloat (Sottie et al., 2014). In this context, Ali et al. (2017) reported that adding hydrolyzed tannin (40 g) to the concentrate feed mixture of dairy cows increased milk yield and quality. It also improved udder health by decreasing the number of somatic cells. Hashemi et al. (2024) also reported that dietary tannins substantially reduced the quantity of *Escherichia coli* in cattle feces without adversely affecting their fecal consistency scores. As a result, they concluded that using tannins as a protein source up to 4% in milk replacer feeding resulted in no adverse effect on the performance characteristics and health of the calves. Hassan et al. (2020) also documented that dietary tannins improved growth performance, digestibility, and rumen functions in lambs, lowered oxidative stress markers, and enhanced antioxidant defense mechanisms. They also noted that adding up to 6% tannins to sheep diets could cause no harmful effects on the general health of lambs.

## 8. EFFECTS of TANNINS on METHANE EMISSION

The oxidation of soil organic matter, the loss of stocked carbon, and the decomposition of dead plant material in pastures release CO<sub>2</sub>. The vast majority of CH<sub>4</sub> produced during ruminal fermentation is emitted through belching and, to a lesser extent, through animal feces. N<sub>2</sub>O is emitted through animal feces and urine excretion. CO<sub>2</sub> accounts for approximately half of global gas

emissions and considerably affects climate change, followed by CH<sub>4</sub> (20%) and N<sub>2</sub>O (6%) (Aboagye et al., 2019). Researchers have focused on discovering natural alternatives for environmentally friendly animal production since animal husbandry significantly impacts climate change (Patra and Saxena, 2009). Tannin-like components in ruminant diets enable animals to utilize nitrogen better, minimize nitrogen losses in excreted urine, and reduce intestinal and soil methane emissions. The antibacterial properties of condensed tannins make them particularly promising as natural feed additives to lower rumen methanogenesis (Patra and Saxena, 2009). More than 12% of dietary energy can be lost as methane and heat since over 50% of dietary protein in ruminants can be converted into ammonia in the rumen and excreted through urine (Callaway et al., 2003). Such low conversion efficiency of nitrogen into animal protein declines productivity through energy loss, and the emitted nitrogen leads to environmental pollution (Herremans et al., 2020). Tannins inhibit some hydrogen-producing protozoa and methane-producing organisms using hydrogen directly in the animal rumen. Thus, they lower greenhouse gas emissions and increase animal productivity (Acar et al., 2020; Ayan et al., 2020). In this regard, tannins have been recognized as potential methanogenic bacterial reducers because of their capacity to decrease rumen degradability by preventing methanogenic bacteria from forming hydrogen bonds (Broderick et al., 2017; Fagundes et al., 2020). In balanced protein-energy diets, tannins can reduce CH<sub>4</sub> generation and ruminal protein degradability, which may improve animal metabolism and benefit the environment (Brutti et al., 2023). Specifically, condensed tannins are considered plant polyphenols that can act on feed digestibility and have the potential to minimize ruminant enteric methane emissions (Battelli et al., 2024). Khiaosa-Ard et al. (2009) reported that CT extract inhibited methane generation by stimulating bacterial population growth and increasing competition between bacteria involved in bio-hydrogenation and others. Fonseca et al. (2023) documented that tannin-containing diets suppressed methanogenic archaeal communities in ruminants and positively affected cellulolytic populations, making them an effective agency in declining rumen methane production. Battelli et al. (2024) stated that CT reduced ruminant CH<sub>4</sub> emissions; however, this reduction was related to the shift from urine to fecal N excretion but not to the increase in N utilization efficiency of CT. The nitrogen excretion shift from urine to feces favorably



impacts the environment since the N element in feces is highly stable and thus lessens the release of  $\text{NH}_3$  and  $\text{N}_2\text{O}$  into the atmosphere (Mueller-Harvey et al., 2019; Hristov et al., 2022). However, numerous studies also revealed that many feed types may lower ruminant methane production. For instance, tannins in *Lotus corniculatus* (Woodward et al., 2001), *Hedysarum coronarium* (Woodward et al., 2002), *Lotus pedunculatus* (Waghorn et al., 2002), *Kobe lespedeza* (Animut et al., 2008), *Populus deltoides* (Patra et al., 2008), *Vaccinium vitis idaea* L. (Cieslak et al., 2012), and *Caragana korshinskii* (Niu et al., 2024) reduced methane release.

## 9. CONCLUSION

Tannins are plentiful in feeds and forage legumes, which ruminants abundantly consume. It is necessary to analyze feed consumption, the structure and molecular weight of the compound, and the physiology of the consuming animal species to acknowledge the healthy and detrimental effects of tannins on ruminants. In essence, the positive or negative impacts of the condensed tannins depend on the concentration, amount, type, chemical structure of the crude protein, and feed composition in the diet. Hence, analyzing feed tannin content and supplementing it is essential in determining the tannin content in animal diets. This ratio should be at a level that will not create a toxic effect on the animals and should not negatively affect microbial protein synthesis in the rumen. The proper tannin ratio facilitates microbial protein synthesis and endogenous nitrogen use in the rumen. It also plays a critical role in averting infections in herds by strengthening the immune system in ruminants. In conclusion, diets with optimum tannin contents potentially ensure the sustainability of ruminant production systems.

## REFERENCES

- Abebe, D.G., Cherkos, S.D., Ejeta, T.T., Dejene, M., Shignato, T.K., Geletu, A.S. 2024. Nutritional and chemical composition of sainfoin (*Onobrychis viciifolia*) accessions in mid-altitude of soddo and abeshgie woredas of ethiopia. J. Anim. Feed Res., 14(3): 171-184.
- Aboagye, I.A., Beauchemin, K.A. 2019. Potential of molecular weight and structure of tannins to reduce methane emissions from ruminants: A review. Animals (Basel) 9: 1-18.
- Acar, Z., Tan, M., Ayan, I., Asci, O.O., Mut, H., Basaran, U., Gulumser, E., Can, M., Kaymak, G. 2020. Status and development possibilities of forage crops agriculture in Turkey. Turkish Agricultural Engineering IX. Technical Congress Proceedings Book-1, TMMOB Chamber of Agricultural Engineers, 13-17 January, Ankara, Turkey, p. 529-555.
- Acuña, H., Concha, A., Figueroa, M. 2008. Condensed tannin concentrations of three lotus species grown in different environments. Chil. J. Agric. Res., 68(1): 31-41.
- Aguerre, M.J., Duval, B., Powell, J.M., Vadas, P.A., Wattiaux, M.A. 2020. Effects of feeding a quebracho–chestnut tannin extract on lactating cow performance and nitrogen utilization efficiency. J. Dairy Sci., 103: 2264-2271.
- Alba-Hurtado, F., Muñoz-Guzmán, M.A. 2013. Immune responses associated with resistance to haemonchosis in sheep. BioMed Res. Int., 1-11.
- Ali, M., Mehboob, H.A., Mirza, M.A., Raza, H., Osredkar, M. 2017. Effect of hydrolysable tannin supplementation on production performance of dairy crossbred cows. J. Anim. Plant Sci., 27(4): 1088-1093.
- Alonso-Díaz, M.A., Torres-Acosta, J.F.J., Sandoval-Castro, C.A., Hoste, H. 2010. Tannins in tropical tree fodders fed to small ruminants: A friendly foe?, Small Rumin. Res., 89(2–3): 164-173.
- Amesa, S., Asfaw, M. 2018. Effects of tannin on feed intake, body weight gain and health of goats. J. Nutr., 7(1): 01-04.
- Amit, M., Cohen, I., Marcovics, A., Muklada, H., Glasser, T.A., Ungar, E.D., Landau, S.Y. 2013. Self-medication with tannin-rich browse in goats infected with gastro-intestinal nematodes. Veterinary Parasitology. Elsevier B.V. 198(3-4): 305-311.

- Animut, G., Puchala, R., Goetsch, A.L., Patra, A.K., Sahlu, T., Varel, V.H., Wells J. 2008. Methane emission by goats consuming different sources of condensed tannins. *Anim. Feed Sci. Technol.*, 144: 228-241.
- Atiba, E.M., Laban, R.K., Sun, Z., Qingzhang, Z., Aschalew, N.D. 2021. Implications of tannin containing plants for productivity and health in small ruminant animals: A Review. *Agric. Rev.*, 42(2): 156-165.
- Atwood, S.B., Provenza, F.D., Wiedmeier, R.D., Banner, R.E. 2001. Changes in preferences of gestating heifers fed untreated or ammoniated straw in different flavors. *J. Anim. Sci.*, 79: 3027-3033.
- Ayan, I., Acar, Z., Mut, H., Can, M., Kaymak, G., Tunalı, U. 2020. Current status, sustainability and future of meadow and pasture areas. *Turkish Agricultural Engineering IX. Technical Congress Proceedings Book-1, TMMOB Chamber of Agricultural Engineers*, 13-17 January, Ankara, Turkey, p.105-119.
- Banchero, G., Vázquez, A., Vera, M., Quintans, G. 2012. Adding condensed tannins to the diet increases ovulation rate in sheep. *Anim. Prod. Sci.*, 52(9): 853-856.
- Battelli, M., Colombini, S., Crovetto, G.M., Galassi, G., Abeni, F., Petrera, F., Manfredi, M.T., Rapetti, L. 2024. Condensed tannins fed to dairy goats: Effects on digestibility, milk production, blood parameters, methane emission, and energy and nitrogen balances. *J. Dairy Sci.*, 107(6): 3614-3630.
- Beauchamp, G.K., Mennella, J.A. 2009. Early flavor learning and its impact on later feeding behavior. *J. Pediatr. Gastroenterol. Nutr.* 48: S25-S30.
- Benchaar, C., Chouinard, P.Y. 2009. Assessment of the potential of cinnamaldehyde, condensed tannins, and saponins to modify milk fatty acid composition of dairy cows. *J. Dairy Sci.*, 92: 3392-3396.
- Berard, N.C., Wang, Y., Wittenberg, K.M., Krause, D.O., Coulman, B.E., McAllister, T.A., Ominski, K.H. 2011. Condensed tannin concentrations found in vegetative and mature forage legumes grown in western Canada. *Can. J. Plant Sci.*, 91: 669-675.
- Besharati, M., Maggiolino, A., Palangi, V., Kaya, A., Jabbar, M., Eseceli, H., De Palo, P., Lorenzo, J.M. 2022. Tannin in ruminant nutrition: Review. *Molecules*, 27: 8273.

- Bhatta, R., Krishnamoorthy, U., Mohammed, F. 2000. Effect of feeding tamarind (*Tamarindus indica*) seed husk as a source of tannin on dry matter intake, digestibility of nutrients and production performance of crossbred dairy cows in mid-lactation. Anim. Feed Sci. Tech., 83: 67-74.
- Boga, M., Kocadayıogulları, F., Erkan Can, M. 2021. Use of tannin in ruminant animal nutrition. BSJ Eng. Sci., 4(4): 217-225.
- Broderick, G.A., Grabber, J.H., Muck, R.E., Hymes-Fecht, U.C. 2017. Replacing alfalfa silage with tannin-containing birdsfoot trefoil silage in total mixed rations for lactating dairy cows. J. Dairy Sci. 100 (5): 3548-3562.
- Bueno, I.C.S., Brandi, R.A., Franzolin, R., Benetel, G., Fagundes, G.M., Abdalla, A.L., Louvandini, H., Muir, J.P. 2015. In vitro methane production and tolerance to condensed tannins in five ruminant species. Anim. Feed Sci. Technol. 205: 1-9.
- Bunglavan, S.J., Dutta, N. 2013. Use of tannins as organic protectants of proteins in digestion of ruminants. J. Livest. Sci., 4: 67-77.
- Brutti, D.D., Canozzi, M.E.A., Sartori, E.D., Colombatto, D., Barcellos, J.O.J. 2023. Effects of the use of tannins on the ruminal fermentation of cattle: A meta-analysis and meta-regression. Anim. Feed Sci. Technol., 306: 115806.
- Callaway, T.R., Edrington, T.S., Rychlik, J.L., Genovese, K.J., Poole, T.L., Jung, Y.S., Nisbet, D.J. 2003. Ionophores: their use as ruminant growth promotants and impact on food safety. Curr. Issues Intest. Microbiol., 4: 43-51.
- Cieslak, A., Zmora, P., Pers-Kamczyc, E., Szumacher-Strabel, M. 2012. Effects of tannins source (*Vaccinium vitis idaea* L.) on rumen microbial fermentation in vivo. Anim. Feed Sci. Technol., 176: 102-106.
- Cipriano-Salazar, M., Rojas-Hernández, S., Olivares-Pérez, J., Jiménez-Guillén, R., Cruz-Lagunas, B., Camacho-Díaz, L.M., Ugbogu, A.E. 2018. Antibacterial activities of tannic acid against isolated ruminal bacteria from sheep. Microb Pathog., 117: 255-258.
- Clauss, M., Gehrke, J., Hatt, J.M., Dierenfeld, E.S., Flach, E.J., Hermes, R., Castell, J., Streich, W.J., Fickel, J. 2005. Tannin-binding salivary proteins in three captive rhinoceros species. Comp. Biochem. Physiol. A Mol. Integr. Physiol., 140(1): 67-72.

- da Costa, G., Lamy, E., Capelae, Silva F., Andersen, J., Sales Baptistai E., Coelho, A.V. 2008. Salivary amylase induction by tannin-enriched diets as a possible countermeasure against tannins. *J. Chem. Ecol.*, 34(3): 376-387.
- Dogan, U., Gunal, M. 2020. Effects of chestnut and mimosa tannin extract supplementations to feeds on some in vitro rumen fermentation parameters. *MKU Tar. Bil. Derg*, 25(3): 341-351.
- Dos Santos, S.K., de Fátima França Biz, J., Salgado, J.A., de Macedo, R.E.F., Sotomaior, C.S. 2022. Intake and performance of growing lambs supplemented with quebracho tannins. *Trop. Anim. Health Prod.*, 54(1): 71.
- Dschaak, C.M., Williams, C.M., Holt, M.S., Eun, J.S., Young, A.J., Min, B.R. 2011. Effects of supplementing condensed tannin extract on intake, digestion, ruminal fermentation, and milk production of lactating dairy cows. *J. Dairy Sci.*, 94: 2508-2519.
- Ece, Z., Avci, M. 2018. Effect of zeolite and acorn added to alfalfa hay and dairy cattle ration on in vitro organic matter digestibility and methane production. *Harran University Journal of the Faculty of Veterinary Medicine*, 7(1): 67-73.
- Engelen, L., van den Keybus, P.A., de Wijk, R.A., Veerman, E.C., Amerongen, A.V., Bosman, F., Prinz, J.F., van der Bilt, A. 2007. The effect of saliva composition on texture perception of semi-solids. *Arch. Oral Biol.*, 52: 518-525.
- Fagundes, G.M., Benetel, G., Welter, K.C., Melo, F.A., Muir, J.P., Carriero, M.M., Souza, R.L.M., Meo-Filho, P., Frighetto, R.T.S., Berndt, A., Bueno, I.C.S. 2020. Tannin as a natural rumen modifier to control methanogenesis in beef cattle in tropical systems: friend or foe to biogas energy production? *Res. Vet. Sci.*, 132: 88-96.
- Fonseca, N.V.B., Cardoso, A.d.S., Bahia, A.S.R.d.S., Messana, J.D., Vicente, E.F., Reis, R.A. 2023. Additive tannins in ruminant nutrition: an alternative to achieve sustainability in animal production. *Sustainability*, 15: 4162.
- Gao, C., Qi, M., Zhou, Y. 2024. Chestnut tannin extract modulates growth performance and fatty acid composition in finishing Tan lambs by

- regulating blood antioxidant capacity, rumen fermentation, and biohydrogenation. *BMC Vet. Res.*, 20(1): 23.
- Gardhouse, K.A. 2020. Effect of sainfoin (*Onobrychis viciifolia* Scop.) variety and harvest maturity on quality, yield, and condensed tannin content. Master of Science in Animal and Range Sciences. Montana State University, Bozeman, Montana.
- Girard, M., Dohme-Meier, F., Silacci, P., Ampuero Kragten, S., Kreuzer, M., Bee, G. 2016. Forage legumes rich in condensed tannins may increase n-3 fatty acid levels and sensory quality of lamb meat. *J. Sci. Food Agric.*, 96: 1923-1933.
- Grazziotin, R.C.B., Halfen, J., Rosa, F., Schmitt, E., Anderson, J.L., Ballard, V., Osorio, J.S. 2020. Altered rumen fermentation patterns in lactating dairy cows supplemented with phytochemicals improve milk production and efficiency. *J. Dairy Sci.*, 103: 301-312.
- Hassan, T.M.M., Ahmed-Farid, O.A., Abdel-Fattah, F.A.I. 2020. Effects of different sources and levels of tannins on live performance and antioxidant response of Ossimi lambs. *J. Agric. Sci.*, 1-10.
- Hashemi, M., Azarfar, A., Fadayifar, A., Azizi, A. 2024. Chemical composition of corn steep liquor precipitated with tannin and its effect on trait performance and health of Holstein dairy calves. *Iranian J. Anim. Sci.*, 55(1): 47-70.
- Herremans, S., Vanwindekens, F., Decruyenaere, V., Beckers, Y., Froidmont, E. 2020. Effect of dietary tannins on milk yield and composition, nitrogen partitioning and nitrogen use efficiency of lactating dairy cows: a meta-analysis. *J. Anim. Physiol. Anim. Nutr.*, 104(5): 1209-1218.
- Hoste, H., Jackson, F., Athanasiadou, S., Thamsborg, S.M., Hoskin, S.O. 2006. The effects of tannin-rich plants on parasitic nematodes in ruminants. *Trends Parasitol.*, 22(6): 253-261.
- Hristov, A.N., Melgar, A., Wasson, D., Arndt, C. 2022. Symposium review: Effective nutritional strategies to mitigate enteric methane in dairy cattle. *J. Dairy Sci.*, 105: 8543-8557.
- Ibrahima, F.I., Kirkpinar, F. 2019. Properties of moringa (*Moringa oleifera*) plant and its use in animal nutrition. 5th International Student Symposium Proceedings Book-7- Science-Agriculture-Health, December 6-8, Istanbul, Turkey, p.140-162.

- Kamel, H.E.M., Al-Dobaib, S.N., Salem, A.Z.M., López, S., Alaba, P.A. 2018. Influence of dietary supplementation with sunflower oil and quebracho tannins on growth performance and meat fatty acid profile of Awassi lambs. *Anim. Feed Sci. Technol.*, 235: 97-104.
- Kaymak Bayram, G., Can, M., Acar, Z., Ayan, I., Gulumser, E. 2023. Roughage quality of gelemen clover (*Trifolium meneghinianum* Clem.) in different development periods. *ISPEC J. Agric. Sci.*, 7(4): 778-783.
- Khiaosa-Ard, R., Bryner, S.F., Scheeder, M.R.L., Wettstein, H.-R., Leiber, F., Kreuzer, M., Soliva, C.R. 2009. Evidence for the inhibition of the terminal step of ruminal  $\alpha$ -linolenic acid biohydrogenation by condensed tannins. *J. Dairy Sci.*, 92: 177-188.
- Kokten, K., Bakoglu, A., Kocak, A., Bagci, E., Akcura, M., Kaplan, M. 2011. Chemical composition of the seeds of some *Medicago* species. *Chem. Nat. Compd.*, 47(4): 619-621.
- Kuloglu, R. 2007. Effect of tannic acid on some fibrolitic enzymes of rumen bacteria. T.R. University of Kahramanmaras Sutcu Imam Institute of Natural and Applied Sciences, Department of Animal Science, MSc Thesis, Kahramanmaras, Turkey.
- Kumar, Y., Yadav, D.N., Ahmad, T., Narsaiah, K. 2015. Recent trends in the use of natural antioxidants for meat and meat products. *Compr. Rev. Food Sci. Food Saf.*, 4: 796-812.
- Kushwaha, R., Rai, S.N., Singh, A.K. 2012. Influence of feeding *Acacia nilotica* pods on intake, nutrient utilization and immune status in pregnant goats. *Indian J. Anim. Res.*, 46: 8-14.
- Lagrange, S., Villalba, J.J. 2019. Tannin-containing legumes and forage diversity influence foraging behavior, diet digestibility and nitrogen excretion by lambs. *J. Anim. Sci.*, 97: 3994-4009.
- Lees, G. L. 1993. *Onobrychis viciifolia* scop. (sainfoin): In vitro culture and the production of condensed tannins. Pages 269-286 in Y. P. S. Bajaj, ed. *Biotechnology in agriculture and forestry*. Springer Verlag, Berlin, Germany.
- Lees, G.L., Hinks, C.F., Suttill, N.H. 1994. Effect of high temperature on condensed tannin accumulation in leaf tissues of big trefoil (*Lotus uliginosus* Schkur). *J. Sci. Food Agric.*, 65: 415-421.

- Lees, G.L., Gruber, M.Y., Suttill, N.H. 1995. Condensed tannins in sainfoin. II. Occurrence and changes during leaf development. *Can. J. Bot.*, 73: 1540-1547.
- Lisonbee, L. D., Villalba, J.J., Provenza, F.D., Hall, J.O. 2009. Tannins and self-medication: Implications for sustainable parasite control in herbivores. *Behav. Processes*, 82(2): 184-189.
- MacAdam, J.W., Brummer, J., Islam, A., Shewmaker, G. 2013. The benefits of tannin-containing forages. Utah State University, Plants, Soils & Climate. September, AG/Forages/2013-03pr.
- Makkar, H.P.S. 2003. Effects and fate of tannins in ruminant animals, adaptation to tannins, and strategies to overcome detrimental effects of feeding tannin-rich feeds. *Small Rumin. Res.*, 49: 241-256.
- Marshall, A.H., Ribaimont, F., Collins, R.P., Bryant, D., Abberton, M.T. 2005. Variation in tannin content and morphological traits in *Lotus corniculatus* L. (birdsfoot trefoil). p. 245. In O'Mara, F.P., R.J. Wilkins, L. Mannerje, D.K. Lovett, P.A.M. Rogers, T.M. Boland (eds.). XX International Grassland Congress: Offered papers. Dublin, Ireland. Wageningen Academic Publishers, Wageningen, The Netherlands.
- McMahon, L.R., McAllister, T.A., Berg, B.P., Majak, W., Acharya, S.N., Popp, J.D. 2000. A review of the effects of forage condensed tannins on ruminal fermentation and bloat in grazing cattle. *Can. J. Plant Sci.*, 80: 469-485.
- McSweeney, C.S., Palmer, B., McNeill, D.M., Krause, D.O. 2001. Microbial interactions with tannins: nutritional consequences for ruminants. *Anim. Feed Sci. Technol.*, 91: 83-93.
- Merera, C., Ayana, T., Gudeta, T. 2013. Effect of feeding *Leucaena pallida* with concentrate and antihelmentic treatment on growth performance and nematode parasite infestation of Horro ewe lambs in Ethiopia. *Int. J. Livest. Prod.*, 4(10): 155-160.
- Miller, R.P., Ehlke, N.J. 1995. Condensed tannins in birdsfoot trefoil: genetic relationships with forage yield and quality in NC-83 germplasm. *Euphytica*, 92: 383-391.
- Min, B.R., Barry, T.N., Attwood, G.T., McNabb, W.C. 2003. The effect of condensed tannins on the nutrition and health of ruminants fed fresh temperate forages. A review. *Anim. Feed Sci. Technol.*, 106: 3-19.



- Min, B.R., Solaiman, S. 2018. Comparative aspects of plant tannins on digestive physiology, nutrition and microbial community changes in sheep and goats: A review. *J. Anim. Physiol. Anim. Nutr.*, 102: 1181-1193.
- Molnar, M., Kovač, M.J., Pavić, V. 2024. A comprehensive analysis of diversity, structure, biosynthesis and extraction of biologically active tannins from various plant-based materials using deep eutectic solvents. *Molecules* 29: 2615.
- Moore, D.A., Terrill, T.H., Kouakou, B., Shaik, S.A., Mosjidis, J.A., Miller, J.E., Vanguru, M., Kannan, G., Burke, J.M. 2008. The effects of feeding *Sericea lespedeza* hay on growth rate of goats naturally infected with gastrointestinal nematodes. *J. Anim. Sci.*, 86: 2328-2337.
- Morris, P., Carron, T.R., Robbins, M.P., Webb, K.J. 1993. Distribution of condensed tannins in flowering plants of *Lotus corniculatus* var. *japonicus* and tannin accumulation by transformed root cultures. *Lotus Newsl.*, 24: 60-63.
- Mueller-Harvey, I. 2006. Unravelling the conundrum of tannins in animal nutrition and health. *J. Sci. Food Agric.*, 86: 2010-2037.
- Mueller-Harvey, I., Bee, G., Dohme-Meier, F., Hoste, H., Karonen, M., Kölliker, R., Lüscher, A., Niderkorn, V., Pellikaan, W.F., Salminen, J.P., Sköt, L., Smith, L.M.J., Thamsborg, S.M., Totterdell, P., Wilkinson, I., Williams A.R., Azuhwi, B.N., Baert, N., Brinkhaus, A.G., Copani, G., Desrues, O., Drake, C., Engström, M., Fryganas, C., Girard, M., Huyen, N.T., Kempf, K., Malisch, C., Mora-Ortiz, M., Quijada, J., Ramsay, A., Ropiak, H.M., Waghorn, G.C. 2019. Benefits of condensed tannins in forage legumes fed to ruminants: Importance of structure, concentration, and diet composition. *Crop Sci.*, 59: 861-885.
- Niu, X., Xing, Y., Wang, J., Bai, L., Xie, Y., Zhu, S., Sun, M., Yang, J., Li, D., Liu, Y. 2024. Effects of *Caragana korshinskii* tannin on fermentation, methane emission, community of methanogens, and metabolome of rumen in sheep. *Front. Microbiol.*, 15: 1334045.
- Ozturk, Y.E., Gulumser, E. 2023. Forage yield, nutritional value and phytotrepic traits of hops (*Humulus lupulus* L.). *ISPEC J. Agric. Sci.*, 7(2): 350-358.

- Parkins, J.J., Holmes, P.H. 1989. Effects of gastrointestinal helminth parasites on ruminant nutrition. *Nutr. Res. Rev.*, 2: 227-246.
- Patra, A.K., Kamra, D.N., Agarwal, N. 2008. Effect of extracts of leaves on rumen methanogenesis, enzyme activities and fermentation in in vitro gas production test. *Indian J. Anim. Sci.*, 78: 91-96.
- Patra, A.K., Saxena, J. 2009. Dietary phytochemicals as rumen modifiers: a review of the effects on microbial populations. *Antonie Van Leeuwenhoek*, 96: 363-375.
- Patra, A.K., Saxena, J. 2011. Exploitation of dietary tannins to improve rumen metabolism and ruminant nutrition. *J. Sci. Food Agric.*, 91: 24-37.
- Ramirez-Restrepo, C.A., Barry, T.N., Lopez-Villalobos, N., Kemp, N., Harvey, T.G. 2005. Use of *Lotus corniculatus* containing condensed tannins to increase reproductive efficiency in ewes under commercial dryland farming conditions. *Anim. Feed Sci. Technol.*, 121: 23-43.
- Riedl, K.M., Carando, S., Alessio, H.M., McCarthy, M., Hagerman, A.E. 2002. Antioxidant activity of tannins and tannin-protein complexes: Assessment in vitro and in vivo. In: Morello MJ, Shahidi F and Ho C-T (eds) *Free Radicals in Food*. ACS Symposium Series, Washington, DC: American Chemical Society, pp.188-200.
- Rodríguez, R., de la Fuente, G., Gómez, S., Fondevila, M. 2014. Biological effect of tannins from different vegetal origin on microbial and fermentation traits in vitro. *J. Anim. Prod. Sci.*, 54: 1039-1046.
- Roldan, M.B., Cousins, G., Muetzel, S., Zeller, W.E., Fraser, K., Salminen, J-P., Blanc, A., Kaur, R., Richardson, K., Maher, D., Jahufer, Z., Woodfield, D.R., Caradus, J.R., Voisey, C.R. 2022. Condensed tannins in white clover (*Trifolium repens*) foliar tissues expressing the transcription factor tamyb14-1 bind to forage protein and reduce ammonia and methane emissions in vitro. *Front. Plant Sci.*, 12: 777354.
- Schmitt, M.H., Ward, D., Shrader, A.M. 2020. Salivary tannin-binding proteins: A foraging advantage for goats? *Livest. Sci.*, 234: 103974.
- Sezer, M. 2024. Hay yield and quality of different grass pea (*Lathyrus sativus* L.) genotypes. Bilecik Seyh Edebali Univ. Graduate Education Institute Field Crops Department, MSc Thesis, Bilecik, Turkey.
- Shimada, T. 2006. Salivary proteins as a defence against dietary tannins. *J. Chem. Ecol.*, 32: 1149-1163.

- Singh, S., McCallum, J., Gruber, M.Y., Towers, G.H.N., Muir, A.D., Bohm, B.A., Koupai-Abyazani, M.R., Glass, A.D.M. 1997. Biosynthesis of Flavan-3-ols by leaf extracts of *Onobrychis viciifolia*. *Phytochemistry*, 44: 425-432.
- Sokerya, S., Waller, P.J., Try, P., Höglund, J. 2009. The effect of long-term feeding of fresh and ensiled cassava (*Manihot esculenta*) foliage on gastrointestinal nematode infections in goats. *Trop. Anim. Health Prod.*, 41(2): 251-258.
- Sorensen, S.J., McLister, D.J., Dearing, M.D. 2005. Novel plant secondary metabolites impact dietary specialists more than generalists (*Neotoma* spp.). *Ecology*, 86: 140-154.
- Sottie, E.T., Acharya, S.N., McAllister, T., Thomas, J., Wang, Y., Iwaasa, A. 2014. Alfalfa pasture bloat can be eliminated by intermixing with newly-developed sainfoin population *Agron. J.*, 106: 1470-1478.
- Taylor, N.L., Quesenberry, K.H. 1996. Red clover science. Vol 28. Kluwer Academic Publishers, Dordrecht, the Netherlands. 226 pp.
- Tong, Z., He, W., Fan, X., Guo, A. 2022. Biological function of plant tannin and its application in animal health. *Front. Vet. Sci.*, 8: 803657.
- Ulger, I., Kaplan, M. 2016. Variations in potential nutritive value, gas and methane Production of local sainfoin (*Onobrychis sativa*) populations. *Alinteri J. Agric. Sci.*, 31(2): 42-47.
- Unver, E., Agma Okur, A., Tahtabicen, E., Kara, B., Samlı, H.E. 2014. Tannins and their impacts on animal nutrition. *Turkish Journal of Agriculture - Food Science and Technology*, 2(6): 263-267.
- Uzun, F., Ocak, N. 2018. Soil preferences, neighbor plants and feed values of birdsfoot trefoil (*Lotus corniculatus* L.) and narrowleaf birdsfoot trefoil (*Lotus tenuis* Waldst. & Kit.) grown in natural flora. *Anadolu J. Agric. Sci.*, 33: 37-46.
- Van Soest, P.J. 1994. Nutritional ecology of the ruminant; Cornell University Press: Ithaca, NY, USA, Vol.476.
- Vasta, V., Mele, M., Serra, A., Priolo A. 2008. The effect of tannin supplementation on lamb ruminal biohydrogenation. "Competition for Resources in a Changing World: New Drive for Rural Development", Tropentag, October 7-9, 2008, Hohenheim.

- Vasta, V., Luciano, G. 2011. The effects of dietary consumption of plant secondary compounds on small ruminants' products quality. *Small Rumin. Res.*, 101: 150-159.
- Waghorn, G.C., Shelton, I.D., McNabb, W.C., McCutcheon, S.N. 1994. Effects of condensed tannins in *Lotus pedunculatus* on its nutritive value for sheep. 2. Nitrogenous aspects. *J. Agric. Sci.*, 123: 109-119.
- Waghorn, G.C., Tavendale, M.H., Woodfield, D.R. 2002. Methanogenesis from forages fed to sheep. ? *Proc. N.Z. Grassland Assoc.*, 64: 167-171.
- Waghorn, G. 2008. Beneficial and detrimental effects of dietary condensed tannins for sustainable sheep and goat production—Progress and challenges. *Anim. Feed Sci. Technol.*, 147: 116-139.
- Wang, Y., Douglas, G.B., Waghorn, G.C., Barry, T.N., Foote, A.G., Purchas, R.W. 1996. Effect of condensed tannins upon the performance of lambs grazing *Lotus corniculatus* and lucerne (*Medicago sativa*). *J. Agric. Sci.*, 126: 87-98.
- Wang, X., Yang, G., Feng, Y., Ren, G., Han, X. 2012. Optimizing feeding composition and carbon–nitrogen ratios for improved methane yield during anaerobic co-digestion of dairy, chicken manure and wheat straw. *Bioresour. Technol.*, 120: 78-83.
- Woodward, S.L., Waghorn, G.C., Ulyatt M.J., Lassey, K.R. 2001. Early indications that feeding *Lotus* will reduce methane emissions from ruminants. *Proc. N.Z. Soc. Anim. Prod.*, 61: 23-26.
- Woodward, S.L., Waghorn, G.C., Lassey, K.R., Laboyrie, P.G. 2002. Does feeding sulla (*Hedysarum coronarium*) reduce methane emissions from dairy cows? *Proc. N.Z. Soc. Anim. Prod.*, 62: 227-230.
- Yerra, S., Kilari, E.K. 2018. The tannin content of *Lathyrus Sativus* cultivated in some states of India. *Int. J. Biol. Sci.*, 7(11): 31-35.
- Zulfiqar, U., Ahmed, S., Ahmad, N., Shahzad, F., Javed, M.Q., Younas, U., Irshad, I. 2024. Effects of tannic acid supplementation on growth performance, nutrients di-gestibility, and blood metabolite in lohi male lambs. *Insights Anim. Sci.*, 1(1): 12-17.



## **CHAPTER 5**

### **USES AND PROPERTIES OF SILKWORM (*Bombyx mori* L.) SILK**

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## INTRODUCTION

The holometabolous insect *Bombyx mori* L. (*B. mori*) is a member of the family Bombycidae and the order Lepidoptera. It produces a lot of sericin until the end of the fifth larval stage and forms silk thread that is used to make cocoons in addition to fibroin, which creates the perfect environment for the larvae to transform into adults (Kundu et al. 2008). As shown in Figure 1, the silkworm has a brief and quick life cycle with four stages (Habeanu et al. 2023):

- 1st stage: egg,
- 2nd stage: larva,
- 3rd stage: pupa (in cocoon),
- 4th stage: butterfly (adult)



**Figure 1.** Silkworm (*Bombyx mori* L.) life cycle

**Reference:** Habeanu et al. (2023)

The greatest amount of silk protein (about 0.5 g per larva) is generated in the fifth larval stage, or final larval instar, even though it is produced throughout the larval stage (Ma et al. 2024). The extrusion of silk from the strands at the head and the tugging of the fiber with a distinctive figure-eight head movement are characteristics of this spinning stage. The silkworms create



a silk cocoon at the end of the 5th instar by turning the substantial amount of silk from the silk gland into a continuous raw silk thread (Asakura and Williamson, 2023). The fiber threads can reach a length of over one kilometer after they are released from the silk cocoon.

Because of its simplicity of production, wide supply, and distinctive fabric qualities, *B. mori* silk has become more significant among the various types of silk (Huang et al. 2018). Furthermore, because of its biocompatibility, strong mechanical performance, ease of processing, tunable degradation, ample supply, and convenience of acquiring from the established sericulture business, silk derived from *B. mori* has been the most commonly used material for centuries (Rockwood et al. 2011). In the textile business, fibroin is transformed into raw silk and used to make different kinds of yarn and silk fabrics, while the cocoon is processed and sericin is mostly eliminated by a procedure known as degumming (Mondal et al. 2007). The mechanical characteristics of silkworm fibroin and its distinct interactions with tissue cells have drawn attention in recent years. According to Lawrence and Infanger (2024), fibroin offers a rich biopolymer platform that can be used to create biomaterials in a variety of forms, including water-containing medicines and three-dimensional structures. Fibrin has currently been studied as a biomedical material in a variety of fields, such as skin tissue, vascular grafts, nerve and ocular healing, drug release, ligaments, tendons, and bone and cartilage. The biomedical uses of silk fibroin are therefore very promising (Wenk et al. 2011; Kasoju and Bora 2012; Koh et al. 2015; Guo et al. 2020; Li and Sun 2022; Lu et al. 2024; Wang et al. 2024).

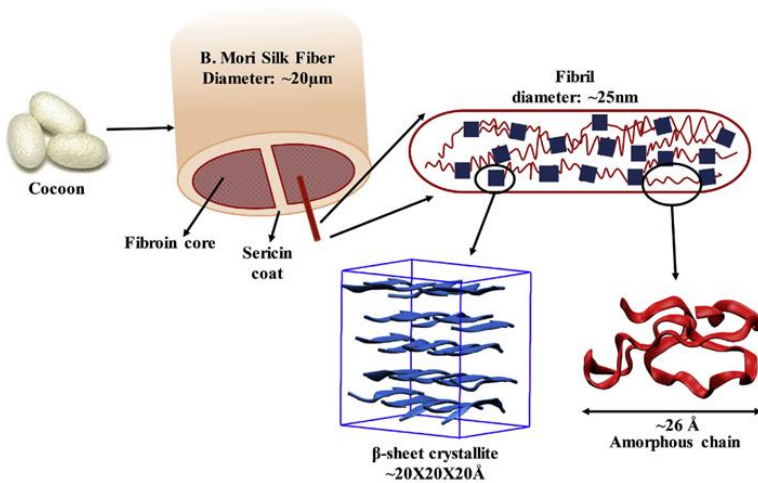
The fibroin filaments in the silk thread made by *B. mori*, a crucial part of raw silk and a substance employed of the cocoon, are encased and held together by sericin, which is naturally occurring polymer. Reusing and recovering silk that is abandoned by the textile industry generally has significant commercial and scientific value (Silva et al. 2022). Use in the food and cosmetic industries is made possible by the series's antioxidant capability and the very hydrophobic amino acids that make up its structure. However, its qualities including moisturizing power, wound healing, stimulating cell proliferation, radiation protection, anti-tumor, anti-microbial, anti-inflammatory, anti-coagulant, anti-bacterial, and anti-diabetic activities make it a useful biomaterial (Kunz et al. 2016; Khosropanah et al. 2022).

*B. mori* is one of the most economically significant insects, which is a model organism utilized in medicine in many impoverished nations, and a great representative of the lepidopteran species for many scientific investigations (Habeanu et al. 2023). The structure, secretion mechanism, and applications of the silk generated by the *B. mori* silkworm, which produces around 90% of the world's silk, have all been investigated in this paper.

## **1. STRUCTURE OF NATURAL SILKWORM SILK AND SILK GLAND**

Silk has a crystalline structure and is a protein-based fiber. According to Kim et al. (2023), it is made up of two biopolymers: fibroin and sericin. Fibrin is the inner core protein made up of hydrophobic amino acids, glycine, and alanine repeat sequences (70–80%), whereas sericin, an antigenic glue-like protein, makes up the hydrophilic coating of the outside silk layer (20–30%) (Sobajo et al. 2008; Sun et al. 2019; Reddy et al. 2020). Waxy matter (range between 0.4 to 0.8%), carbohydrates (from 1.2 to 1.65%), inorganic matter (approximately 0.7%), and pigment (approximately 0.2%) are some of the other minor constituents of silk, which is generated by *B. Mori* (Gore et al. 2019). A glycoprotein P25 (approximately 25 kDa) is hydrophobically bonded to the H-L complex, which is made up of two type chains: the heavy chain (H-chain, approximately with a molecular weight of 390 kDa) and the light chain (L-chain, approximately molecular weight of 26 kDa), which are joined by disulfide bonds to create the H-L complex. Silk fibroin is created by combining the H-chain, and L-chain, and P25 in a 6:6:1 molar ratio (Inoue et al. 2000). Basic micelle elements are also formed as a result of this. Before it becomes fibers, a significant amount of fibroin can move through the silk gland lumen in a straight line because to the creation of micelle components. Light chains offer minimal mechanical support in silk fibers, while heavy chains create unique  $\beta$ -sheet structures that serve as the primary structural element and give the required mechanical strength (Koh et al. 2015). In all, glycine (45.9%), alanine (30.3%), serine (12.1%), tyrrthophan (5.3%), valine (1.8%), and 15 other amino acid types (4.7%) are present in the heavy chain of fibroin (Zhou et al. 2001; Huang et al. 2018; McGill et al. 2019). Aspartic acid (33.4%) and serine (16.7%) are the series' primary constituents (Aramwit et al. 2012; Tansil et al. 2012; Kunz et al. 2016; Cao and Zhang 2017). In another words, sericin

is made up of amino acids with around 25% non-polar groups and roughly 75% polar side chains, whereas fibroin is made up of amino acids with roughly 76% mol of non-polar side chains and roughly 21% polar groups. Because of this compositional difference, sericin dissolves in water more readily than fibroin (Chopra and Gulrajani 1994). Silk has a density of 1.3–1.4 g cm<sup>-3</sup> and a Young's modulus of 8.9–17.4 GPa. These values are comparable to those of human bone, which normally has a range of 1.8 to 2.0 g cm<sup>-3</sup> and 3 to 20 GPa. Because of this, silk may be a better option for artificial bone materials than ceramic or metal implants (Lu et al., 2024).



**Figure 2.** Structural components of *B. mori* silk fiber

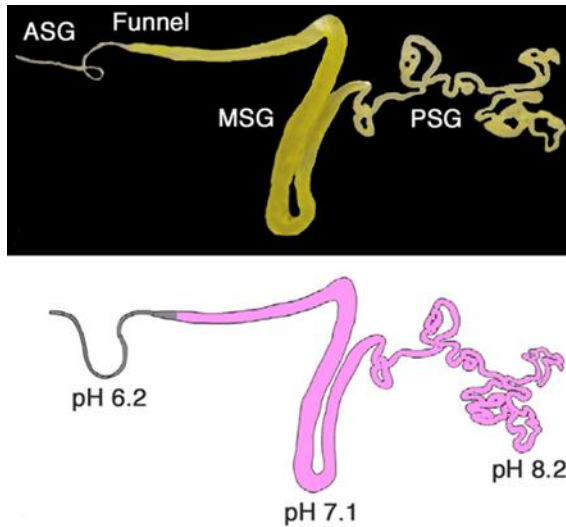
**Reference:** Patel et al. (2020)

The silk gland produces and stores very large amounts of silk proteins. The silk gland of *B. mori* is a tubular epithelium that is separated into three portions with different pH values which is maintained with regulation of carbonic anhydrase enzyme (Domigan et al. 2015), as shown in Figure 3:

- the posterior silk gland-PSG (pH between 7.2 and 8.2)
- middle silk gland-MSG (pH between 7 and 7.2)
- anterior silk gland-ASG (pH between 6.2 and 6.8)

The physical characteristics of silk fibers, such as their stickiness or viscosity, are influenced by varying pH levels (Pritchard et al. 2012; Herold and Scheibel 2017; Sehadova et al. 2021; Silva et al. 2022). Carbonic anhydrase

is also produced by one of the four types of epithelial cells found in *B. mori* silk glands. The process that creates the intraluminal pH gradient that controls the aggregation of silk proteins and the subsequent production of fibers from soluble silk proteins requires carbonic anhydrase.



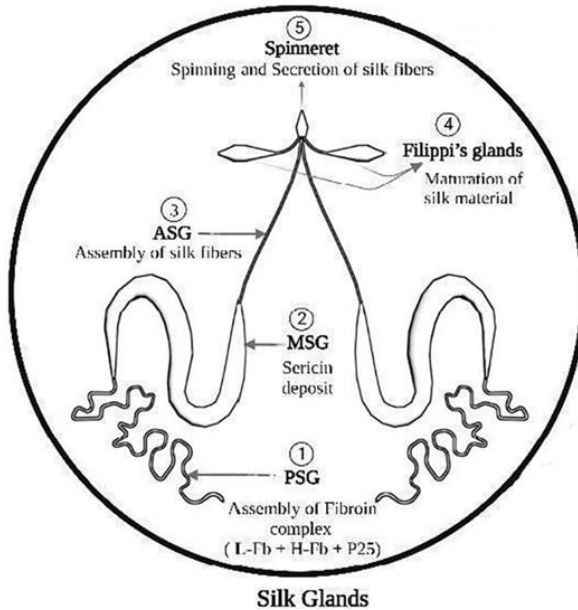
**Figure 3.** The silk glands' structure in a mature silkworm

**Reference:** Domigan et al. (2015)

Fibroin is produced in PSG. MSG cells produce three different forms of sericin: sericin 1, sericin 2, and sericin 3. Processing liquid silk is the responsibility of ASG, which does not manufacture silk. The primary component of silk is synthesized by the roughly 500 gland cells that make up the long PSG. About 300 secretory cells make up MSG, which is where silk proteins are kept until they are spun into a cocoon in its lumen. ASG is a narrow duct with around 250 cells that does not have a secretory role (Grzelak 1995). During the early phases of embryogenesis, these cells divide roughly ten times before going through an irreversible endoreplication process that encourages the formation of silk glands in the following phase without increasing the cell count (Ma et al., 2024).

Since silkworms typically spin their silks via a protein self-assembly process from highly concentrated protein gels or solutions into solid fibers, they

have evolved biological fiber spinning systems over millions of years. There are five steps in the silk gland's production of silk fibers (Figure 4).



**Figure 4.** Natural production of silk

**Reference:** Bitar et al. (2024)

The H-Fb, L-Fb, and P25 subunits are first synthesized in PSG, followed by the formation of  $\beta$ -sheet structures and the eventual fibroin complex, which is held together by disulfide bonds. The fibroin complex then travels to the MSG, where sericin is released to coat the fibroin core's surface and create silk complexes. The pH and metal ion concentrations subsequently carry the complexes along the ASG and transform them into silk fibers. The Filippi's gland produces mature silk fiber, which is then extruded through the spinneret to spin a cocoon. (Bitar et al. 2024; Anderson et al. 2016). Furthermore, the orientation of the protein molecules in the silk thread is impacted by the precise and constant movement of *B. mori*'s head during cocoon spinning. This causes the silk proteins to crystallize and come together, which increases their hydrophobicity and causes water to evaporate from the thread's surface (Liu and Zhang 2014).

Fibrin, the main component of silk fibers, is coated with sericin, an adhesive protein (Kapoor and Kundu, 2016; Katsuma et al. 2018; Ma et al. 2024). Because they aid in the production of cocoons, the adhesive layers produced by the globular-shaped sericin are also referred to as silk glue (Dai et al. 2019; Dinjaski and Kaplan 2016). While silk sericin protein is often soluble and can be eliminated through a thermochemical process called degumming, silk fibroin protein is resistant to water. In the silk business, sericin is extracted from fibroin to enhance the fibers' smoothness, brightness, lightness, and dyeability (Gupta et al. 2013). The most crucial step in guaranteeing biocompatibility is the elimination of fibroin fibers from the series (Lamboni et al. 2015). since an organism's employment of sericin and fibroin together tends to produce a pro-inflammatory response (DeBari and Abbott 2019). As a result, a silk fibroin solution consisting of three distinct proteins (H, L chain, and P25) is left over after the sericin coating is removed. It is believed that the presence of the heavy chain protein is what gives the biomaterials made from these solutions their primary characteristics (Bitar et al., 2024). However, depending on where it comes from, silk's composition, structure, and qualities can differ significantly. Silk fiber materials have more compact  $\beta$ -type protein structures. Both the touch and shine of these materials are softer (Fu et al. 2015; Saric and Scheibel 2019).

### • Sericin: Properties

The alternate splicing of sericin genes results in the formation of the glycoprotein sericin. The synthesis of sericin is controlled by at least three genes, namely as Ser1, Ser2, and Ser3. According to Kunz et al. (2016), the Ser1 gene is roughly 23 kb in size and has nine exons; the Ser2 gene ranges in size from 28 to 2574 bp and has thirteen exons; and the Ser3 gene is roughly 3.5 bp in size and has three exons. According to Rajput and Singh (2015), the series' organic composition is carbon (46.5), oxygen (31%), nitrogen (16.5), and hydrogen (6%). It could be used in the food and cosmetic sector as a moisturizer, wound healer, cell proliferation stimulator, antimicrobial, antioxidant, anticancer, coagulant, and radiation protector due to its solubility, organic composition, and structural organization of the chemical groups in the series (Lamboni et al. 2015; Gilotra et al. 2018; Kumar and Abrahamse 2022).

Serine includes 18 amino acids, positively and negatively charged, aromatic, polar, and non-polar amino acids (Kunz et al. 2016). Furthermore, serine is water soluble due to its high concentration of hydrophilic amino acids, particularly critical amino acids. The size of the resultant serine molecules varies based on temperature, pH, and processing time when serine is hydrolyzed in acidic or alkaline solutions, dissolved in a polar solvent, or broken down by a protease. At 50–60°C or above, sericin dissolves in water on average. The series becomes less soluble at low temperatures, which causes a gel to develop (Dash et al. 2007). Therefore, when the temperature varies, the protein's structure changes as well. According to Kunz et al. (2016), sericin dissolves in the solution when heated and gels when cooled. While sericin peptides with high molecular weight ( $\geq 20$  kDa) are primarily utilized as medical biomaterials, composite polymers, biodegradable biomaterials, hydrogels, functional biomembranes, functional fibers, and textiles. Sericin peptides with low molecular weight ( $\leq 20$  kDa) or sericin hydrolysates are utilized in cosmetic products, such as skin and hair care, and health products, and pharmaceuticals (Zhang 2002). Around 50,000 tons of silk, which the textile industry considers trash and which is made from 1 million tons of fresh cocoons annually worldwide, are reportedly frequently disposed of in sewage systems, endangering the environment (Aramwit et al. 2012; Lamboni et al. 2015). In addition, it raises the oxygen demand for chemicals and biological processes and pollutes water. Therefore, the recovery and reuse of the thrown series contribute to both the evaluation of materials with high scientific and economic value and the minimizing of environmental difficulties (Kunz et al. 2016).

### • **Fibroin: Properties**

Because of its exceptional mechanical strength, which comes from its structure, the silk fibroin fiber derived from *B. mori* has been utilized as a superior textile material for more than 5000 years (Asakura and Williamson 2023). Silk fibroin's strong tensile strength (300–740 MPa), high toughness (70–78 MJ.m<sup>-3</sup>), and big breaking strain (4–26%) are crucial for producing an exceptional textile material (Vollrath and Porter 2009; Koh et al. 2015; Guo et al. 2020). These days, textiles can be made from a variety of natural resources. Nonetheless, silk fibroin is unique among them due to its remarkable moisture

absorption capabilities, soft-touch texture, exceptional mechanical qualities, ease of dyeing, excellent biocompatibility, and incredibly bright/beautiful look (Tansil et al. 2012). Silk obtained from *B. mori* cocoons has a tensile strength of approximately 0.5 gigapascals (GPa), a break elongation of 15%, and a fracture energy (toughness) of  $6 \times 10^4 \text{ J kg}^{-1}$  (Shao and Vollrath 2002). Silk fibroin H-chain is a highly organized biopolymer consisting of 11 hydrophilic regions and 12 hydrophobic regions. Hydrophobic regions contain amino acids in repeating sequences (hence called repeating regions), while hydrophilic regions contain amino acids in non-repeating sequences (hence called non-repeating regions) (Koh et al. 2015). Hydrophobic regions make up a large portion of silk proteins and primarily contain glycine, alanine, serine, and a lower content of tyrosine, valine, and threonine. Through hydrogen bonding and hydrophobic interactions, these hydrophobic regions in the structure of silk fibroin organize the formation of  $\beta$ -sheet crystallites, which give silk fibers their high strength, thermal stability, and insolubility (Foo et al. 2006). This results in the formation of highly organized crystalline regions in silk fibroin. The tensile strength of fibroin is based on these structures. Conversely, the hydrophilic sections of silk fibroin constitute a non-crystalline (semi-amorphous) region and are primarily composed of glutamic acid, aspartic acid, arginine, and lysine. Accordingly, fibroin is a continuous long molecular chain with a molecular weight of roughly 325,000 and is composed of roughly two-thirds crystalline phase and one-third amorphous phase (Cheng et al. 2014). The elasticity and robustness of fibroin are revealed by the combination of hydrophobic and hydrophilic regions (Zhang et al. 2009). As a result, fibroin fibers outperform even high-strength synthetic fibers like Kevlar and Aramid in terms of tensile strength, breaking elongation, and toughness (Koh et al. 2015). A polymer's mechanical characteristics and biodegradability are significantly influenced by its molecular weight. However, Jin and Kaplan (2003) reported that the interactions between  $\beta$ -sheet crystals, as well as the size and spacing of the crystals, play a critical role in silk processing and must be taken into account in this process. Basically, silk fibroin could form  $\beta$ -sheet crystals of various sizes and intervals, either intra-molecularly or inter-molecularly, parallel or antiparallel, along the axis of the silk fiber. The separation (splitting) of protein chains from the intramolecular  $\beta$ -sheet crystalline structures causes the silk fibers to elongate, while the separation



from the intermolecular  $\beta$ -sheet crystalline structures weakens the bonds between the protein molecules in the silk fibers, resulting in a failure of pairing (Wu et al. 2009). When  $\beta$ -sheet crystals are arranged in a parallel manner, adjacent  $\beta$ -strands form long and non-linear hydrogen bonds, while anti-parallel adjacent  $\beta$ -strands form short and linear hydrogen bonds. These variations in hydrogen bonds lead to different arrangements of  $\beta$ -strands, thereby affecting the mechanical performance of silk fibers (Jin and Kaplan 2003). For example, it has been discovered that in antiparallel arranged  $\beta$ -sheet crystals, the hydrogen bond is stronger, and therefore, considering their fracture toughness and hardness, they are superior to their parallel counterparts. Additionally, it has been reported that when the  $\beta$ -sheet crystal size is limited to a few nanometers (2–4 nm), silk fibers exhibit greater mechanical strength, stiffness, and toughness compared to  $\beta$ -sheet crystals of larger sizes (Gore et al. 2019).

However, particularly in the past decade, silk fibroin has gained recognition as a superior biomaterial with a multitude of possible uses (Chen et al. 2020; Guo et al. 2020; Kong et al. 2020; Zuluaga-Vélez et al. 2021; Zhang et al. 2022; Kim et al. 2023; Lu et al. 2024). One limiting factor for clinical applications in materials intended for use as biomaterials is the biomaterial's immunogenicity or heterogeneity. Because when a heterologous antigen enters the body, B cells, dendritic cells, macrophages, and mast cells in immune system become activated and produce antibodies and various cytokines targeting the antigen epitopes on biomaterials with the aim of attacking and eliminating the "foreigners" through humoral and cellular immune responses. Thus, the most crucial factor is whether the materials to be employed as biomaterials are biocompatible (Zhang et al. 2009). Because of its amino acid sequence, silk fibroin presents potential for chemical changes that will provide biocompatibility. Potential reactive side groups utilized for these chemical alterations include the amines, phenols, alcohols, carboxyl groups, and thiols found in silk fibroin's structure. With their alteration, variations in silk fibroin's hydrophilicity and charge could also modify the degree of functionalization (Wenk et al. 2011). This way, it becomes easier to process silk fibroin in different forms such as sponge, fiber, hydrogel, etc. (Yang et al. 2007). Fibroin materials in different forms exhibit high biocompatibility by interacting positively with biological systems without causing adverse immunological reactions, supporting their adhesion, proliferation, growth, and functionality

(Hakimi et al. 2007). It has been reported that different forms of silk fibroin with good biocompatibility can significantly support the healing and regeneration of damaged nerves (Rajabi et al. 2018; Chen et al. 2020).

## **2. USES of SILK-BASED MATERIALS**

It is well known that silk has been mainly and largely used for more than 5000 years in the textile sector and for surgical purposes. As mentioned below, silk has excellent properties including biodegradability, biocompatibility and unique physical, chemical and mechanical specialities that have provided a huge attraction for different intended use. Therefore, silkworm silk has been used recently in a variety of industries, mainly in textile sector, numerous scientific studies have been conducted to determine its potential uses (Chand et al. 2023). Along with its biocompatible and biodegradable qualities, silk also has the ability to retain moisture, adhere to the skin, and gel. These qualities make it a valuable biomedical material with a wide range of commercial practices in the pharmaceutical, cosmetic and food industries (Jastrzebska et al. 2015; Wang et al. 2015; Soumya et al. 2017; Fan et al. 2019).

### **Biomedical usage of silk**

Silk is a biological substance because it contains hydrophobic amino acids and sericin, which has antioxidant properties. The antibacterial, anticoagulant, anticancer, and anti-inflammatory properties of silk are made possible by the antioxidant activity of sericin (Kunz et al. 2016). According to Chand et al. (2023), moisture also has a medicinal effect by promoting cell proliferation, wound healing, UV protection, and the creation of cosmetics like lotions and shampoos.

Silk is widely used in sutures, surgical fabrics and öeshes, tissue engineering, clinical experiments, and new biomedical applications such as films, electro-spun materials, scaffolds, hydrogels, and particles because of its biocompatibility and biodegradation qualities (Holland et al. 2019; Koh and Lee 2021; Saleh 2021).

Silk has biocompatible and biodegradable specialities because its sericin and proteinous nature make it vulnerable to the body's digestible proteolytic enzymes. Because of its propensity to retain moisture, gel, and adhere to skin, it may find extensive usage in the medical, pharmaceutical, and cosmetic industries (Padamwar and Pawar 2004). Scientific reports have clearly

demonstrated that the sericin has an anti-tumor activity. Foods containing sericin could prevent constipation, treat bowel cancer, and promote the mineral absorption (Joseph and Justin Raj 2012; Kato et al. 2000).

Biomaterials derived from silk have beneficial impacts on fibroblast and keratinocyte development and proliferation (Zhang et al. 2009a). Therapeutic uses of silk sericin have been investigated, including antibacterial (Basal et al. 2010), wound-coagulant and wound-healing properties (Padol et al. 2011). According to Joseph and Justin Raj (2012) and Padamwar et al. (2005), silk sericin and silk fibroin can also be utilized in skin, nail and hair cosmetics as creams and ointments that increase skin elasticity and have anti-aging and anti-wrinkle properties. Nail cosmetics containing sericin with a range of 0.2 to 20% could potentially provide a preventive effect for nail brittleness, chapping and impart inherent gloss in nails (Yamada et al. 2001).

There are many kinds of different commercially produced silk-based materials in biomedical practices. Some of them are listed here according to usage aim (Babu and Suamte 2024):

- Therapeutic apparel for individuals with skin conditions
- Medialization of vocal folds and sufficiency of vocal folds
- Perforation in the tympanic membrane
- Repairing peripheral nerves
- Hair care
- Cream for moisturizing
- Skin health and anti-aging care
- Surgical adhesive dressing (sterile)
- Topical antiseptic and ointment for wound healing
- Transparent surgical incision port wound dressing
- Transparent bandage for wounds with mild to moderate exudation
- Hydrogel wound dressing
- Antimicrobial and surface antiseptic/disinfectant spray for topical use
- Antimicrobial and non-adherent gauze bandage
- Antimicrobial adhesive wound dressing after surgery
- Antimicrobial surgical mesh and surgical powder for treating wounds

Previous studies indicated that silk fabricated through non-weaving and electrospinning could be used in wound dressings, and as drug carriers (Altman et al. 2003; Li et al. 2015; Wharram et al. 2010; Farokhi et al. 2018). Silk fiber-

based wound dressing material with unique antibacterial qualities containing silver nanoparticles have been developed (Xia et al. 2009). Additionally, the size of the wound, collagen, and epithelialization decreased when the wound dressing made up of two layers: a bioactive layer with glutaraldehyde cross-linked silk fibroin gelatin with a sericin sponge, and also silk woven fabric coated with wax, was applied (Wang et al. 2006; Kamalathevan et al. 2018; Chouhan et al. 2020).

Products made of silk could be utilized in many ways to improve the health of the skin. For instance, because of their antibacterial qualities, silk clothing has been developed as a textile-based treatment for atopic dermatitis. Silk's hygienic qualities minimize inflammation by protecting the skin from bacteria, viruses, and other contaminants (Hung et al. 2019; Macias et al. 2011). Additionally, the smooth and thin structure of silk filament threads makes them a comfortable material for the skin, minimizing skin irritation and scratching from friction (Criton and Gangadharan 2017). According to a prior study by Hung et al. (2019), wearing silk clothing significantly reduced the severity of dermatitis symptoms.

### **3. SILK FIBER as an INDUSTRIAL and ENGINEERING MATERIAL**

As mentioned below, fibrin and sericin are the two main protein components of silk. While sericin is obtained as a waste product in the textile sector during the process of separating fibroin from sericin, fibroin is mostly used in textiles and industrial areas. Their low repeatability compromises the silk's high tensile strength and stiffness values (Pérez-rigueiro et al. 1998; Soumya et al. 2017). Sericin is a valuable biomaterial that has been shown to be successful in tissue engineering, drug administration, culture media, and cryopreservation (Kunz et al. 2016).

In order to replace, improve, and preserve damaged or dysfunctional tissues, such as cartilage, bone, skin, 103lüoride organs, tissue engineering combines the concepts of biological sciences with engineering techniques (Caddeo et al. 2017). The final bio-substitute's functionality depends on the biomaterial selection and the techniques employed. Silk is suitable for application in tissue engineering because of its strong mechanical qualities, low inflammatory response, and slow rate of degradation. Sericin must be totally

eliminated before usage, nevertheless, as it may trigger an immunological reaction (Song 2011). Bombyx mori silk is the kind of silk that is frequently utilized in tissue engineering (Caddeo et al. 2017; Bandyopadhyay et al. 2019). Scaffolds in the form of skin grafts or artificial skin, artificial liver, bone grafts, cardiac tissue, artificial pancreas, and artificial intervertebral disc are examples of silk-based tissue engineering (Behrens et al. 2021).

Recently, polymeric methods for drug delivery have gained interest and importance (Kamalha et al. 2013). These systems enhance the physicochemical characteristics of medications by acting as reservoirs for their active ingredients (Tomeh et al. 2019). Additionally, polymeric drug delivery methods are effective in intracellular transport, selective targeting, and some are biocompatible, all of which contribute to better treatment outcomes and patient quality of life (Luo et al. 2019; Tomeh et al. 2019). Stabilizing the active component in medications, regulating the drug's release mechanism, being biocompatible and biodegradable, and reducing the negative consequences of tissue-specific targeting of extremely hazardous pharmaceuticals are all qualities of a good drug delivery system (Yin et al. 2018; Rezaei et al. 2020).

Silk fibroin is utilized in drug delivery systems because of its favorable mechanical qualities, mild aqueous processing conditions, biodegradability, biocompatibility, and capacity to improve the stability of small molecules and proteins that are the active ingredients in medications (Li et al. 2015; Choi et al. 2018). Nevertheless, a variety of methods can be used to treat silk fibroin solutions in order to create a variety of delivery systems, including films, hydrogels, scaffolds, microspheres, nanoparticles, and microcapsules (Seib 2018). Furthermore, silk fibroin contains amino and carboxyl groups that enable bio-functionalization with various biomolecules for precise medication administration (Vepari and Kaplan 2007). Hydrogels, microparticles, lyophilized sponges, films, nanofibers, and nanoparticles are examples of silk-based drug delivery methods.

In recent times, silk-based biosensors have increasingly gained interest by many researchers (Ru et al. 2022). The development of silk-based food sensors in the form of passive metamaterial antennas has allowed for detailed monitoring of food quality (Babu 2022) and biological analyses (Babu 2020). To enable close contact with the nano and microstructures that might probe and track changes in the surrounding environment, silk protein-based substrates

have been created and applied to the surface of an apple. The sensor is edible and made entirely of biodegradable materials, suggesting potential applications in the food and medical industries (Tao et al. 2012).

Furthermore, silk fibroin hydrogels have been used in metal–insulator–metal (MIM) absorber-based surface Plasmon resonance (SPR) sensors. The resulting MIM structure is extremely sensitive to variations in the refractive index and thickness of the thin 20 nm silk fibroin hydrogel insulator layer sandwiched between two 200 nm gold films. Thus, the hydrogel characteristics of the silk spacer, which can hold water molecules up to 60% of its 105lūori, improve analytic sensitivity. The silk hydrogel's refractive index and swelling ratio have an impact on sensitivity. Silk plasmonic structures are appropriate for glucose sensor applications because the silk polymer chains may also function as fluidic channels that allow analytes to pass through a nano-sized layer in water (Lee et al. 2015).

A mixture of reduced graphene oxide (RGO)/glucose oxidase (Gox) and silk nanofibril was used to create a dependable glucose sensor. This sensor covered both diabetes patients (0–100  $\mu\text{M}$ ) and healthy individuals because it demonstrated detection even at very low limits (300 nM) and had a high sensitivity of 18.0  $\mu\text{A}/\text{Mm}$ , which is within the sweat glucose range. According to Chen et al. (2022), tests on sweat samples revealed good reliability and correlation with data from a standard commercial glucometer.

In a different study, Li et al. (2021) employed spider dragline silk (SDS) to develop a novel humidity sensor that depends on the dragline silk's refractive shift mechanism in response to environmental humidity variations. In order to obtain an optical spectrum, the SDS was wrapped on a tapered single mode fiber, which allowed 105lūorid construction of a multimode interference structure. The multimode interference spectrum shifted as a result of changes in the environment's humidity, which also affected SDS's refractive index. According to the testing results, the suggested SDS-based sensor's average sensitivity was 0.532 nm/%RH over a range of 70% to 89% RH. The humidity sensing curve was roughly fitted using the linear approach, and the highest sensitivity was found at 0.789 nm/%RH over a range of 70%RH/- 89%RH (Li et al. 2021).

By carbonizing 105lūo silk georgette at a high temperature and then encasing it in the elastic polymer poly-dimethylsiloxane (PDMS), a wearable

strain sensor was created. This has demonstrated encouraging potential for use in tracking a variety of human motion-based activities (Wang et al. 2017a). The idea behind silk-based wearable sensors is that silk fibroin can be thermally treated to become an electrically conductive graphite nano-carbon (Cho et al. 2015). Carbon membranes made from transparent and flexible silk nanofibers have also been created for multipurpose electronic skin that can monitor physiological signals in humans (Wang et al. 2017b; Wang et al. 2017c). Silk and poly-vinylidene fluoride-co-trifluoroethylene have also been developed to create self-powered pressure sensor sheets for wearable technology (Jung et al. 2020). For application in epidermal electronics, calcium-modified silk fibroin has been created and demonstrated to have outstanding adhesive qualities in addition to superior stretchability, conductivity, and reusability. This enables a robust interaction between a biological surface and a sensor. Accordingly, calcium-modified silk fibroin exhibits potential for use as an adhesive for biomedical sensors based on the skin (Seo et al. 2018).

Another intriguing application for silk is coating optical fibers that are often non-biocompatible for biosensing inside the human body. Fluorophore 5,6-carboxynaphthofluorescein (CNF) doping of silica exposed core fibers following a thin silk coating has been documented. Remote pH measurement along the fiber length is made possible by the fluorescent signals produced by the doped-silk layer when applied to mice. These signals are coupled into the core of the silica-exposed core fiber (Khalid et al. 2020).

#### 4. CONCLUSION

Silk is a natural engineering material with unique properties. *B. mori* silk; due to its impressive mechanical properties, biocompatibility, and biodegradability, it has garnered significant interest in both biomedicine and tissue engineering fields. However, silk has cancer-preventive, antioxidant, antibacterial, anticoagulant, anti-inflammatory, anti-thrombotic, and anti-diabetic properties. Additionally, because they are renewable proteins with appealing flavors and high essential amino acid content, they are also gaining interest in the food industry. Considering the serious environmental pollution caused by the disposal of sericin and its beneficial properties as waste, interest in recycling this biomaterial, which could have strong and positive economic, social, and environmental impacts, is increasing day by day. However, since

natural silk is a renewable and biodegradable material, it is generally assumed to be inherently sustainable. However, sustainability is entirely dependent on the continuity of silkworm farming. Silk farming typically involves the cultivation of mulberry trees, followed by the breeding of silkworm colonies and the production of silk. Therefore, it is of vital importance for sectors that will use silk as a raw material and develop sustainable products made from natural silk to be aware of the necessity of ensuring the sustainability and preservation of sericulture.



## REFERENCES

- Altman, G.H., Diaz, F., Jakuba, C., Calabro, T., Horan, R.L., Chen, J., Lu, H., Richmond, J., Kaplan, D.L. 2003. Silk-based biomaterials. *Biomaterials*, 24(3): 401-416.
- Anderson, M. Johansson, J., Rising, A. 2016. Silk spinning in silkworms and spiders. *Int. J. Mol. Sci.*, 17: 1290.
- Aramwit, P., Siritientong, T., Srichana, T. 2012. Potential applications of silk sericin, a natural protein from textile industry by-products. *Waste Manag. Res.*, 30: 217-224.
- Asakura, T., Williamson, M.P. 2023. A review on the structure of Bombyx mori silk fibroin fiber studied using solid-state NMR: An antipolar lamella with an 8-residue repeat. *Int. J. Biol. Macromol.*, 245: 125537.
- Babu, P.J., Saranya, S., Longchar, B., Rajasekhar, A. 2022. Nanobiotechnology-mediated sustainable agriculture and post-harvest management, *Curr. Res. Biotechnol.*, 4: 326-336.
- Babu, P.J., Suamte, L. 2024. Applications of silk-based biomaterials in biomedicine and biotechnology. *Eng. Regen.*, 5: 56-69.
- Bandyopadhyay, A., Chowdhury, S.K., Dey, S., Moses, J.C., Mandal, B. 2019. Silk: a promising biomaterial opening new vistas towards affordable healthcare solutions. *J. Indian Inst. Sci.*, 1-43.
- Basal, G., Altıok, D., Bayraktar, O. 2010. Antibacterial properties of silk fibroin/chitosan blend films loaded with plant extract. *Fibers Polym.*, 11(1): 21-27.
- Behrens, M.R.; Ruder, W.C. 2021. Biopolymers in Regenerative Medicine: Overview, Current Advances, and Future Trends. In *Biopolymers for Biomedical and Biotechnological Applications*; Rehm, B.H.A., Moradali, M.F., Eds.; Wiley-VCH Verlag GmbH: Weinheim, Germany, pp. 357-380.
- Bitar, L., Isella, B., Bertella, F., Bettker Vasconcelos, C., Harings, J., Kopp, A., van der Meer, Y., Vaughan, T.J., Bortesi, L. 2024. Sustainable Bombyx mori's silk fibroin for biomedical applications as a molecular biotechnology challenge: A review. *Int. J. Biol. Macromol.*, 264 (Pt 1): 130374.

- Caddeo, S., Boffito, M., Sartori, S. 2017. Tissue engineering approaches in the design of healthy and pathological in vitro tissue models. *Front. Bioeng. Biotechnol.*, 5: 40.
- Cao, T.T., Zhang, Y.Q. 2017. The potential of silk sericin protein as a serum substitute or an additive in cell culture and cryopreservation. *Amino Acids.*, 49(6): 1029-1039.
- Chand, S., Chand, S., Raula, B. 2023. Usage of silkworm materials in various ground of science and research. *J. Nat. Fibers*, 20(1): 2139328.
- Chen, S., Liu, S., Zhang, L., Han, Q., Liu, H., Shen, J., Li, G., Zhang, L., Yang, Y. 2020. Construction of injectable silk fibroin/polydopamine hydrogel for treatment of spinal cord injury. *Chem. Eng. J.*, 399, p.125795.
- Cheng, Y., Koh, L.D., Li, D., Ji, B., Han, M.Y., Zhang, Y.W. 2014. On the strength of  $\beta$ -sheet crystallites of *Bombyx mori* silk fibroin. *J. R. Soc. Interface*, 11: 20140305.
- Cho, S.Y., Yun, Y.S., Lee, S., Jang, D., Park, K.Y., Kim, J.K., Kim, B.H., Kang, K., Kaplan, D.L., Jin, H.J. 2015. Carbonization of a stable  $\beta$ -sheet-rich silk protein into a pseudographitic pyroprotein. *Nat. Commun.*, 6: 7145.
- Choi, M., Choi, D., Hong, J. 2018. Multilayered controlled drug release silk fibroin nanofilm by manipulating secondary structure. *Biomacromolecules*, 19(7): 3096-3103.
- Chopra, S., Gulrajani, M.L. 1994. Comparative evaluation of the various methods of degumming silk. *Indian J. Fibre Text. Res.*, 19: 76-83.
- Chouhan, D., Mandal, B.B. 2020. Silk biomaterials in wound healing and skin regeneration therapeutics: From bench to bedside. *Acta Biomater.*, 103 :24-51.
- Criton, S., Gangadharan, G. 2017. Nonpharmacological management of atopic dermatitis. *Indian J. Paediatr. Dermatol.*, 18(3): 166.
- Dai, Z.J., Sun, W., Zhang, Z. 2019. Comparative analysis of iTRAQbased proteomes for cocoons between the domestic silkworm (*Bombyx mori*) and wild silkworm (*Bombyx mandarina*). *J. Proteom.*, 192: 366-373.
- Dash, R., Ghosh, S.K., Kaplan, D.L., Kundu, S.C. 2007. Purification and biochemical characterization of a 70 kDa sericin from tropical tasar silkworm, *Antheraea mylitta*. *Comp. Biochem. Physiol. B Biochem. Mol. Biol.*, 147: 129-134.

- DeBari, M.K., Abbott, R.D. 2019. Microscopic considerations for optimizing silk biomaterials. Wiley Interdisciplinary Reviews: Nanomed. Nanobiotechnol., 11(2): e1534.
- Dinjaski, N., Kaplan, D.L. 2016. Recombinant protein blends: Silk beyond natural design. Curr. Opin. Biotechnol., 39: 1-7.
- Domigan, L.J., Andersson, M., Alberti, K.A., Chesler, M., Xu, Q., Johansson, J., Rising, A., Kaplan, D.L. 2015. Carbonic anhydrase generates a pH gradient in Bombyx mori silk glands. Insect Biochem. Mol. Biol., 65: 100-106.
- Fan, S., Zhang, Y., Huang, X., Geng, L., Shao, H., Hu, X., Zhang, Y.P. 2019. Silk materials for medical, electronic and optical applications. Sci. China Technol. Sci., 62(6): 903-918.
- Farokhi, M., Mottaghitab, F., Fatahi, Y., Khademhosseini, A., Kaplan, D. 2018. Overview of silk fibroin use in wound dressings. Trends Biotechnol., 36(9): 907-922.
- Foo, C., Bini, E., Hensman, J., Knight, D.P., Lewis, R.V., Kaplan, D.L. 2006. Role of pH and charge on silk protein assembly in insects and spiders. Appl. Phys. A, 82: 223-233.
- Fu, J., Su, J., Wang, P., Yu, Y., Wang, Q., Cavaco-Paulo, A. 2015. Enzymatic processing of protein-based fibers. Appl. Microbiol. Biotechnol., 99(24): 10387-10397.
- Gilotra, S., Chouhan, D., Bhardwaj, N., Nandi, S.K., Mandal, B.B. 2018. Potential of silk sericin based nanofibrous mats for wound dressing applications. Mater. Sci. Eng. C., 90: 420-432.
- Gore, P.M., Naebe, M., Wang, X., Kandasubramanian, B. 2019. Progress in silk materials for integrated water treatments: Fabrication, modification and applications. Chem. Eng. J., 374: 437-470.
- Grzelak, K. 1995. Control of expression of silk protein genes. Comp. Biochem. Physiol., 110(4): 671-681.
- Guo, C., Li, C., Vu, H.V., Hanna, P., Lechtig, A., Qiu, Y., Mu, X., Ling, S., Nazarian, A., Lin, S.J., Kaplan, D.L. 2020. Thermoplastic moulding of regenerated silk. Nat. Mater., 19: 102-108.
- Gupta, D., Agrawal, A., Chaudhary, H., Gulrajani, M., Gupta, C. 2013. Cleaner process for extraction of sericin using infrared. J. Clean. Prod., 52: 488-494.

- Hãbeanu, M., Gheorghe, A., Mihalcea, T. 2023. Nutritional value of silkworm pupae (*Bombyx mori*) with emphases on fatty acids profile and their potential applications for humans and animals. *Insects*, 14: 254.
- Hakimi, O., Knight, D.P., Vollrath, F., Vadgama, P. 2007. Spider and mulberry silkworm silks as compatible biomaterials, *Compos. B. Eng.*, 38(3): 324-337.
- Herold, H.M., Scheibel, T. 2017. Applicability of biotechnologically produced insect silks. *Z. Naturforsch. C*, 72(9-10): 365385.
- Holland, C., Numata, K., Rnjak-Kovacina, J., Seib, P. 2019. The biomedical use of silk: past, present, future. *Adv. Healthc. Mater.*, 8(1): 1800465.
- Huang, W., Ling, S., Li, C., Omenetto, F.G., Kaplan, D.L. 2018. Silkworm silk-based materials and devices generated using bionanotechnology. *Chem. Soc. Rev.*, 47(17): 6486-6504.
- Hung, M.H., Sartika, D., Chang, S.J., Chen, S.J., Wang, C.C., Hung, Y.J., Cherng, J.H., Chiu, Y.K. 2019. Influence of silk clothing therapy in patients with atopic dermatitis. *Dermatol. Reports.*, 11(2): 8176.
- Inoue, S., Tanka, K., Arisaka, F., Kimura, S., Ohtomo, K., Mizuno, S. 2000. Silk fibroin of *Bombyx mori* is secreted, assembling a high molecular mass elementary unit consisting of H-chain, L-chain, and P25, with a 6:6:1 molar ratio. *J. Biol. Chem.*, 275: 40517-40528.
- Jastrzebska, K., Kucharczyk, K., Florczak, A., Dondajewska, E., Mackiewicz, A., Kozłowska, H.D. 2015. Silk as an innovative biomaterial for cancer therapy. *Rep. Pract. Oncol. Radiother.*, 20(2):87-98.
- Jin, H.J., Kaplan, D.L. 2003. Mechanism of silk processing in insects and spiders. *Nature*, 424: 1057-1061.
- Joseph, B., Raj, S.J. 2012. Therapeutic applications and properties of silk proteins from *Bombyx mori*. *Front. Life Sci.*, 6(3-4): 55-60.
- Jung, M., Lee, K.J., Kang, J.W., Jeon, S. 2020. Silk-Based Self Powered Pressure Sensor for Applications in Wearable Device. 2020 International Conference on Electronics, Information, and Communication (ICEIC), Barcelona, Spain, 2020, pp. 1-3.
- Kamathevan, P., Ooi, P., Loo, Y. 2018. Silk-based biomaterials in cutaneous wound healing: A systematic review. *Adv. Skin Wound Care.*, 31(12): 565-573.

- Kamalha, E., Zheng, Y.S., Zeng, Y.C., Fredrick, M. 2013. FTIR and WAXD study of regenerated silk fibroin. *Adv. Mater. Res.*, 677: 211-215.
- Kapoor, S., Kundu, S.C. 2016. Silk protein-based hydrogels: Promising advanced materials for biomedical applications. *Acta Biomater.*, 31: 17-32.
- Kasoju, N., Bora, U. 2012. Silk Fibroin in Tissue Engineering. *Adv. Healthcare Mater.*, 1: 393-412.
- Kato, M., Isobe, K., Dai, Y., Liu, W., Takahashi, M., Nakashima, I. 2000. Further characterization of the Sho-saio-to- mediated anti-tumor effect on melanoma developed in RET-transgenic mice. *J. Invest. Dermatol.*, 114(3):599-601.
- Katsuma, S., Kiuchi, T., Kawamoto, M., Fujimoto, T., Sahara, K. 2018. Unique sex determination system in the silkworm, *Bombyx mori*: Current status and beyond. *Proceedings of the Japan Academy Series B: Physical and Biological Sciences*, 94(5): 205-216.
- Khalid, A., Peng, L., Arman, A., Warren-Smith, S., Schartner, E., Sylvia, G., et al. 2020. Silk: A bio-derived coating for optical fiber sensing applications. *Sens. Actuators B: Chem.*, 311: 127864.
- Khosropanah, M.H., Vaghasloo, M.A., Shakibaei, M., Mueller, A.L., Kajbafzadeh, A.M., Amani, L., Haririan, I., Azimzadeh, A., Hassannejad, Z., Zolbin, M.M. 2022. Biomedical applications of silkworm (*Bombyx Mori*) proteins in regenerative medicine (a narrative review). *J. Tissue Eng. Regen. Med.*, 16(2): 91-109.
- Kim, Y.J., Kim, S.W., Kim, K.Y., Ki, C.S., Um, I.C. 2023. Structural characteristics and properties of cocoon and regenerated silk fibroin from different silkworm strains. *Int. J. Mol. Sci.*, 24: 4965.
- Koh, L.D.D., Cheng, Y., Teng, C.P.P., Khin, Y.W.W., Loh, X.J.J., Tee, S.Y.Y., Low, M., Ye, E., Yu, H.D.D., Zhang, Y.W.W., Han, M.Y.Y. 2015. Structures, mechanical properties and applications of silk fibroin materials, *Prog. Polym. Sci.*, 46: 86-110.
- Koh, E., Lee, Y.T. 2021. Preparation of an omniphobic nanofiber membrane by the self- assembly of hydrophobic nanoparticles for membrane distillation. *Sep. Purif. Technol.*, 259: 118134.

- Kong, Y., Zhang, L., Han, Q., Chen, S., Liu, Y., Mu, H., Liu, Y., Li, G., Chen, X., Yang, Y. 2020. Effect of anisotropic silk fibroin topographies on dorsal root ganglion. *J. Mater. Res.*, 35(13): 1738-1748.
- Kumar, S.S.D., Abrahamse, H. 2022. Sericin-based nanomaterials and their applications in drug delivery. In *Bio-Based Nanomaterials*; Elsevier: Amsterdam, The Netherlands, pp. 211-229.
- Kundu, S.C., Dash, B.C., R. Dash, Kaplan, D.L. 2008. Natural protective glue protein, sericin bioengineered by silkworms: potential for biomedical and biotechnological applications. *Prog. Polym. Sci.*, 33(10): 998-1012.
- Kunz, R., Brancalhão, R., Ribeiro, L., Natali, M. 2016. Silkworm sericin: properties and biomedical applications. *Biomed Res. Int.*, 2016: 8175701.
- Lamboni, L., Gauthier, M., Yang, G., Wang, Q. 2015. Silk sericin: A versatile material for tissue engineering and drug delivery. *Biotechnol. Adv.*, 33: 1855-1867.
- Lawrence, B.D., Infanger, D.W. 202. Effect of silk fibroin protein hydrolysis on biochemistry, gelation kinetics, and NF- $\kappa$ B bioactivity in vitro. *Int. J. Biol. Macromol.*, 272(Pt 1): 132702.
- Lee, M., Jeon, H., Kim, S. 2015. A highly tunable and fully biocompatible silk nanoplasmonic optical sensor. *Nano Lett.*, 15(5): 3358-3363.
- Li, G., Li, Y., Chen, G., He, J., Han, Y., Wang, X., Kaplan, D.L. 2015. Silk-based biomaterials in biomedical textiles and fiber-based implants. *Adv. Healthc. Mater.*, 4(8): 1134-1151.
- Li, Q., Chen, G., Cui, Y., Ji, S., Liu, Z., Wan, C., Liu, Y., Lu, Y., Wang, C., Zhang, N. 2021. Highly thermal-wet comfortable and conformal silk-based electrodes for on-skin sensors with sweat tolerance. *ACS Nano*, 15(6): 9955-9966.
- Li, G., Sun, S. 2022. Silk fibroin-based biomaterials for tissue engineering applications. *Molecules*, 27: 2757.
- Liu, X., Zhang, K.Q. 2014. Silk Fiber - molecular formation mechanism, structure- property relationship and advanced applications. In: *Oligomerization Chem Biol Compd.*, Chapter 3, 69-102.
- Lu, L., Liu, X., Sun, Y., Wang, S., Liu, J., Ge, S., Wei, T., Zhang, H., Su, J., Zhang, Y., Fan, W. 2024. Silk-fabric reinforced silk for artificial bones. *Adv. Mater.* 36: 2308748.

- Luo, Z., Li, J., Qu, J., Sheng, W., Yang, J., Li, M. 2019. Cationized Bombyx mori silk fibroin as a delivery carrier of the VEGF165–Ang-1 coexpression plasmid for dermal tissue regeneration. *J. Mater. Chem. B.*, 7(1): 80-94.
- Ma, Y., Li, Q., Tang, Y., Zhang, Z., Liu, R., Luo, Q., Wang, Y., Hu, J., Chen, Y., Li, Z., Zhao, C., Ran, Y., Mu, Y., Li, Y., Xu, X., Gong, Y., He, Z., Ba, Y., Guo, K., Dong, K., Li, X., Tan, W., Zhu, Y., Xiang, Z., Xu, H. 2024. The architecture of silk-secreting organs during the final larval stage of silkworms revealed by singlenucleus and spatial transcriptomics. *Cell Reports*, 43: 114460.
- Macias, E., Pereira, F., Rietkerk, W., Safai, B. 2011. Superantigens in dermatology. *J. Am. Acad. Dermatol.*, 64(3): 455-472.
- McGill, M., Holland, G.P., Kaplan, D.L. 2019. Experimental methods for characterizing the secondary structure and thermal properties of silk proteins. *Macromol. Rapid Commun.*, 40(1) e1800390.
- Mondal, M., Trivedy, K., Kumar, S.N. 2007. The silk proteins, sericin and fibroin in silkworm, Bombyxmori Linn., A review. *Casp. J. Environ. Sci.*, 5(2): 63-76.
- Padamwar, M.N., Pawar, A.P. 2004. Silk sericin and its applications: A review. *J. Sci. Ind. Res.*, (63): 323-329.
- Padamwar, M.N., Pawar, A.P., Daithankar, A.V., Mahadik, K.R. 2005. Silk sericin as a moisturizer: An in vivo study. *J. Cosmet. Dermatol.*, 4(4): 250-257.
- Padol, A.R., Jayakumar, K., Shridhar, N.B., Narayana Swamy, H.D., Narayana Swamy, M., Mohan, K. 2011. Safety evaluation of silk protein film (a novel wound healing agent) in terms of acute dermal toxicity, acute dermal irritation and skin sensitization. *Toxicol. Int.*, 18(1):17-21.
- Patel, M., Dubey, D.K., Singh, S.P. 2020. Phenomenological models of Bombyx mori silk fibroin and their mechanical behavior using molecular dynamics simulations. *Mater. Sci. Eng. C.*, 108: 110414.
- Pérez-Rigueiro, J., Viney, C., Llorca, J., Elices, M. 1998. Silkworm silk as an engineering material. *J. Appl. Polym. Sci.*, 70(12):2439-2947.
- Pritchard, E. M., Dennis, P. B., Omenetto, F., Naik, R.R., Kaplan, D.L. 2012. Review physical and chemical aspects of stabilization of compounds in silk. *Biopolymers*, 97(6): 479-498.

- Rajabi, M., Firouzi, M., Hassannejad, Z., Haririan, I., Zahedi, P. 2018. Fabrication and characterization of electrospun laminin-functionalized silk fibroin/poly (ethylene oxide) nanofibrous scaffolds for peripheral nerve regeneration. *J. Biomed. Mater. Res. B. Appl. Biomater.*, 106(4): 1595-1604.
- Rajput, S.K., Singh, M.K. 2015. Sericin-A unique biomaterial. *IOSR J. Polym. Text. Eng.*, 2: 29-35.
- Reddy, R., Jiang, Q., Aramwit, P., Reddy, N. 2020. Litter to leaf: The unexplored potential of silk byproducts. *Trends Biotechnol.*, 39(7): 706-718.
- Rezaei, F., Damoogh, S., Reis, R., Kundu, S., Mottaghitlab, F., Farokhi, M. 2020. Dual drug delivery system based on pH-sensitive silk fibroin/alginate nanoparticles entrapped in PNIPAM hydrogel for treating severe infected burn wound. *Biofabrication*, 13(1): 015005.
- Rockwood, D.N., Preda, R.C., Yucel, T., Wang, X., Lovett, M.L., Kaplan, D.L. 2011. Materials fabrication from *Bombyx mori* silk fibroin. *Nat. Protoc.*, 6: 1612-1631.
- Ru, M., Hai, A.M., Wang, L., Yan, S., Zhang, Q. 2022. Recent progress in silk-based biosensors. *Int. J. Biol. Macromol.*, 224: 422-436.
- Saleh, T.A. 2021. Protocols for synthesis of nanomaterials, polymers, and green materials as adsorbents for water treatment technologies. *Environ. Sci. Technol.*, 24: 101821.
- Saric, M., Scheibel, T. 2019. Engineering of silk proteins for materials applications. *Curr. Opin. Biotechnol.*, 60: 213-220.
- Sehadova, H., Zavodska, R., Rouhova, L., Zurovec, M., Sauman, I. 2021. The role of filippi's glands in the silk moths cocoon construction. *Int. J. Mol. Sci.*, 22: 13523.
- Seib, P. 2018. Reverse-engineered silk hydrogels for cell and drug delivery. *Ther. Deliv.*, 9(6): 469-487.
- Seo, J.W., Kim, H., Kim, K., Choi, S., Lee, H. 2018. Calcium-modified silk as a biocompatible and strong adhesive for epidermal electronics. *Adv. Funct. Mater.*, 28(36): 1800802.
- Shao, Z., Vollrath, F. 2002. Surprising strength of silkworm silk. *Nature*, 418: 741.



- Silva, A.S., Costa, E.C., Reis, S., Spencer, C., Calhelha, R.C., Miguel, S.P., Ribeiro, M.P., Barros, L., Vaz, J.A., Coutinho, P. 2022. Silk Sericin: a promising sustainable biomaterial for biomedical and pharmaceutical applications. *Polymers*, 14: 4931.
- Sobajo, C., Behzad, F., Yuan, X.F., Bayat, A. 2008. Silk: a potential medium for tissue engineering. *Eplasty*. 8: e47.
- Song, G. 2011. Improving comfort in clothing. In: Woodhead Publishing Series in Textiles, Woodhead Publishing Limited, India, 449-459.
- Soumya, M., Reddy, H., Nageswari, G., Venkatappa, B. 2017. Silkworm (*Bombyx mori*) and its constituents: A fascinating insect in science and research. *J. Entomol. Zool. Stud.*, 5(5):1701-1705.
- Sun, F., Ye, C.J., Li, B., Wang, T., Fan, T. 2019. Application of mass spectrometry in silkworm research. *Biomed. Chromatogr.*, 33(4): e4476.
- Tansil, N.C., Koh, L.D., Han, M.Y. 2012. Functional silk: colored and luminescent. *Adv. Mater.*, 24: 1388-1397.
- Tao, H., Kainerstorfer, J.M., Siebert, S.M., Pritchard, E.M., Sassaroli, A., Panilaitis, B.J., Brenckle, M.A., Amsden, J.J., Levitt, J., Fantini, S., Kaplan, D.L., Omenetto, F.G. 2012. Implantable, multifunctional, bioresorbable optics. *Proc. Natl. Acad. Sci.*, 109(48): 19584-19589.
- Tomeh, M.A., Hadianamrei, R., Zhao, X. 2019. Silk fibroin as a functional biomaterial for drug and gene delivery. *Pharmaceutics*, 11(10): 494.
- Vepari, C., Kaplan, D. 2007. Silk as a biomaterial. *Prog. Polym. Sci.*, 32(8-9): 991-1007.
- Vollrath, F., Porter, D. 2009. Silks as ancient models for modern polymers. *Polymer*, 50(24): 5623-5632.
- Wang, M., Yu, J., Kaplan, D., Rutledge, G. 2006. Production of submicron diameter silk fibers under benign processing conditions by two-fluid electrospinning. *Macromol.*, 39(3): 1102-1107.
- Wang, F., Wolf, N., Rocks, E.M., Vuong, T., Hu, X. 2015. Comparative studies of regenerated water-based Mori, Thai, Eri, Muga and Tussah silk fibroin films. *J. Therm. Anal. Calorim.*, 122(3):1069-1076.
- Wang, C., Xia, K., Jian, M., Wang, H., Zhang, M., Zhang, Y. 2017a. Carbonized silk georgette as an ultrasensitive wearable strain sensor for full-range human activity monitoring. *J. Mater. Chem. C.*, 5(30): 7604-7611.

- Wang, C., Xia, K., Zhang, M., Jian, M., Zhang, Y. 2017b. An all-silk-derived dual-mode E-skin for simultaneous temperature–pressure detection. *ACS Appl. Mater. Interfaces*, 9(45): 39484-39492.
- Wang, Q., Jian, M., Wang, C., Zhang, Y. 2017c. Carbonized silk nanofiber membrane for transparent and sensitive electronic skin. *Adv. Funct. Mater.*, 27(9): 1605657.
- Wang, H.Y., Zhang, Y., Zhang, M., Zhang, Y.Q. 2024. Functional modification of silk fibroin from silkworms and its application to medical biomaterials: A review. *Int. J. Biol. Macromol.*, 259(Pt1): 129099.
- Wenk, E., Merkle, H.P., Meinel, L. 2011. Silk fibroin as a vehicle for drug delivery applications. *J. Control. Release.*, 150(2): 128-141.
- Wharram, S., Zhang, X., Kaplan, D., McCarthy, S. 2010. Electrospun silk material systems for wound healing. *Macromol. Biosci.*, 10(3): 246-257.
- Wu, X., Liu, X.Y., Du, N., Xu, G., Li, B. 2009. Unraveled mechanism in silk engineering: Fast reeling induced silk toughening. *Appl. Phys. Lett.*, 95: 093703.
- Xia, Y., Gao, G., Li, Y. 2009. Preparation and properties of nanometer titanium dioxide/silk fibroin blend membrane. *J. Biomed. Mater. Res. B. Appl. Biomater.*, 90(2): 653-658.
- Yamada, H., Yamasaki, K., Zozaki, K. 2001. Nail cosmetics containing sericin. *Chem. Abstr.*, 134(14): 197888.
- Yang, Y., Ding, F., Wu, J., Hu, W., Liu, W., Liu, J. and Gu, X., 2007. Development and evaluation of silk fibroin-based nerve grafts used for peripheral nerve regeneration. *Biomater.*, 28(36): 5526-5535.
- Yin, Z., Kuang, D., Wang, S., Zheng, Z., Yadavalli, V., Lu, S. 2018. Swellable silk fibroin microneedles for transdermal drug delivery. *Int. J. Biol. Macromol.*, 106: 48-56.
- Zhang, Y.Q. 2002. Applications of natural silk protein sericin in biomaterials. *Biotechnol. Adv.*, 20(2): 91-100.
- Zhang, Q., Yan, S., Li, M. 2009. Silk Fibroin Based Porous Materials. *Materials*, 2(4):2276-2295.
- Zhang, X., Reagan, M., Kaplan, D. 2009a. Electrospun silk biomaterial scaffolds for regenerative medicine. *Adv. Drug Deliv. Rev.*, 61(12): 988-1006.

- Zhang, H., Zhang, H., Wang, H., Zhao, Y., Chai, R. 2022. Natural proteins-derived asymmetric porous conduit for peripheral nerve regeneration. *Appl. Mater. Today*, 27: p.101431.
- Zhou, C.Z., Confalonieri, F., Jacquet, M., Perasso, R., Li, Z.G., Janin, J. 2001. Silk fibroin: Structural implications of a remarkable amino acid sequence. *Proteins*, 44: 119-122.
- Zuluaga-Vélez, A., Quintero-Martinez, A., Orozco, L.M., Sepúlveda-Arias, J.C. 2021. Silk fibroin nanocomposites as tissue engineering scaffolds - A systematic review. *Biomed. Pharmacother.*, 141: 111924.

## CHAPTER 6

### EFFECT OF VARIOUS ORGANIC BASED MATERIALS ON THE COMPRESSIVE RESISTANCE OF WOOD MATERIAL

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## INTRODUCTION

Türkiye's forest area has been determined as 22.34 million hectares. This forest area is 28.5% of the country's total area. Scots pine wood is one of our primary forest tree species spreading over an area of 1,522,931 hectares. As a result of the changes made to the structure of Scots pine wood, it is made suitable for use in a wide variety of areas. Scots pine wood is mainly used in the fields of wood pulp, cellulose production, pole and molding board manufacturing, building construction, vehicle manufacturing, carpentry, furniture, particle board and coating industry, etc. (OGM, 2015).

It Wood, which has been used for various purposes since the beginning of human history, is one of the most important raw materials. With the rapid development of technology, the areas of use of wood have diversified and the amount used has also increased. This increase in the use of wood has caused it to be among the decreasing natural resources today (Kartal and Imamura, 2004). Since wood has a hygroscopic structure, it exchanges moisture with the surrounding air in order to adapt to the temperature and relative humidity of the air in the environment it is in. If this exchange occurs below the fiber saturation point, it changes in size and volume, and for this reason, it becomes vulnerable to biotic and abiotic factors. The most common protection method known is impregnation. The process of penetrating chemical substances with protective properties against various factors (rot, burning, dimensional work, etc.) in a way suitable for the place of use is known as impregnation. In impregnation, the success of the process depends on the degree of protection, the impregnation material and the properties of the wood, as well as the amount of net dry impregnation material attached to the wood (retention) and the depth of penetration of the impregnation material into the wood (Örs and Keskin, 2008).

The Wood material that is protected by impregnation against biological deterioration in the place of use, which has a high risk of decay, can sometimes be harmful to the environment and other living things. In recent years, the use of impregnation materials has been under pressure by some environmental organizations (Kartal and Kantay, 2006).

Generally used impregnation materials are divided into 3 groups as oily, organic solvent and water-soluble impregnation materials. Water-soluble impregnation materials are mostly preferred in the protection of wood. These are widely used in areas such as picnic tables, highway guardrails, roofing

materials, packaging containers, wooden materials used in balconies and terraces, park garden arrangements and landscape timber (Aytaşkın, 2009).

Creosote is the most common oily impregnation material and is mostly used in the impregnation of railway sleepers. Organic-based impregnation materials are widely preferred in the impregnation of external doors, prefabricated structural elements and window frames (Temiz, 2004).

Within the scope of the research, the impregnation feature of the medicinal aromatic plant extract (*Black Cumin*) on larex wood and its effects on the change in compressive strength from mechanical properties were determined by correlating it with the application of water-based varnish.

## 1. MATERIAL AND METHOD

Within the scope of the study, larex wood (*Larix decidua* Mill.) wood was used. Sapwood samples cut in the radial direction were made according to TS 2471. Extract preparation was carried out from Black Cumin (*Nigella Sativa* L.) as a medicinal aromatic plant species.

### 1.1. Experimental Sample Preparation

While preparing the samples, the wood was prepared according to (TS 2470) from sapwood that does not show any irregularity in the fibrous structure, cracks, knots, tulle formation and discoloration, and was cut to  $20 \times 20 \times 30 \pm 1$  mm dimensions in accordance with TS 2595 principles for compressive strength tests.

### 1.2. Impregnation / Drying / Varnish Process

The impregnation process was applied in accordance with the conditions in “ASTM–D 1413-76”. Experimental samples were prepared in  $20 \times 20 \times 300 \pm 1$  mm and  $20 \times 20 \times 30 \pm 1$  mm dimensions and were subjected to 30 minutes of vacuum and 30 minutes of diffusion process. In order for the impregnation material not to be affected by wood moisture, the experimental samples were made completely dry.

After the impregnation and diffusion process, the samples were kept in an air-dry environment for a while. Then, they were arranged so that they would not touch each other and placed in the oven and the temperature was fixed at  $103 \pm 2^\circ\text{C}$ . They were kept in the oven for 24 hours and made completely dry. At the end of the period, they were removed from the oven and completely dry

measurements were made. Water-based system varnish application in the experimental phase was carried out in accordance with ASTM D-3023 standard.

1.3. Plant Extract Preparation

The black cumin plant, a medicinal aromatic plant species, was left to dry in the laboratory for 1-2 months until it reached a constant weight level. After drying for 1-2 months, it was passed through a blade blender (grinder) and turned into powder.

The extraction process was carried out in methanol by mixing in a shaker at room temperature for 24 hours. It was then filtered using ordinary filter paper and completed with the relevant solvents to certain volumes (5 L of methanol extract was prepared to be 1% concentration)” (Ceylan, 2020).

2. FINDINGS AND DISCUSSION

2.1. Extract (Solution) Feature

Solution properties are given in Table 1.

Table 1. Weight loss (%)

Plant extract (Black cumin)	Solvent	Degree (°C)	pH		Density (g/ml)	
			Bİ	Aİ	Bİ	Aİ
1%	Methanol	22°C	6.10	6.15	0.930	0.930

Bİ: Before impregnation    Aİ: After impregnation

No change was found before and after impregnation of black cumin solution (1%).

2.2. % Retention

% retention change are given in Table 2.

Table 2. Retention (%)

Plant extract (Black cumin)	Solvent	Degree (°C)	Retention (%)
1%	Methanol	22°C	0.042

Black cumin plant extract adhered to larex wood and the reasons for the low level obtained may be due to wood type, anatomical structure of wood, concentration, plant type and impregnation method.



### 2.3. Compression Strength (N/mm<sup>2</sup>)

Compressive strength change are given in Table 3.

**Table 3.** Compressive Strength Change ( N/mm<sup>2</sup>)

Plant Extract/Varnish/	Mean	HG
Control	62.56	C
Varnish	69.67	A
1% Plant Extract	64.25	D
1% Plant Extract+Varnish	67.86	B

HG: Homogeneity group

The highest value in the change of pressure resistance was determined in the varnish (69.67 N/mm<sup>2</sup>) and the lowest value in the control sample (62.56). Water-based varnish application and plant extract structure increased the pressure resistance value.

### 3. CONCLUSION

As a result, it is possible to increase the service life of wood material in the place of use and protect it against factors that degrade and cause destruction with impregnation. Today, many impregnation materials are used to protect wood material against biotic pests, abiotic factors and combustion. Boron compounds and a wide variety of chemicals are used in the wood protection industry. The most important desired features of human/environment friendly preservatives are that they are natural/organic. Medical aromatic plant extracts are also the most important of these. It can be said that it can be used easily in all kinds of environments. It can be used as a preservative with natural varnishes in all kinds of interior/exterior spaces.

## REFERENCES

- ASTM-D 1413-07, 2007. Standard Test Method of Testing Wood Preservatives by Laboratory Soilblock Cultures, ASTM, USA, 1-9.
- Aytaşkın, A., (2009). Some technological properties of wood impregnated with various chemical substances, Master thesis, Karabük University, Graduate School of Natural and Applied Sciences, Karabük, 134p.
- Ceylan, Ş., (2020). Possibilities of using rain herb (antioxidant/antibacterial) extract in wood industry (furniture/construction), Artvin Coruh University Scientific Research Project, Artvin.
- Kartal, S.N., & Imamura, Y., (2004). The use of boron as wood preservative systems for wood and wood-based composites. 3. International Boron Symposium, Eskişehir, Vol. I, 333-338.
- Kartal, S., Kantay, R., (2006). Use of wood preservatives in sensitive environments such as picnic tables and playground equipments, Düzce University Faculty of Forestry Journal of Forestry, 56(2), 43-51.
- OGM., (2015). General Directorate of Forestry, Department of Forest Management and Planning, Forest Assets of Türkiye, Ankara, pp.10-20.
- Örs, Y., & Keskin, H., (2008). Wood Material Technology, Gazi University Publication, Publication No:2000/352, Ankara, 1-6, 144-155.
- Temiz, A., (2004). Physical and mechanical properties of impregnated alder (*Alnus glutinosa* (L.) Gaertn. subsp. *barbata* (C.A.Mey.) Yalt) wood. Master thesis, Karadeniz Technical University Graduate School of Natural and Applied Sciences, Trabzon, 113 p.
- TS 2471 (1976) Wood, Determination of Moisture Content for Physical and Mechanical Tests
- TS 2595 (1977) Wood-Determination of Ultimate Stress In Compression Parallel to Grain



## **CHAPTER 7**

### **PHYTOCHEMICALS AND POLYPHENOLS**

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## INTRODUCTION

Phytochemicals are secondary metabolites found in plants, distinct from primary metabolites, and play a crucial role in environmental adaptation, pathogen protection, and plant defense mechanisms (Al-Khayri et al., 2023; Kumar et al., 2023; Rasouli et al., 2017). These compounds are part of the plant's response to environmental stress factors and are recognized for their biological activities (D'Angelo, 2020; Yeshi, et al., 2022; Šamec, et al. 2021). Phytochemicals are classified into various chemical groups, such as polyphenols, terpenoids, alkaloids, and organosulfur compounds, each exhibiting specific functions in plants and diverse effects on human health (Fatima et al., 2021; Pham et al., 2020; Santhiravel et al., 2022; Upadhyay & Dixit, 2015). These compounds have garnered significant attention in both nutritional and medical research, particularly due to their antioxidant properties, contributions to cellular defense systems, and potential health benefits (Johnson, 2007; Muscolo et al., 2024).

Polyphenols represent the most prevalent and important group of phytochemicals, encompassing subclasses such as flavonoids, stilbenes, phenolic acids, and lignans (Alqarni et al., 2024; Rasouli et al., 2017). Among these, flavonoids are the most widely known and commonly found compounds, often associated with the color pigments in plants (D'Angelo, 2020; Roy et al., 2022; Shen et al., 2022). Additionally, terpenoids, such as carotenoids and limonoids, typically exhibit anti-inflammatory and immune-modulatory effects, regulating other metabolic functions in plants (Johnson, 2007; Kim et al., 2022; Teshome et al., 2023). Furthermore, organosulfur compounds, notably found in vegetables like broccoli and garlic, have garnered attention for their cancer-preventive properties (Adeeyo et al., 2021; D'Angelo, 2020). The biological effects of these compounds stem from their potent ability to modulate cellular signaling pathways (Javed et al., 2021; Upadhyay & Dixit, 2015).

Flavonoids, in particular, alleviate the effects of oxidative stress by inhibiting lipid peroxidation in cell membranes (Alsawaf et al., 2022; Rasouli et al., 2017). On the other hand, certain phytochemicals, such as organosulfur compounds, can reduce the effects of carcinogens that cause DNA damage by stimulating detoxification enzymes (Johnson, 2007; Ruhee et al., 2020). These mechanisms play a crucial role in understanding the health effects of

phytochemicals (Cote et al., 2022; D'Angelo, 2020). In addition, phytochemicals have been reported to exhibit protective effects against various health issues, such as cancer, cardiovascular diseases, diabetes, and metabolic disorders, by regulating cellular signaling pathways and biological activities (Upadhyay & Dixit, 2015).

Epidemiological studies have shown that diets rich in phytochemicals, particularly from regular consumption of foods like vegetables, fruits, and tea, significantly reduce the risk of chronic diseases (D'Angelo, 2020). In addition to their antioxidant effects, polyphenols have shown promising results in cancer research due to their ability to halt cell proliferation or trigger apoptosis (Johnson, 2007). Furthermore, numerous studies have demonstrated the protective effects of phytochemicals against metabolic diseases, cardiovascular diseases, and diabetes (Rasouli et al., 2017).

In light of this information, phytochemicals are not only essential for plants but are also of critical importance to human health (Upadhyay & Dixit, 2015). These compounds, which hold great potential for future biomedical applications, are expected to play an essential role in the development of new treatment options and health strategies in the pharmaceutical field (D'Angelo, 2020).

## **1. POLYPHENOLS AND PHYTOCHEMICALS**

### **1.1. Chemical Structure and Classification of Polyphenols**

Polyphenols are organic compounds consisting of one or more phenolic rings attached to hydroxyl groups. Their chemical structures are crucial in determining their antioxidant capacity and biological activity levels. These structures play a significant role in reducing the effects of oxidative stress in the body and explain the protective health benefits of polyphenols (Rasouli et al., 2017; Manach et al., 2004). Polyphenols are typically divided into major subclasses, including flavonoids, phenolic acids, stilbenes, and lignans (Cao et al., 2017). These subclasses are key determinants of each compound's biological effects and activities in the body (Zhao et al., 2018).

**Flavonoids:** Flavonoids constitute the largest subgroup of polyphenols and are further divided into subclasses such as flavones, flavonols, flavanones, isoflavones, anthocyanidins, and flavan-3-ols (Çetinkaya et al., 2022; Upadhyay & Dixit, 2015). Flavonoids serve as color pigments in plants and are

particularly known for their antioxidant, anti-inflammatory, antimicrobial, and cardioprotective properties (Scalbert et al., 2005; D'Angelo, 2020). Studies have shown that flavonoids have significant health effects, such as inhibiting the growth of cancer cells and preventing heart diseases (Li et al., 2016; Ullah et al., 2020).

**Phenolic Acids:** Phenolic acids are divided into two main groups: hydroxycinnamic and hydroxybenzoic acids, both possessing strong free radical scavenging properties (D'Angelo, 2020; Manach et al., 2004). These compounds play a vital role in the prevention of diseases such as cancer, cardiovascular diseases, and diabetes, in addition to their antioxidant properties (Cao et al., 2017; Ozdemir et al., 2023). Phenolic acids have also been shown to perform detoxification functions by preventing the accumulation of toxins in the body (Firuzi et al., 2017).

**Stilbenes:** The most studied compound in the stilbene class is resveratrol, which is recognized for its anti-inflammatory and anticancer properties. Resveratrol has shown promising results in pharmaceutical research, particularly due to its potential in slowing down the aging process (Johnson, 2007; Baur & Sinclair, 2006). Furthermore, resveratrol has been highlighted for its positive effects on cardiovascular health (Brown et al., 2024; Ghanim et al., 2010). Studies suggest that resveratrol may delay the aging process of cells and reduce the risk of heart, diabetic diseases and cancer (Baur & Sinclair, 2006; Ozdemir & Tuzcu, 2015).

**Lignans:** Lignans, especially those that interact with the gut microbiota, exhibit antioxidant and hormone-regulating effects (Rasouli et al., 2017). Lignans play a significant role in the prevention of hormone-related cancers, such as prostate cancer (Adlercreutz et al., 2007). Additionally, lignans have been shown to be effective in preventing diabetes and cardiovascular diseases (Madsen et al., 2014; van der Velde et al., 2016).

- **Polyphenols** (e.g., flavonoids, phenolic acids, tannins)
- **Terpenoids** (e.g., carotenoids, limonoids)
- **Alkaloids** (e.g., caffeine, morphine)



- **Sulfur-containing compounds** (e.g., glucosinolates, allyl sulfides)

Each of these classes has specific mechanisms of action that contribute to their health-promoting effects. For instance, terpenoids, known for their lipid solubility, play essential roles in cell membrane stability and immune modulation. Alkaloids exhibit various physiological effects and are often potent due to their interactions with neurotransmitters (Molyneux et al., 2007; Tilkat et al., 2024).

## 1.2. Biological Roles of Phytochemicals

Phytochemicals serve as part of the plant defense mechanisms, providing protection against environmental stress, UV radiation, and pathogens (Johnson, 2007; Shubayr 2023). These compounds enhance the survival abilities of plants while offering numerous health benefits for humans (Gohil & Patel, 2019). Phytochemicals confer health benefits through mechanisms such as antioxidant, anti-inflammatory, detoxification, and anticancer effects (D'Angelo, 2020).

**Antioxidant Effects:** Phytochemicals neutralize free radicals effectively, preventing lipid peroxidation in cell membranes (Rasouli et al., 2017; Manach et al., 2004). This reduces the harmful effects of oxidative stress and delays aging. Flavonoids and stilbenes, in particular, stand out with their antioxidant properties, playing an essential role in preventing cancer and heart diseases (Li et al., 2016; Gohil & Patel, 2019).

**Anti-inflammatory Effects:** The anti-inflammatory effects of phytochemicals arise from the suppression of inflammation markers in cells. Compounds such as flavonoids and terpenoids reduce inflammation by inhibiting the production of pro-inflammatory cytokines (D'Angelo, 2020; Gohil & Patel, 2019). Additionally, these compounds have been reported to modulate the immune system and regulate immune responses (Johnson, 2007; Li et al., 2016).

**Detoxification and Anticancer Effects:** Some phytochemicals promote detoxification enzymes, helping eliminate accumulated harmful substances in the body. Compounds such as organosulfur compounds and stilbenes reduce the effects of carcinogens and prevent the development of cancer (Firuzi et al., 2017; Gohil & Patel, 2019). Numerous studies have shown the anticancer

effects of phytochemicals, particularly those abundant in fruits and vegetables, on cancer cells (Ayaz et al., 2022; Cao et al., 2017).

### **1.3. Bioavailability and Metabolism of Polyphenols**

The bioavailability of polyphenols is limited by the absorption processes in the gastrointestinal system. For these compounds to be effectively utilized in the body, their metabolic conversion by the gut microbiota is crucial (Rasouli et al., 2017; Scalbert et al., 2005). Polyphenols are typically metabolized in the gut and liver, with their metabolites entering the bloodstream to exert biological effects in target tissues (Firuza et al., 2017; Luca et al., 2020; Manach et al., 2004).

**Limitations of Bioavailability:** Although polyphenols generally have low bioavailability, the gut microbiota can enhance their biological activity (D'Angelo, 2020). Microbial metabolism facilitates the conversion of polyphenols into active metabolites, thereby enhancing their biological effects. Therefore, the presence of a healthy gut microbiota is vital for the effectiveness of polyphenols and phytochemicals (Rasouli et al., 2017).

**Metabolism and Effects:** Once metabolized, polyphenols typically reach biological targets and affect molecular mechanisms within cells. In particular, phenolic acids and flavonoids exhibit antioxidant and anti-inflammatory effects, showing health benefits (Manach et al., 2004; Upadhyay & Dixit, 2015). Additionally, some polyphenols inhibit cell growth, preventing the proliferation of cancer cells (Johnson, 2007; Zhao et al., 2018).

## **2. EFFECTS OF POLYPHENOLS ON HEALTH**

### **2.1 Antioxidant Mechanisms**

Polyphenols prevent cellular damage by neutralizing reactive oxygen species (ROS). ROS induce oxidative stress in cells, leading to oxidative damage to DNA, lipids, and proteins. Polyphenols effectively neutralize these free radicals, reducing oxidative damage and helping cells remain healthy (Cao et al., 2017; Upadhyay & Dixit, 2015). Additionally, polyphenols enhance the activity of endogenous antioxidant enzymes, strengthening the body's defense mechanisms. Antioxidant enzymes such as glutathione peroxidase, superoxide dismutase, and catalase are activated by polyphenols, contributing to the prevention of oxidative damage (Erten et al., 2024; Scalbert et al., 2005). It has

been shown that compounds like flavonoids increase the activity of these enzymes, thereby preventing cellular damage (Manach et al., 2004; Rasouli et al., 2017). These mechanisms play a significant role in preventing the development of diseases such as cardiovascular diseases and cancer. Maintaining low oxidative stress improves overall health and delays the aging process (Rasouli et al., 2017; Yang et al., 2024).

## **2.2 Anti-inflammatory Properties**

Polyphenols inhibit enzymes that play a key role in the inflammatory process, thereby reducing inflammation. Inhibition of enzymes such as cyclooxygenase-2 (COX-2) and nuclear factor kappa B (NF- $\kappa$ B) constitutes the primary mechanism behind the anti-inflammatory effects of polyphenols (D'Angelo, 2020; Johnson, 2007; Orhan et al., 2022). These compounds, particularly flavonoids and stilbenes, reduce the production of inflammation markers and regulate the immune system (Baur & Sinclair, 2006; Li et al., 2016). It has been demonstrated that compounds such as quercetin and resveratrol suppress the production of inflammatory cytokines, indicating their crucial role in preventing various diseases through their anti-inflammatory effects (D'Angelo, 2020; Liu et al., 2023). Quercetin, in particular, is emerging as a potential agent in the treatment of inflammation-related diseases such as asthma, arthritis, and cardiovascular diseases (Gohil & Patel, 2019). These mechanisms demonstrate that polyphenols play a protective role not only against oxidative stress but also against inflammation (Wu et al., 2021).

## **2.3 Prevention of Cardiovascular Diseases**

Polyphenols inhibit enzymes that play a key role in the inflammatory process, thereby reducing inflammation. Inhibition of enzymes such as cyclooxygenase-2 (COX-2) and nuclear factor kappa B (NF- $\kappa$ B) constitutes the primary mechanism behind the anti-inflammatory effects of polyphenols (D'Angelo, 2020; Johnson, 2007). These compounds, particularly flavonoids and stilbenes, reduce the production of inflammation markers and regulate the immune system (Baur & Sinclair, 2006; Li et al., 2016). It has been demonstrated that compounds such as quercetin and resveratrol suppress the production of inflammatory cytokines, indicating their crucial role in preventing various diseases through their anti-inflammatory effects (D'Angelo, 2020; Liu et al., 2023). Quercetin, in particular, is emerging as a potential agent

in the treatment of inflammation-related diseases such as asthma, arthritis, and cardiovascular diseases (Gohil & Patel, 2019). These mechanisms demonstrate that polyphenols play a protective role not only against oxidative stress but also against inflammation (Wu et al., 2021).

## **2.4. Management of Diabetes and Metabolic Syndrome**

Polyphenols play a crucial role in the management of diabetes and metabolic syndrome. These compounds have been shown to increase insulin sensitivity and regulate glucose metabolism, helping balance blood sugar levels (D'Angelo, 2020; Gohil & Patel, 2019). Specifically, epigallocatechin gallate (EGCG) enhances the expression of glucose transporter-4 (GLUT-4), promoting glucose uptake in cells and supporting cellular energy balance (Johnson, 2007). This mechanism contributes to the improvement of insulin resistance and normalizes blood sugar levels.

Moreover, polyphenols may aid in the treatment of metabolic syndrome by increasing the oxidation of free fatty acids. Polyphenols enhance insulin effectiveness, providing significant support in the management of diabetes. In individuals with metabolic syndrome, polyphenols have been shown to have beneficial effects on body weight, blood sugar levels, and lipid profiles (Firuzi et al., 2017). These effects highlight the important role of polyphenols in the management of diabetes and metabolic syndrome (Gasmi et al., 2022; Li et al., 2016).

## **3. CANCER AND POLYPHENOLS**

### **3.1. Cancer Prevention: Epidemiological Data**

There is strong evidence that diet plays a crucial role in cancer prevention. Numerous epidemiological studies have shown that diets rich in polyphenols reduce the risk of various types of cancer. Individuals with high fruit and vegetable consumption are found to have a lower risk of developing cancers, especially breast, colon, lung, and stomach cancers (Johnson, 2007; Rasouli et al., 2017). According to the World Cancer Research Fund, plant-based diets can reduce the overall risk of cancer by up to 30% (Rasouli et al., 2017). Studies emphasize that a diet enriched with polyphenols, particularly compounds with anticancer properties, is a significant factor in cancer prevention (Li et al., 2016). Moreover, polyphenols derived from fruits and

vegetables have been shown to enhance the ability of cells to repair DNA damage and inhibit the proliferation of cancer cells (Cao et al., 2017).

### **3.2. Cellular and Molecular Mechanisms**

Polyphenols target multiple stages of the cancer development process. These compounds exhibit various biological mechanisms to prevent the growth and spread of cancer cells (Briguglio et al., 2020).

#### **3.2.1. Suppression of Tumor Cell Proliferation**

Polyphenols can halt the uncontrolled proliferation of tumor cells by targeting cell cycle regulatory proteins. For example, resveratrol suppresses the expression of cyclin D1 and cyclin E proteins, blocking the G1-S transition and preventing tumor cell division (Upadhyay & Dixit, 2015; Li et al., 2016). Other polyphenols, such as flavonoids, can also affect other stages of the cell cycle to inhibit the growth of cancer cells (Briguglio et al., 2020; Manach et al., 2004).

#### **3.2.2. Induction of Apoptosis**

Polyphenols induce programmed cell death (apoptosis) to eliminate cancer cells. Epigallocatechin gallate (EGCG) increases the expression of Bax proteins while suppressing anti-apoptotic proteins such as Bcl-2, thereby promoting apoptosis in cancer cells (D'Angelo, 2020; Johnson, 2007). This mechanism prevents cancer cell survival and tumor growth. Additionally, polyphenols repair DNA damage by correcting genetic alterations in cancer cells (Baur & Sinclair, 2006). The increased apoptosis process represents a promising approach in cancer treatment, and polyphenols can effectively modulate these processes (Cháirez-Ramírez et al., 2021; Gohil & Patel, 2019).

#### **3.2.3. Inhibition of Angiogenesis and Metastasis**

Angiogenesis (formation of new blood vessels) and metastasis are crucial processes in cancer progression that are inhibited by polyphenols. EGCG suppresses the expression of vascular endothelial growth factor (VEGF), preventing the formation of blood vessels within tumors (Rasouli et al., 2017). This effect of EGCG reduces the metastatic potential of cancer and prevents the spread of tumors in the body (Li et al., 2016). Additionally, polyphenols can alter the tumor microenvironment where cancer cells interact, thus preventing

the metastatic process (Baur & Sinclair, 2006). Inhibition of angiogenesis is considered a potential strategy in cancer therapy (Liu et al., 2023).

### **3.3. Polyphenol-Based Therapies: Resveratrol, EGCG, and More**

Polyphenols show promise as complementary or preventive agents in cancer treatment. The various effects these compounds exert on cancer cells make them valuable in supporting cancer therapy (Dehelean et al., 2021; Sauter et al., 2020).

#### **3.3.1. Resveratrol**

Resveratrol activates the p53 gene, enhancing tumor-suppressing mechanisms. P53 is a key tumor suppressor gene that regulates the cell cycle and repairs DNA damage. Resveratrol also helps protect healthy cells by reducing oxidative stress (Johnson, 2007; Baur & Sinclair, 2006). This mechanism prevents the proliferation of cancer cells and prevents them from developing resistance to treatment. Additionally, resveratrol affects intracellular signaling pathways to slow cancer cell growth and inhibit metastasis (Behroozaghdam et al., 2022; Upadhyay & Dixit, 2015).

#### **3.3.2. Epigallocatechin Gallate (EGCG)**

EGCG, a polyphenol derived from green tea, has numerous beneficial effects in cancer treatment. EGCG reduces DNA damage in cancer cells and triggers apoptosis mechanisms (D'Angelo, 2020; Ozdemir, 2020). Additionally, EGCG's antioxidant properties neutralize free radicals in cells, thus inhibiting the growth of cancer cells (Li et al., 2016). Clinical studies have demonstrated that EGCG prevents the spread of metastatic cells and may assist in cancer treatment (Manach et al., 2004).

#### **3.3.3. Curcumin**

Curcumin, the active compound in turmeric, is recognized for its anti-inflammatory effects. This compound suppresses inflammation and modulates immune cells in the tumor microenvironment (Tuzcu et al., 2024; Upadhyay & Dixit, 2015; Johnson, 2007). Curcumin may also induce genetic and epigenetic changes that prevent the spread of cancer cells. Moreover, curcumin is being

explored as a potential therapeutic agent in cancer treatment by enhancing immune cell activation within the tumor microenvironment (Li et al., 2016).

## **4. The Role of Polyphenols in the Food Industry**

### **4.1. Use as Antioxidants**

In the food industry, polyphenols are commonly used to slow down oxidation, thereby extending the shelf life of products. Oxidation leads to the deterioration of lipids, changes in color, loss of flavor, and a decrease in nutritional value in food products. In this context, polyphenols, as natural antioxidants, help preserve the freshness and quality of food, particularly by preventing the degradation of fats (Rasouli et al., 2017; Li et al., 2016). Flavonoids and other phenolic compounds increase the stability of food products due to their ability to neutralize free radicals (Manach et al., 2004). Polyphenols are frequently used in the food industry, especially in ready-made meals, beverages, and snacks, to maintain quality (Johnson, 2007). Another study has shown that green tea polyphenols extend the shelf life of food products by inhibiting microbial activity (Heimler et al., 2018).

### **4.2. Contribution to Extending the Shelf Life of Food**

Polyphenols not only prevent oxidation but also inhibit microbial growth, thus preventing food spoilage. This property is especially significant in the meat, dairy, and fruit and vegetable processing industries. For instance, extracts from grape skins and seeds have been shown to inhibit both oxidation and microbial growth in meat products, significantly extending their shelf life (D'Angelo, 2020; Rahman et al., 2020). Additionally, tea polyphenols have been shown to prevent the growth of pathogenic microorganisms in meat and fish products, helping these items remain fresh for longer (Rasouli et al., 2017). These polyphenols also contribute to preserving the taste, color, and texture of food products, thus enhancing food safety (Zhao et al., 2015; Li et al., 2016).

### **4.3. Functional Foods and Health Supplements**

Functional foods contain biologically active components that offer health benefits and are often enriched with polyphenols. Polyphenols impart antioxidant, anti-inflammatory, and immune-boosting properties to these foods (Johnson, 2007; Fernandes et al., 2020; Ozdemir, 2024). When combined with probiotics, polyphenols improve gut health and strengthen the immune system.

Studies have shown that polyphenol-enriched foods, supplemented with probiotics, enhance digestive health, regulate immune responses, and increase the body's resistance to diseases (D'Angelo, 2020; Gänzle, 2015). Furthermore, polyphenols may play a crucial role in the prevention of cardiovascular diseases, diabetes, and certain types of cancer (Manach et al., 2004; Lopes et al., 2020). These properties ensure the widespread use of polyphenols in the functional food and health supplement industries (Basu & Rhim, 2020).

#### **4.4. Polyphenols and Food Processing**

Food processing is an important factor that can affect the biological activity of polyphenols. Environmental factors such as heat, light, and oxygen can cause chemical changes in polyphenols, potentially limiting their benefits (Chen et al., 2017). For example, elevated temperatures can disrupt the structural integrity of flavonoids, leading to a reduction in their antioxidant capacity (Müller et al., 2021). However, some polyphenols, especially phenolic acids and flavonoids, are more resistant to high temperatures and can maintain their activity to some extent during food processing (Xu et al., 2020).

Furthermore, polyphenols' efficiency in food processing, such as in the extraction of fruit and vegetable essences, depends on the extraction methods used. Different solvents, such as water, alcohol, and organic solvents, can affect the polyphenol content and biological activities to varying degrees (Jahanbakhshi et al., 2019). Advanced techniques such as high-performance liquid chromatography (HPLC) are effective for maximizing polyphenol yield during extraction, offering more efficient processing possibilities in the food industry (Vivas et al., 2018).

Additionally, polyphenols in food processing can have direct health effects as functional foods. For example, in fermented foods, polyphenols may interact with microorganisms to exhibit probiotic properties (Bermúdez-Brito et al., 2012). This highlights the potential of food processing technologies to interact with and enhance polyphenols' effectiveness (Kasote et al., 2021).

#### **4.5. Polyphenols and Food Safety**

Polyphenols not only improve food quality and nutritional value but also enhance food safety. Food safety is a critical area for preventing potential hazards caused by microorganisms in food products. Polyphenols possess antimicrobial properties and can inhibit the growth of pathogenic bacteria



(Lopez et al., 2018; Ozdemir et al., 2022, 2023). For example, grape seed extracts have been shown to provide effective protection against pathogens such as *Salmonella* and *Escherichia coli* in meat products (González-Aguilar et al., 2018). Moreover, polyphenols can help prevent foodborne illnesses, thereby improving food safety.

The antimicrobial properties of polyphenols are primarily attributed to their ability to prevent microbial proliferation and inhibit toxin production. This characteristic makes polyphenols viable as natural preservatives in the food industry (Ozdemir et al., 2024; Nabavi et al., 2015). As a result, polyphenols not only improve food quality but also support the production of healthy and safe food (de Araújo et al., 2021).

## **5. Potential Health Applications of Polyphenols**

### **5.1. Polyphenols and Potential Applications in Cancer Treatment**

Polyphenols hold promising potential in cancer treatment. They can play a significant role at various stages, from early detection to therapy. Recent studies have increasingly focused on the clinical potential of polyphenols in cancer treatment. While cancer treatment traditionally relies on methods such as surgery, chemotherapy, and radiotherapy, polyphenols may offer alternative treatment options that target tumor cells with fewer invasive procedures and reduced side effects (Briguglio et al., 2020; Montané et al., 2020; Rogovskii et al., 2022).

### **5.2. Polyphenols and Inhibition of Cancer Cell Proliferation**

Polyphenols inhibit the proliferation of cancer cells and suppress tumor growth. These effects occur by influencing cell cycle regulators, halting the uncontrolled division of cancer cells. Compounds such as resveratrol, EGCG, and curcumin have been shown to play a role in inhibiting proliferation in tumor cells (D'Angelo, 2020). These compounds prevent cancer cells from dividing by inhibiting regulators such as cyclin D1 and p21 in the G1 phase of the cell cycle (D'costa et al., 2023).

### **5.3. Polyphenols and Induction of Apoptosis**

Apoptosis, the programmed cell death process, is a key target in cancer therapy as inducing this process can limit tumor growth. Polyphenols can

trigger apoptosis through various mechanisms. For example, compounds such as EGCG and resveratrol reduce the expression of anti-apoptotic proteins like Bcl-2 and increase the levels of pro-apoptotic proteins like Bax. This effect promotes cell death and prevents the survival of cancer cells (Upadhyay & Dixit, 2015). Moreover, polyphenols can enhance apoptosis by activating tumor suppressor genes such as p53 (Chimento et al., 2023).

#### **5.4. Polyphenols and Angiogenesis Inhibition**

The progression of cancer is closely linked to angiogenesis, the formation of new blood vessels. Polyphenols can be effective at this critical stage of cancer. Compounds like EGCG inhibit vascular endothelial growth factor (VEGF), preventing tumor cells from forming new blood vessels (Rasouli et al., 2017). Additionally, compounds such as curcumin and quercetin have been shown to exert inhibitory effects on angiogenesis (Hasan et al., 2022).

#### **5.5. Polyphenols and Inhibition of Metastasis**

Polyphenols are also effective in the metastasis phase of cancer. Metastasis, the spread of cancer cells from the primary tumor to other parts of the body, is one of the most challenging aspects of cancer treatment. Polyphenols can inhibit the mobility of cancer cells and reduce the invasion of tumor cells into surrounding tissues by inhibiting matrix metalloproteinases (MMPs), thereby preventing metastasis (Johnson, 2007).

#### **5.6. Polyphenols and Effects on the Immune System**

Immune system modulation is another important strategy in cancer treatment. Polyphenols can enhance immune system activity, boosting the action of cancer-fighting cells. Resveratrol and EGCG promote the activation of T cells and help macrophages recognize and eliminate cancer cells (D'Angelo, 2020). Furthermore, polyphenols may regulate inflammation, preventing cancer cells from evading immune surveillance (Huang et al., 2022).

#### **5.7. Polyphenols and Clinical Applications: Current Status and Future Perspectives**

Polyphenols are being investigated as complementary treatments in clinical settings. Specifically, their use alongside chemotherapy and

radiotherapy may offer additional therapeutic benefits. Recent clinical trials confirm the potential of polyphenols in cancer treatment, but further research is needed to fully establish their efficacy and safety (Rasouli et al., 2017; Sharma et al., 2022).

## **6. Polyphenols and Reaction Mechanisms**

### **6.1. Polyphenols and Enzymes: Their Interactions**

Polyphenols are compounds with numerous biological effects, interacting with various enzymes in the body. These interactions play a crucial role in the regulation of the biological activities of polyphenols. Enzymes like polyphenol oxidase (PPO) catalyze the oxidation of polyphenols, often leading to physical changes such as color alteration and degradation. This process is particularly important in controlling the oxidation of fruits and vegetables in the food industry (Rasouli et al., 2017). PPO accelerates the oxidation of polyphenols, causing browning and potentially affecting the quality of food products (Kaya et al., 2024a; Kaya et al., 2024b).

Additionally, polyphenols demonstrate beneficial health effects by inhibiting certain enzymes. For example, polyphenols affect numerous enzymatic mechanisms that play significant roles in cancer prevention. Flavonoids, by inhibiting enzymes like cyclooxygenase (COX) and lipoxygenase (LOX), can reduce inflammation and inhibit the proliferation of cancer cells (D'Angelo, 2020). Furthermore, polyphenols regulate various biological processes by influencing intracellular signaling pathways, thereby enhancing their antioxidant, anticancer, and anti-inflammatory properties (Upadhyay and Dixit, 2015).

### **6.2. Polyphenols and Metabolism**

Polyphenols do not typically exist in the body in their free form. Upon ingestion, they undergo various biotransformations in the gastrointestinal system. Initially, polyphenols are absorbed in the stomach and small intestine, then metabolized in the liver. During this process, polyphenols are converted into conjugates (glucuronates, sulfates, and methyl groups), thereby increasing their bioavailability and converting them into more active metabolites (Rasouli et al., 2017).

The metabolism of polyphenols involves the role of various microorganisms that either activate them or modulate their biological effects.

The gut microbiota plays a significant role in the biotransformation of polyphenols. Polyphenols are converted by the bacteria in the intestines into smaller and more active metabolites. For instance, flavonoids such as quercetin and kaempferol are rapidly metabolized by the gut microbiota, and these metabolites may exhibit very different biological activities compared to the original compounds (D'Angelo, 2020).

Moreover, polyphenols can initiate numerous biochemical reactions in the body and participate in various metabolic pathways that improve health. For example, polyphenols enhance the activity of antioxidant enzymes (glutathione peroxidase and superoxide dismutase), combating cellular stress (Johnson, 2007). Additionally, polyphenols have been shown to increase insulin sensitivity, potentially aiding in the management of metabolic syndrome (Wang et al., 2022a).

### **6.3. Polyphenols and Bioavailability**

Polyphenols exhibit varying effects depending on the absorption and bioavailability processes in the gastrointestinal system. Their bioavailability levels differ based on properties such as water solubility and molecular structure. For instance, polyphenols like flavonoids typically have low bioavailability in the intestine, though certain flavonoid metabolites may have higher bioavailability (D'Angelo, 2020). These differing bioavailability rates can alter the biological effects of polyphenols.

After absorption in the intestines, polyphenols are transported to the liver, where they undergo biotransformation. This metabolic process can influence the strength and duration of the biological effects of polyphenols. Additionally, polyphenols enter conjugation reactions in the liver, transforming into metabolites that enhance their bioavailability. Specifically, glucuronidation and sulfation are key reactions that increase the bioavailability of polyphenols (Upadhyay and Dixit, 2015).

Polyphenols can also be metabolized by interacting with the gut microbiota, producing active metabolites. For example, EGCG from green tea is metabolized by the microbiome, leading to significant changes in its biological effects (Johnson, 2007). The interactions of polyphenols with the gut flora can substantially modulate their health impacts (Catalkaya et al., 2020).

## **7. The Future Role and Importance of Polyphenols**

### **7.1. Potential in Health and Pharmaceutical Industries**

Polyphenols are increasingly being researched for their potential in health applications. Numerous studies have shown that polyphenols exhibit positive effects in the treatment of cardiovascular diseases, diabetes, cancer, and neurological disorders such as Alzheimer's and Parkinson's (Kim et al., 2020). With their free radical scavenging properties, polyphenols provide cellular protection and assist in the regulation of inflammation (Huang et al., 2019). In recent years, research on polyphenols derived from plant sources, particularly green tea and grape seeds, has demonstrated their potential for use in pharmaceutical formulations.

Polyphenols are gaining attention not only as natural therapeutic agents but also as potential treatment options in the pharmaceutical industry. For instance, compounds like resveratrol and quercetin, which inhibit the growth of cancer cells and prevent metastasis, show promise in cancer treatment (Rasouli et al., 2020). Furthermore, polyphenols may play a neuroprotective role in Alzheimer's disease by protecting brain cells (Chen et al., 2018).

### **7.2. Role in the Food Industry**

Polyphenols are increasingly utilized in the food industry. They play an important role as natural antioxidants to extend the shelf life of food products and enhance their nutritional value (Patel et al., 2021). The antioxidant properties of polyphenols help prevent oxidation during food processing and preserve food quality. Additionally, polyphenols contribute aesthetic qualities such as taste, aroma, and color, making them attractive for food production.

Functional food production aims to design foods that promote health. Polyphenols, when combined with probiotics, can enhance immune function and improve gut health (Al-Solumani et al., 2020). Additionally, polyphenols function as food additives in the food industry, providing a wide range of applications. Various studies suggest that polyphenols can be used as substitutes for sugar, contributing to the production of low-calorie foods (Chang et al., 2021).

### **7.3. Agriculture and Sustainability**

In agriculture, polyphenols may help reduce pesticide use and promote organic farming practices. Polyphenols strengthen plant defense mechanisms, providing natural protection against pests (Wang et al., 2018). This holds significant potential for environmental sustainability.

The use of polyphenols in agricultural production not only serves as an eco-friendly alternative but also plays a crucial role in improving plant health and increasing productivity. Research has shown that polyphenol-rich plants are more resistant to diseases and pests, and the quality of products derived from these plants is enhanced (Singh et al., 2020).

## **8. CONCLUSION**

As one of the most important phytochemicals found in nature, polyphenols exhibit a broad range of positive effects on health. These compounds are gaining increasing importance in scientific literature due to their antioxidant properties, anti-inflammatory effects, roles in preventing cardiovascular diseases, and potential contributions to the treatment of chronic diseases such as cancer. Recent research highlights the need for further exploration into polyphenols, as a deeper understanding of their biological activities presents significant potential for health applications (Johnson, 2007; Patel et al., 2021; Upadhyay and Dixit, 2015).

Polyphenols not only offer health benefits but also hold a significant place in the food industry. They are used as natural antioxidants to extend the shelf life of food products, prevent oxidation, and improve food quality (Rasouli et al., 2017). Moreover, in functional food production and health supplements, polyphenols enhance nutritional value and strengthen the immune system (Johnson, 2007).

Furthermore, the use of polyphenols in agriculture offers important opportunities for environmental sustainability and reducing pesticide use. By strengthening plant defense mechanisms, polyphenols contribute to increased agricultural productivity while promoting eco-friendly practices (Wang et al., 2018; Wang et al., 2022b).

Research into polyphenols and other phytochemicals is expected to make significant contributions to the development of more effective and natural therapeutic methods, as well as improving applications in the pharmaceutical

and food industries. Gaining further insight into the bioavailability, metabolism, and reaction mechanisms of these compounds will enable their broader use in health and food sectors.

In conclusion, polyphenols possess great potential in health, agriculture, and the food industry. However, to fully realize this potential, more clinical and epidemiological studies are required, and a better understanding of the biological effects of these compounds is essential. Future research will further solidify the role of polyphenols in these areas and increase their contributions to human health.

## REFERENCES

- Adeeyo, A. O., Ndou, T. M., Alabi, M. A., Mkoyi, H. D., Enitan, E. M., Beswa, D., ... & Odiyo, J. O. (2021). Structure: Activity and emerging applications of spices and herbs. In: R.S. Ahmad (ed.). Herbs and spices-new processing technologies. Intechopen.
- Al-Khayri, J. M., Rashmi, R., Toppo, V., Chole, P. B., Banadka, A., Sudheer, W. N., ... & Rezk, A. A. S. (2023). Plant secondary metabolites: The weapons for biotic stress management. *Metabolites*, 13(6), 716.
- Alqarni, S., Alsebai, M., Alsaigh, B. A., Alrashedy, A. S., Albahrani, I. T., Aljohar, A. Y., & Alazmi, A. O. (2024). Do polyphenols affect body fat and/or glucose metabolism?. *Frontiers in Nutrition*, 11, 1376508.
- Alsawaf, S., Alnuaimi, F., Afzal, S., Thomas, R. M., Chelakkot, A. L., Ramadan, W. S., ... & Vazhappilly, C. G. (2022). Plant flavonoids on oxidative stress-mediated kidney inflammation. *Biology*, 11(12), 1717.
- Ayaz, M., Nawaz, A., Ahmad, S., Mosa, O. F., Eisa Hamdoon, A. A., Khalifa, M. A., ... & Ananda Murthy, H. C. (2022). Underlying anticancer mechanisms and synergistic combinations of phytochemicals with cancer chemotherapeutics: potential benefits and risks. *Journal of Food Quality*, 1, 1189034.
- Baskar, R., et al.. 2017. Polyphenols in Cancer Chemoprevention: Molecular Mechanisms and Therapeutic Opportunities. *International Journal of Molecular Sciences*, 18(4), 924.
- Behl, T., Bungau, S., Kumar, K., Zengin, G., Khan, F., Kumar, A., ... & Mosteanu, D. E. (2020). Pleiotropic effects of polyphenols in cardiovascular system. *Biomedicine & Pharmacotherapy*, 130, 110714.
- Behroozaghdam, M., Dehghani, M., Zabolian, A., Kamali, D., Javanshir, S., Hasani Sadi, F., ... & Bishayee, A. (2022). Resveratrol in breast cancer treatment: from cellular effects to molecular mechanisms of action. *Cellular and Molecular Life Sciences*, 79(11), 539.
- Briguglio, G., Costa, C., Pollicino, M., Giambò, F., Catania, S., & Fenga, C. (2020). Polyphenols in cancer prevention: New insights. *International Journal of Functional Nutrition*, 1(2), 1-1.
- Brown, K., Theofanous, D., Britton, R. G., Aburido, G., Pepper, C., Sri Undru, S., & Howells, L. (2024). Resveratrol for the management of human health: how far have we come? A systematic review of resveratrol clinical trials to highlight gaps and opportunities. *International Journal of Molecular Sciences*, 25(2), 747.
- Catalkaya, G., Venema, K., Lucini, L., Rocchetti, G., Delmas, D., Daglia, M., ... & Capanoglu, E. (2020). Interaction of dietary polyphenols and gut microbiota: Microbial metabolism of polyphenols, influence on the gut



- microbiota, and implications on host health. *Food Frontiers*, 1(2), 109-133.
- Cháirez-Ramírez, M. H., de la Cruz-López, K. G., & García-Carrancá, A. (2021). Polyphenols as antitumor agents targeting key players in cancer-driving signaling pathways. *Frontiers in pharmacology*, 12, 710304.
- Chimento, A., De Luca, A., D'Amico, M., De Amicis, F., & Pezzi, V. (2023). The involvement of natural polyphenols in molecular mechanisms inducing apoptosis in tumor cells: A promising adjuvant in cancer therapy. *International Journal of Molecular Sciences*, 24(2), 1680.
- Cote, B., Elbarbry, F., Bui, F., Su, J. W., Seo, K., Nguyen, A., ... & Rao, D. A. (2022). Mechanistic basis for the role of phytochemicals in inflammation-associated chronic diseases. *Molecules*, 27(3), 781.
- Çetinkaya, S., Akça, K. T., & Süntar, I. (2022). Flavonoids and anticancer activity: Structure–activity relationship. *Studies in Natural Products Chemistry*, 74, 81-115.
- D'Angelo, A. (2020). *Phytochemicals and Their Role in Human Health*. Elsevier.
- D'costa, M., Bothe, A., Das, S., Kumar, S. U., Gnanasambandan, R., & Doss, C. G. P. (2023). CDK regulators—Cell cycle progression or apoptosis—Scenarios in normal cells and cancerous cells. *Advances in Protein Chemistry and Structural Biology*, 135, 125-177.
- de Araújo, F. F., de Paulo Farias, D., Neri-Numa, I. A., & Pastore, G. M. (2021). Polyphenols and their applications: An approach in food chemistry and innovation potential. *Food chemistry*, 338, 127535.
- Dehelean, C. A., Marcovici, I., Soica, C., Mioc, M., Coricovac, D., Iurciuc, S., ... & Pinzaru, I. (2021). Plant-derived anticancer compounds as new perspectives in drug discovery and alternative therapy. *Molecules*, 26(4), 1109.
- Erten, F., Ozdemir, O., Tokmak, M., Durmus, A. S., Ozercan, I. H., Morde, A., ... & Sahin, K. (2024). Novel formulations ameliorate osteoarthritis in rats by inhibiting inflammation and oxidative stress. *Food Science & Nutrition*, 12(10), 7896-7912.
- Fatima, N., Baqri, S. S. R., Alsulimani, A., Fagoonee, S., Slama, P., Kesari, K., ... & Haque, S. (2021). Phytochemicals from Indian ethnomedicines: Promising prospects for the management of oxidative stress and cancer. *Antioxidants*, 10(10), 1606.
- Garcia, D., et al. 2018. Antioxidant Properties of Polyphenols: A Critical Review.” *Journal of Agricultural and Food Chemistry*, 66:1021-1031.

- Gasmi, A., Mujawdiya, P. K., Noor, S., Lysiuk, R., Darmohray, R., Piscopo, S., ... & Bjørklund, G. (2022). Polyphenols in metabolic diseases. *Molecules*, 27(19), 6280.
- Hasan, A. A., Tatarskiy, V., & Kalinina, E. (2022). Synthetic pathways and the therapeutic potential of quercetin and curcumin. *International Journal of Molecular Sciences*, 23(22), 14413.
- Huang, X., Wang, Y., Yang, W., Dong, J., & Li, L. (2022). Regulation of dietary polyphenols on cancer cell pyroptosis and the tumor immune microenvironment. *Frontiers in Nutrition*, 9, 974896.
- Javed, Z., Sadia, H., Iqbal, M. J., Shamas, S., Malik, K., Ahmed, R., ... & Sharifi-Rad, J. (2021). Apigenin role as cell-signaling pathways modulator: implications in cancer prevention and treatment. *Cancer Cell International*, 21, 1-11.
- Johnson, J. 2007. The health benefits of phytochemicals: evidence from epidemiological and experimental studies. *Journal of Nutritional Biochemistry*, 18: 577-582.
- Kasote, D., Tiozon Jr, R. N., Sartagoda, K. J. D., Itagi, H., Roy, P., Kohli, A., ... & Sreenivasulu, N. (2021). Food processing technologies to develop functional foods with enriched bioactive phenolic compounds in cereals. *Frontiers in plant science*, 12, 771276.
- Kaya, M. O. et al. "Rational Design, Synthesis, and Computational Investigation of Dihydropyridine [2, 3-d] Pyrimidines as Polyphenol Oxidase Inhibitors with Improved Potency." *The Protein Journal* 43.4 (2024a): 869-887.
- Kaya, M. O., Kerimak-Öner, M. N., Demirci, T., Musatat, A. B., Özdemir, O., Kaya, Y., & Arslan, M. (2024). Rational design, synthesis, and computational investigation of dihydropyridine [2, 3-d] pyrimidines as polyphenol oxidase inhibitors with improved potency. *The Protein Journal*, 43(4), 869-887.
- Kim, M., et al. 2021. Health benefits and mechanisms of polyphenol consumption: A review of recent clinical trials. *Nutrients*, 13: 1165.
- Kim, K., Song, M., Liu, Y., & Ji, P. (2022). Enterotoxigenic *Escherichia coli* infection of weaned pigs: Intestinal challenges and nutritional intervention to enhance disease resistance. *Frontiers in immunology*, 13, 885253.
- Kumar, S., Korra, T., Thakur, R., Arutselvan, R., Kashyap, A. S., Nehela, Y., ... & Keswani, C. (2023). Role of plant secondary metabolites in defence and transcriptional regulation in response to biotic stress. *Plant Stress*, 8, 100154.

- Liu, Y., et al.. 2020. Polyphenol-rich diets and their role in cancer prevention: An overview. *Critical Reviews in Food Science and Nutrition*, 60(8):1356-1369.
- Liu, W., Cui, X., Zhong, Y., Ma, R., Liu, B., & Xia, Y. (2023). Phenolic metabolites as therapeutic in inflammation and neoplasms: Molecular pathways explaining their efficacy. *Pharmacological research*, 193, 106812.
- Liu, Z. L., Chen, H. H., Zheng, L. L., Sun, L. P., & Shi, L. (2023). Angiogenic signaling pathways and anti-angiogenic therapy for cancer. *Signal transduction and targeted therapy*, 8(1), 198.
- Luca, S. V., Macovei, I., Bujor, A., Miron, A., Skalicka-Woźniak, K., Aprotosoae, A. C., & Trifan, A. (2020). Bioactivity of dietary polyphenols: The role of metabolites. *Critical reviews in food science and nutrition*, 60(4), 626-659.
- Montané, X., Kowalczyk, O., Reig-Vano, B., Bajek, A., Roszkowski, K., Tomczyk, R., ... & Tylkowski, B. (2020). Current perspectives of the applications of polyphenols and flavonoids in cancer therapy. *Molecules*, 25(15), 3342.
- Muscolo, A., Mariateresa, O., Giulio, T., & Mariateresa, R. (2024). Oxidative stress: the role of antioxidant phytochemicals in the prevention and treatment of diseases. *International journal of molecular sciences*, 25(6), 3264.
- Orhan, C., Tuzcu, M., Durmus, A. S., Sahin, N., Ozercan, I. H., Deeh, P. B. D., ... & Sahin, K. (2022). Protective effect of a novel polyherbal formulation on experimentally induced osteoarthritis in a rat model. *Biomedicine & Pharmacotherapy*, 151, 113052.
- Ozdemir, O., & Tuzcu, Z. (2015). Resveratrol attenuates diabetic nephropathy by modulating organic transporters and heat shock proteins in streptozotocin-induced diabetic rats. *Turkish Journal of Nature and Science*, 4, 36-43.
- Ozdemir, O. 2020. The green tea polyphenol EGCG modulates NGF, BDNF, and CaMKII- $\alpha$  pathways to alleviate neurological damage in autism-induced rats." *Acta Poloniae Pharmaceutica - Drug Research* 77 (6):889-895.
- Özdemir, O., Yılmaz, N., Gok, M., & Kaya, M. O. (2022). Determination of antimicrobial and antioxidant activities of *Lavandula angustifolia* volatile oil. *Türkiye Tarımsal Araştırmalar Dergisi*, 9(3), 265-273.
- Özdemir, O., Kaya, M. O., Gok, M., Yılmaz, N., & Tuzcu, Z. (2023). Chloroform-Methanol Extraction Antimicrobial Potential of Rheum

- Ribes Originating from Elazig/Arıcak Province. *Journal of the Institute of Science and Technology*, 13(2), 830-838.
- Özdemir, O. (2024). Vinegar postbiotic solutions obtained from five red fruits processed using traditional methods exhibit different biochemical properties and antimicrobial and antioxidant effects. *Food Science & Nutrition*.
- Özdemir, O., Yılmaz, N., & Kaya, M. O. (2024). The Effect of Rheum ribes Extract Origin of Elazig Province on Ventilator-Associated Pneumonia and Antioxidant Capacity. *Gazi University Journal of Science Part C: Design and Technology*, 12(1), 25-39.
- Patel, D., et al.. 2021. Health implications of polyphenol consumption in chronic disease prevention: A review.” *Frontiers in Nutrition*, 8: 693274.
- Pham, D. C., Shibu, M. A., Mahalakshmi, B., & Velmurugan, B. K. (2020). Effects of phytochemicals on cellular signaling: reviewing their recent usage approaches. *Critical reviews in food science and nutrition*, 60(20), 3522-3546.
- Rasouli, H., et al. 2017. Polyphenols: Health benefits and their mechanisms of action. *Journal of Medicinal Food*, 20(5):458-469.
- Rogovskii, V. (2022). Polyphenols as the potential disease-modifying therapy in cancer. *Anti-Cancer Agents in Medicinal Chemistry-Anti-Cancer Agents*, 22(13), 2385-2392.
- Roy, A., Khan, A., Ahmad, I., Alghamdi, S., Rajab, B. S., Babalghith, A. O., ... & Islam, M. R. (2022). Flavonoids a bioactive compound from medicinal plants and its therapeutic applications. *BioMed Research International*, 2022(1), 5445291.
- Ruhee, R. T., Roberts, L. A., Ma, S., & Suzuki, K. (2020). Organosulfur compounds: A review of their anti-inflammatory effects in human health. *Frontiers in Nutrition*, 7, 64.
- Šamec, D., Karalija, E., Šola, I., Vujčić Bok, V., & Salopek-Sondi, B. (2021). The role of polyphenols in abiotic stress response: The influence of molecular structure. *Plants*, 10(1), 118.
- Santhiravel, S., Bekhit, A. E. D. A., Mendis, E., Jacobs, J. L., Dunshea, F. R., Rajapakse, N., & Ponnampalam, E. N. (2022). The impact of plant phytochemicals on the gut microbiota of humans for a balanced life. *International journal of molecular sciences*, 23(15), 8124.
- Sauter, E. R. (2020). Cancer prevention and treatment using combination therapy with natural compounds. *Expert Review of Clinical Pharmacology*, 13(3), 265-285.
56. Sharma, P., Hajam, Y. A., Kumar, R., & Rai, S. (2022). Complementary and alternative medicine for the treatment of diabetes and associated

- complications: A review on therapeutic role of polyphenols. *Phytomedicine Plus*, 2(1), 100188.
- Shen, N., Wang, T., Gan, Q., Liu, S., Wang, L., & Jin, B. (2022). Plant flavonoids: Classification, distribution, biosynthesis, and antioxidant activity. *Food chemistry*, 383, 132531.
- Phytochemicals properties of herbal extracts for ultraviolet protection and skin health: A narrative review.
- Singh, R., et al.. 2019. Polyphenols as potential functional food components for managing obesity and Type 2 diabetes. *Frontiers in Pharmacology*, 10:1303.
- Teshome, E., Teka, T. A., Nandasiri, R., Rout, J. R., Harouna, D. V., Astatkie, T., & Urugo, M. M. (2023). Fruit by-products and their industrial applications for nutritional benefits and health promotion: a comprehensive review. *Sustainability*, 15(10), 7840.
- Tilkat, E., Jahan, I., Hoşer, A., Kaplan, A., Özdemir, O., & Onay, A. (2024). Anatolian medicinal plants as potential antiviral agents: bridging traditional knowledge and modern science in the fight against COVID-19 and related viral infections. *Turkish Journal of Biology*, 48(4), 218-241.
- Tuzcu, M., Özdemir, O., Orhan, C., Şahin, N., Morde, A., Padigaru, M., ... & Şahin, K. (2024). Beneficial effects of a novel polyherbal formulation on the skeletal muscle antioxidant status, inflammation, and muscle-signaling proteins in exercised rats. *Turkish Journal of Biology*, 48(1), 59-69.
- Ullah, A., Munir, S., Badshah, S. L., Khan, N., Ghani, L., Poulson, B. G., ... & Jaremko, M. (2020). Important flavonoids and their role as a therapeutic agent. *Molecules*, 25(22), 5243.
- Upadhyay, G., & Dixit, A. (2015). Polyphenols: A Comprehensive Review of Their Biological Activities and Applications. *Phytotherapy Research*, 29(5), 675-689.
- Wang, Z., et al. 2018. The role of polyphenols in sustainable agricultural practices. *Agricultural Research*, 7(2): 245-257.
- Wang, L., et al. 2022a. Polyphenols and their impact on cardiovascular health: mechanisms of action and clinical implications. *Journal of Clinical Medicine*, 11: 4432.
- Wang, Shaohui, et al. 2022b. Natural polyphenols: a potential prevention and treatment strategy for metabolic syndrome." *Food & Function* 13(19): 9734-9753.
- Wu, M., Luo, Q., Nie, R., Yang, X., Tang, Z., & Chen, H. (2021). Potential implications of polyphenols on aging considering oxidative stress,

- inflammation, autophagy, and gut microbiota. Critical reviews in food science and nutrition, 61(13), 2175-2193.
- Xiao, J., et al.. 2021. Bioavailability of polyphenols: Effects of dietary and genetic factors on their metabolism and bioefficacy. Food & Function, 12(5):1747-1763.
- Yang, J., Luo, J., Tian, X., Zhao, Y., Li, Y., & Wu, X. (2024). Progress in Understanding Oxidative Stress, Aging, and Aging-Related Diseases. Antioxidants, 13(4), 394.
- Yeshi, K., Crayn, D., Ritmejerytė, E., & Wangchuk, P. (2022). Plant secondary metabolites produced in response to abiotic stresses has potential application in pharmaceutical product development. Molecules, 27(1), 313.



## **CHAPTER 8**

### **EVALUATION OF PHYTOPHTHORA ROOT AND CROWN ROT DISEASES ON ORNAMENTAL PLANTS IN TÜRKİYE**

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## INTRODUCTION

The fungi-like organism *Phytophthora*, appertain to the family Peronosporaceae and Oomycota phylum in the kingdom Stramenopila (Beakes, 2014; Thines and Choi, 2016). *Phytophthora* species are the most devastating group of plant pathogens on tree, ornamentals and crop plant species also in natural ecosystems. *Phytophthora* species are soil-borne pathogens and they lead to root and crown rot in different ornamental plants (Jung et al., 1996). In many studies conducted in Europe and other countries in the world, many *Phytophthora* species have been found to be the cause of root and crown rot in ornamental plants, forest trees in nurseries, greenhouse plants and natural forest areas (Goss et al., 2011; Hulvey et al., 2010; Moralejo et al., 2009; Schwingle et al., 2007; Themann et al., 2002).

Recently, there has been notably increase in *Phytophthora* species, but there is still much uncertainty over taxonomy of *Phytophthora* (Perez-Sierra and Jung, 2013; de Cock and Levesque, 2013). Taxonomy constantly changes with new species being described as molecular identification. Of the approximately 150 *Phytophthora* species identified in woody plants, 66% are reported to be responsible for root rot and more than 90% for crown rot (Kroon et al., 2012; Jung et al., 2011).

The taxonomic categorisation of *Phytophthora* species is based on morphological characters (e.g., colony development, sporangia, oogonia, antheridia, homothallism) (Gallegly and Hong, 2008; Erwin and Ribeiro, 1996). *Phytophthora* species are primarily identified according to their morphology. In addition to morphological identification, molecular identification is also important for *Phytophthora* species. The species have been identified by molecular techniques, reaching a nearly 330 species divided into 12 clades of phylogenetic features (Scott et al., 2019; Matsiakh and Menkis, 2023). There are still many *Phytophthora* species that can not be taxonomically classified and identified to species level. *Phytophthora* taxonomy has turned into molecular techniques for multilocus phylogenies such as using an ITS region (internal transcribed spacer), *coxI* and *coxII* region (cytochrome oxidase genes) (Cooke et al., 2000; Tyler et al., 2006; Kroon et al., 2004; Blair et al., 2008).

Under suitable growth conditions, *Phytophthora* species are mostly isolated from the soil region of diseased plants and to be cause of serious

economic losses in damaged areas (Perez-Sierra and Jung, 2013). *Phytophthora* species cause symptoms such as root and crown rot in many susceptible plants, as well as necrotic areas in root system, drying, wilting of leaves and death of whole plants, but also infect plants without causing symptoms (Ufer et al., 2008). Climatic conditions and plant development taking a very important role in the occurrence of *Phytophthora* infection. The development and sporulation of *Phytophthora* species are accelerated especially in high humidity conditions, hot weather, moist soils and airtight restricted plant growth areas (Donahoo and Lamour, 2008).

*Phytophthora* species induce several disease symptoms in forest trees, woody shrubs, and other ornamental plants all around the world (Jung et al., 2018; Tremblay et al., 2018). In different plant families, pathogens induce damping-off, root rot, aerial bleeding cankers on aerial and green parts of plants (Matsiakh et al., 2021). *P. nicotianae*, *P. cryptogea*, *P. ramorum*, *P. palmivora*, and *P. cinnamomi* infect various woody plants, but some species like *P. lateralis*, *P. quercina* and *P. × alni* infect limited number of hosts (Jung et al., 2018). *Phytophthora* species can be invader and they can appear as the most dangerous non-native pathogens (Santini et al., 2013; Wingfield et al., 2017; Jung et al., 2013). For example *P. acerina* (Ginetti et al., 2013), *P. pini* (Hong et al., 2011), *P. plurivora* (Jung and Burgess, 2009), *P. multivora* (Scott et al., 2009) and are considered pathogenic to a number of woody ornamental plants.

*Phytophthora* species are most particularly known as pathogens of cultivated plants, ornamental plants and especially forest trees. *Phytophthora* species are pathogenic wide range of healthy ornamental plants, forest trees and also widespread in soils. They can do devastating epidemics in the world (Hansen et al., 2015). Evaluations have indicated that more than 90% of trade plants in nearly 700 nurseries in countries of Europe countries is infected by *Phytophthoras* (Jung et al., 2016).

In this review, to aim sum up the learning on *Phytophthora* species related to ornamental plants in Türkiye; the host range of *Phytophthora*, symptoms of damage, pathways of introduction and control methods applied against the species. Through making use of this review, the researchers can be informed potential risks related to *Phytophthora* species on ornamental plants in Türkiye.

## INVESTIGATION OF PHYTOPHTHORA DISEASES ON ORNAMENTAL PLANTS

It is known that Phytophthora diseases cause intense losses in ornamental plants in the world. The world literature on morphological and molecular identification of the causal Phytophthora species is quite well. Recently, Phytophthora species have important rising and the total number of species has exceeded more than 100 (Perez-Sierra and Jung, 2013; de Cock and Levesque, 2013). There are still many Phytophthora species that cannot be taxonomically classified and identified to species level. Many coniferous, deciduous and evergreen ornamental plant species are susceptible to Phytophthora species. Investigation on the epidemiology, pathogenesis of Phytophthora and ecology has focused on limited aggressive pathogens of cultivated plants and devastating pathogens in forests (Grunwald and Flier, 2005; Rizzo et al., 2005).

On global level, determining the risks level of Phytophthora species is highly complex. Through their skills, Phytophthora species induce many infections in different plants and producing hybrids that can be more virulent than their ancestors under certain conditions (Jung et al., 2013). Owing to their multicycling status and a powerful correlation on free water in the soil, Phytophthora species can optimize ornamental plants to biotic and abiotic factors. The presence of aggressive Phytophthora species (*Phytophthora nicotianae*, *P. cambivora*, *P. cryptogea*, *P. cactorum*, *P. plurivora*, *P. palmivora*, *P. cinnamomi*, *P. ramorum*, *P. gonapodyides*, *P. syringae*, *P. pseudosyringae*.) in ornamental plants means that they should be considered as a important threat to ornamental plants in urban, nursery and forest ecosystems.

The abundance of the Phytophthora species found out in forests, nurseries or greenhouses is superior than in nature, that is indicate the potential risks of pathogens with infected nursery plants (Jung et al., 2016; Blomquist, 2016; Redonto, 2018). Actually, nurseries are notable route of accessing invasive Phytophthora species in Europe (Jung et al., 2016; Santini et al., 2018). Infected plants in nursery often show not any symptoms, passing undetected by phytosanitary controls, treating like ‘pathogen reservoirs’ and undertaking the unwitting dispersion of Phytophthora species (Migliorini et al., 2015).

There are many studies from past to present about *P. lateralis* and *P. ramorum*, which are among the first pathogens to be studied *P. lateralis* was first reported in 1942, and after this year, the incidence of infection in

*Chamaecyparis lawsoniana* (Port Oxford Cedar) production areas has increased rapidly. *P. lateralis* was determined by Tucker and Milbradt in 1942. Phylogenetically, *P. lateralis* is the nearest related to *P. ramorum* (Yang et al., 2017; Brasier et al., 2012). *Phytophthora lateralis* is very aggressive to *C. lawsoniana* (Robin et al., 2015; Hansen et al., 2000). The symptoms are chlorosis, wilting, thinning, dieback and eventually death of plants. *P. lateralis* was isolated from necrotic leaves in Britain, this isolation brought to mind aerial infections (Robin et al., 2011; Green et al., 2013). Also, *P. lateralis* was isolated from leaves of *Thuja occidentalis* in Scottish nursery, it is originally imported in nursery from France (Schlenzig et al., 2011). *Phytophthora lateralis* has spread along the natural habitat of *C. lawsoniana* and it leads to destructive decline with high mortality levels (Jules et al., 2002; Jimerson et al., 2001).

*P. ramorum* is one of the most invasive *Phytophthora* species because of its ability to persist, reproduce and spread in ecosystem (Croucher et al., 2013). Infected ornamental plants, like as *Viburnum*, *Rhododendron* and *Camellia*, often conduce to long distance spread of *P. ramorum*. Apart from being a root and crown rot pathogen, *P. ramorum* is also known as a green part pathogen or aerial pathogen. Sudden Oak Death (SOD) is one of the most devastating epidemic of forests in the world caused by *P. ramorum*. Sudden Oak Disease quickly reached epidemic level in forests in California. A wide range of *Notholithocarpus densiflorus* and *Quercus* sp. trees infected by *P. ramorum* and plants demonstrated wilting and high mortality (Goheen et al., 2012). *P. ramorum* is airborne pathogen and it was first isolated from *Viburnum tinus* and *Rhododendron* sp. in Europe (Werres et al., 2001). Comprehensive researchs achieved in recent years, has provided much information about disease biology, aetiology, population structure and host range of *P. ramorum*. *P. ramorum*'s host range has expanded constantly and it has exceeded to almost 150 host species ranging between herbaceous plants to woody shrubs and trees (Grunwald et al., 2012). Pathogen causes symptoms such as root and crown rot, stem rot, aerial cancer, branch and crown dieback, necrotic lesion, shoot blight and leaf lesions in woody ornamental plants (Grunwald et al., 2008). The disease caused by this pathogen was named 'Sudden Larch Death' (SLD) rapidly reached epidemic proportions on Larch trees (*Larix* spp.) (Brasier and Webber, 2010). *P. ramorum* infections have been found on woody plants such as *Castanea sativa*, *Fagus sylvatica*, *Betula pendula*, *Rhododendron ponticum*,

*Nothofagus* spp. and on other conifers such as *Abies grandis*, *A. procera*, *P. menziesii*, *Tsuga heterophylla* and *Picea sitchensis* (Harris and Webber, 2016; Webber et al., 2010; Brasier and Webber, 2010).

*Phytophthora ramorum* and *P. lateralis* have taken their place in research as the most studied species. They are known as root and crown rot pathogens as well as green parts pathogen. *Phytophthora* species causing rots in root and crowns of ornamentals usually cause similar or the same symptoms in host plants. The number of studies on *Phytophthora cinnamomi*, a soil-borne pathogen, is quite high (Balci et al., 2010; Meadows and Jeffers, 2011). *Quercus* sp., *Chamaecyparis lawsoniana*, *Castanea sativa*, , *Abies* sp. (266 genera in 90 families; mostly woody trees) are infected by *P. cinnamomi* (Erwind and Ribeiro, 1996). Since the 1990s, *P. cinnamomi* and many other *Phytophthora* species have been responsible from oak declines in Europe. *P. cinnamomi* is very important species of forest trees, woody ornamentals, especially rhododendrons and other Ericaceae. With the climate change, *P. cinnamomi* has expanded its distribution area especially in Europe and North America and it has caused more damage (Matsiakh and Menkis, 2023). *P. cinnamomi* has been spreaded for more than one century and it has threatened some of the world's richest plant communities (Hardham, 2005; Shearer et al., 2004).

When the studies in the world literature are examined in more detail, besides the identification of *Phytophthora* species, purposes such as revealing the diversity of the species, determining the host range and sensitivity come to the fore. In a study conducted in eastern Spain and the Balearic Islands in 2001-2006, a regional-scale result was reached for *Phytophthora* diseases (Moralejo et al., 2009). Surveys focused on the symptoms of chlorosis, sudden death, shoot death, drying and defoliation associated with root and crown rot infections. 125 isolates were isolated from 37 different host plants and 17 latent species were identified morphologically and molecularly based on rDNA-ITS region, mitochondrial and nuclear gene regions. *P. hedraiaandra*, *P. ramorum*, *P. niederhaueserii*, *P. taxon 'Pgchlamydo'* and *P. kelmania* have been reported, which were not officially reported until 2001. Additionally, 37 new host-pathogen combinations were recorded for the first time. Another study was carried to reveal the *Phytophthora* diversity on forest trees and woody ornamental plants between 2006-2007 in the Czech Republic. In this study,

more than 360 isolates were obtained from 20 plant taxa. 16 *Phytophthora* species have been reported, the most isolated species are *P. plurivora*, *P. cactorum* and *P. alni* (Cerny et al., 2011).

In a study conducted in Italy to investigate the diversity of *Phytophthora* species in potted outdoor ornamental plants, DNA barcoding method was used, and diversity was determined by nested PCR using primers for the rDNA-ITS region of *Phytophthora* species. As a result of ITS sequencing, 15 different *Phytophthora* taxa were obtained. *P. citrophthora*, *P. nicotianae*, *P. taxon 'Pgchlamydo'*, *P. cinnamomi*, *P. cambivora*, *P. lateralis*, *P. meadii*, *P. parvispora* and *P. niederhauserii* were detected species. For 3 phylotypes (*P. pseudosyringae*, *P. ilicis* or *P. nemorosa*; *P. cryptogea*, *P. erythroseptica*, *P. himalayensis* or *P. sp. 'kelmania'* and *P. citricola* taxon E or III) ITS sequencing was not sufficient. In addition to these phylotypes, 3 new taxa were obtained as *P. cinnamomi*-like, *P. niederhauserii*-like and *P. meadii*-like. The analyzes emphasized that there are very complex *Phytophthora* taxa communities in ornamental plant nurseries in a restricted geographical area. The results have revealed the main mission of ornamental plant nurseries for the existence, spread and evolution of *Phytophthora* species (Prigigallo et al., 2015).

It is known that soil-borne pathogenic *Phytophthoras* are mostly lost in a certain area. Generally, investigations have been carried out in nurseries, parks and forest areas or in a specific region. In some years, plant losses have been noticed on a larger scale and the studies have been carried out in more than one country. In a study carried out within the scope of the European Union Project, symptoms of root and crown rot, drying, yellowing, defoliation and dieback were observed in plants in 2 large European nurseries. Root and soil samples were taken from a total of 17 symptomatic woody ornamental plant species. In addition, asymptomatic plants that did not show any symptoms were also sampled. *Phytophthora* species were identified by isolations and molecular identification methods. *Phytophthora* species were isolated from 87% of symptomatic plants and 70% of asymptomatic plants. The most frequently detected species was *P. cinnamomi* (Migliorini et al., 2015). An important study for the world literature was carried out in a very large area in Europe. As a result of study carried out in 732 nurseries and 2525 outdoor ornamental plant production areas; 49 (91.5%) of 670 nurseries were contaminated with

Phytophthora taxon. It was reported that 56 Phytophthora taxa were found in 1667 (66%) of the other 2525 cultivation areas. It was also emphasized that many of these species are exotic species for Europe. It has also been reported that this source of contamination poses a major risk to the European forest ecosystem (Jung et al., 2016).

**Table 1.** Most known Phytophthora species’s hosts and disease symptoms

Species	Hosts	Disease
<i>P.cinnamomi</i>	>1000 host species	
	Especially in <i>Castanea</i>	
	<i>sativa</i> , <i>Quercus</i> sp.,	Root and crown rot
	<i>Chamaecyparis</i>	
	<i>lawsoniana</i> , <i>Abies</i> sp.,	
	<i>Rhododendron</i> sp.	
<i>P.plurivora</i> ( <i>citricola</i> )	Almost 100 host	
	species	
	Especially in	Root and crown rot, cankers and blight
	<i>Azalea</i> sp.,	
	<i>Rhododendron</i> sp.,	
<i>P.cryptogea</i>	<i>Quercus</i> sp.	
	>150 host species	
	Especially in	
	<i>Gerbera jamesonii</i> ,	
	<i>Quercus</i> sp.,	Root and crown rot
	<i>Castanea sativa</i> , <i>Abies</i>	
	sp., <i>Chamaecyparis</i> sp.,	
	<i>Cupressus</i> sp.,	
	<i>Juglans regia</i> ,	
	<i>Pinus</i> sp.,	
	<i>Rhododendron</i> sp.	
<i>P.quercina</i>	<i>Quercus</i> sp.	Root rot, Oak decline



<i>P.gonapodyides</i>	<i>Chamaecyparis lawsoniana</i> , <i>Fagus sylvatica</i> , <i>Juglans regia</i> , <i>Quercus</i> sp., <i>Rhododendron</i> sp.	Root rot, cankers
<i>P. pseudocryptogea</i>	<i>Quercus</i> sp., <i>Fagus sylvatica</i> , <i>Alnus glutinosa</i>	Root and collar rot, cankers
<i>P.cambivora</i>	Almost 30 host species Especially in <i>Castanea sativa</i> , <i>Quercus</i> sp., <i>Fagus sylvatica</i> , <i>Rhododendron</i> sp., <i>Abies</i> sp., <i>Acer</i> sp., <i>Aesculus hippocastanum</i> , <i>Alnus glutinosa</i> , <i>Juglans regia</i> ,	Root and collar rot, cankers
<i>P.cactorum</i>	>200 host species Especially in <i>Abies</i> sp., <i>Acer</i> sp., <i>Aesculus</i> sp.	Root and crown rot, cankers, blights and wilts
<i>P.chlamydospora</i>	<i>Fagus sylvatica</i> , <i>Juglans regia</i> , <i>Fraxinus excelsior</i> , <i>Quercus</i> sp., <i>Rhododendron</i> sp.	Root and crown rot
<i>P.nicotianae</i> ( <i>parasitica</i> )	>400 host species Especially in <i>Buxus</i> sp., <i>Lavandula</i> sp.,	Root and crown rot, fruit rot, blights

	<i>Rosmarinus sp.</i>	
	<i>Palm trees, Orchids</i>	
	<i>&gt;100 host species</i>	
	<i>Especially in</i>	
	<i>Aesculus sp.,</i>	
<i>P.citrophthora</i>	<i>C.lawsoniana, Juglans regia, Rhododenron sp.,</i>	Root and crown rot, cankers and blights
	<i>Castanes sativa, Buxus sp.</i>	
	<i>Almost 30 host species</i>	
	<i>Especially in Castanea sativa, Cedrus sp.,</i>	Root and crown rot, cankers, wilts, fruit rot
<i>P.syringae</i>	<i>Aesculus sp., Fagus slyvatica, Rhododendron sp.</i>	
	<i>Especially in</i>	
	<i>Quercus sp.,</i>	
	<i>Abies sp.,</i>	
	<i>Aesculus hippocastanum,</i>	
<i>P.ramorum</i>	<i>Alnus sp., Fagus slyvatica, Rhododendron sp.,</i>	Stem cankers, shhot dieback, blights
	<i>Larix kaempferi, Viburnum sp.,</i>	
	<i>Pieris sp.</i>	
	<i>Chamaecyparis lawsoniana, Thuja sp.,</i>	Discoloration and death of foliage, root infection, tree decline
<i>P.lateralis</i>	<i>Taxus brevifolia, Juniperus communis, Cupressus sp.</i>	

Although the number of studies on Phytophthora root and crown rot species is quite high in many countries of the world, studies on Phytophthora diseases in Türkiye are limited and insufficient. In the following section, the researches and studies carried out in Türkiye will be analysed in detail.

### **PHYTOPHTHORA ROOT AND CROWN DISEASES DETECTED ON ORNAMENTAL PLANTS IN TÜRKİYE**

When the studies on Phytophthora root and crown rot diseases in Türkiye are analysed, there is no comprehensive study on the determination of Phytophthora diseases in ornamental plant growing areas. Most of the studies have focused on especially forest trees. For this reason, it is not known whether there are diseases that will economically affect production in the ornamental plants group and which diseases are intense. Studies on ornamental plants are very limited. One of the reasons for this is that ornamental plants are not as important as cultivated plants produced for food. Another reason is that ornamental plants sampling is not as accessible and easy as cultivated plants. Especially in detecting soil-borne Phytophthora diseases, problems such as the size of the sampled plant, the permission taken from the area to be sampled, the inability to wait for the diseased plant or soil sample until sampling and therefore the inability to reach the plant sample limit the studies to be carried out. In addition, information on ornamental plant disease detection and management strategies of is very limited in Türkiye. Most of the studies have focused on identification and the control step has been incomplete. The known management strategy for Phytophthora diseases in ornamental plants is limited to cultural control. There are very few studies on the management of Phytophthora diseases in ornamental plants. Studies both in Türkiye and in other countries have focused on cultivated plants. In Türkiye, Phytophthora root and crown rot diseases in forest trees, ornamentals and nurseries recently have only recently started to be addressed. In this part of the review, Phytophthora species found in forest trees and ornamental plants, their distribution areas and precautions to be taken in control are presented. The contents of the studies on Phytophthora root and crown rot diseases of ornamental plants in Türkiye are described in detail below.

## Phytophthora Root And Crown Rot Diseases On Forest Trees in Türkiye

Many *Phytophthora* species infect oak trees, but *P. quercina* and *P. citricola* are the most common and common distributed species, especially in Europe and Eurasia (Vettraino et al., 2002; Balci and Halmschlager, 2003). The first study on *Phytophthora* diseases in oaks in Türkiye was carried out Balci and Halmschlager in 2003. Survey was carried out rhizosphere soils of healthy and diseased oak in different oak stands in Türkiye. Seven *Phytophthora* species were detected from oak species sampled: *Phytophthora* spp. 1 and *Phytophthora* spp. 2., *P. cryptogea*, *P. citricola*, *P. cinnamomi*, *P. quercina* and *P. gonapodyides*. The most constantly isolated species was *P. quercina*. The second most common species was *P. citricola* and it was divided into three subgroups: type A and B occurred only in the European part of Türkiye and type C occurred only in Anatolia. *P.cinnamomi* was found just one site and it has not played role in the oak decline in Türkiye.

Determination of the role of *Phytophthora* species in the drying of Oak (*Quercus* sp.), sweet chestnut (*Castanea sativa*) and Rhododendron (*Rhododendron* sp.), which are important woody taxa of the Black Sea Region Forest Ecosystem, within the scope of TÜBİTAK project 108O888, only *Phytophthora* forests in the Western Black Sea region were examined. 2 *Phytophthora* species from the Black Sea region Zonguldak Regional Directorate of Forestry; *P. plurivora* (*P. citricola*) and *P. quercina* were obtained (Maden et al., 2012).

Akıllı and other researchers frequently obtained *Phytophthora plurivora* and *P. quercina* from soil samples taken from the oak fields in Zonguldak, Çaycuma and Devrek districts. Researchers often isolated *Pythium* species together with *Phytophthora* species and found that one of them (*P. anandrum*) was as aggressive on oaks as *Phytophthora* species found in this region. These findings reveal the opinion that besides *Phytophthora*, *Pythium* species may also have a role in oak drying (Akıllı et al., 2013a).

Decay symptoms were occurred on oak trees (*Quercus robur*) in Emirgan Grove, İstanbul in 2015. Symptoms included crown dieback, bleeding cankers on the trunk and sparse canopies. Symptoms were generally above soil system, indicating *Phytophthora* infections. Firstly, *Phytophthora* species were not isolated, but two species were isolated by baiting and selective media

techniques from soil samples. By morphological and molecular techniques *P. pseudocryptogea* and *P. plurivora* were isolated. This species species may have played major roles oak declines (Kurbetli et al., 2022).

In Marmara and Aegean regions of Türkiye, sweet chestnut (*Castanea sativa*) is an important tree species. In two regions are produced the large majority of edible nuts, especially using for marron glacé production. The first record of the presence of Phytophthora in chestnuts, an important tree species in Türkiye, dates back to 1951. In the study, laboratory studies on the isolation and diagnosis of the agent from diseased plants were carried out, although cultures similar to the mycelial growth of the agent were obtained several times, morphological features such as sporangium and zoospore used in the diagnosis of the disease agent could not be obtained. However, from the definition of disease symptoms, it is understood that Phytophthora root rot in chestnut has been present in Türkiye since ancient times.

During the control against ink disease in the Cumalıkızık village of Bursa province, it was stated that ink disease caused by *P. cambivora* in chestnuts reportedly dried out 19715 trees in the center of Bursa between 1925 and 1968. Although it was included in this record, no diagnostic study was carried out on *P. cambivora*, only a disease diagnosis based on symptoms and sources was expressed (Akdoğan, 1970). In addition, it is stated in a textbook that ink disease caused by *P. cambivora* in chestnuts, was found in Hopa, Borçka, Sürmene in the Eastern Black Sea region and also in Zonguldak Akçakoca, İstanbul-Belgrade forest, Bursa and İnegöl. However, it is not stated in this source to whom the findings belong (Çanakçıoğlu and Eliçin, 1998).

The first record of Phytophthora based on morphological and molecular characteristics in chestnuts in Türkiye was made by Çeliker and Onoğur in 2009. Researchers found that showing signs of ink disease in Marmara and Aegean regions; They took 11 soil samples from 8 regions: 3 from Balıkesir İvrindi, 1 from İzmir Beydağ, 2 from Kütahya Simav and 2 from Manisa Salihli. The researchers tried to identify Phytophthora species by trapping method using Azelae leaves from these soil samples and obtained 4 isolates that typically resemble Phytophthora sp. The researchers detected “K-2” Phytophthora morphological features in only one of these obtained isolates, and this isolate was sent to Sabine Werres in Germany and Kris van Poucke in Belgium for diagnosis. The first researcher (Sabine Werres) identified this isolate according

to its morphological features. They identified it as *P. cactorum*, and the second investigator identified it as *P. cactorum* × *P. hedraiaandra* based on its molecular characteristics (Çeliker and Onoğur, 2009).

Comprehensive Phytophthora root rot studies on chestnuts in Türkiye were first initiated in the Black Sea Region. In the study, soil samples were collected from 76 regions and by trapping method, 3 Phytophthora species were isolated from the chestnuts; *P. cambivora*, *P. plurivora* (*P. citricola*) and *P. cinnamomi*. Identification of these species was based on both the morphological and physiological characteristics of the agents and the ITS region of the agents using molecular methods (Akıllı et al., 2012a). In two different studies, Phytophthora species were identified by trapping method in a total of 110 soil samples, 49 from the Marmara Region and 61 from the Aegean Region. Phytophthora root rots did not show a uniform distribution in these regions. For example, while *P. cinnamomi* was found only around Istanbul, *P. cambivora* was more common in the Marmara and Aegean regions. The researchers found that there were symptoms of Phytophthora root rot in all parts of these regions, but they could not find this agent in all of the samples taken, and this situation continued during the periods when soil samples were taken. They emphasized that they attributed this to drought (Akıllı et al., 2012b; Katırcıoğlu et al., 2017).

In one of the recent studies, *C. sativa* forests in Marmara and Aegean regions, severe dieback symptoms were investigated. Soil samples were collected from symptomatic chestnut trees and Phytophthora spp. were isolated by soil baiting and selective media techniques. Species were identified by morphological characteristics and molecular techniques. *Phytophthora cambivora* was the most common species detected in symptomatic areas, followed by *P. cinnamomi*, *P. plurivora* and *P. cryptogea*. *Phytophthora cambivora* was detected in Marmara and Aegean regions, while *P. cinnamomi* was detected only in the coastal areas in Marmara region. *Phytophthora cryptogea*, was the first record on chestnut in Türkiye. These results recommend that *P. cinnamomi* and *P. cambivora* act a important role in Western Türkiye (Akıllı et al., 2019a).

Researchers observed sudden wilt and dieback associated with root rot in *Juglans regia* in Bingöl in 2015. Most of roots were definitely rotted and the inner bark of roots showed discoloration. Phytophthora species was permanently isolated from diseased plants. All morphological features were

similar to *Phytophthora chlamydospora* (Hansen et al., 2017), previously known as *P. taxon Pgchlamydo*. *P. chlamydospora* has infected many woody ornamental plants, but this research is the first report of *P. chlamydospora* infection of walnut. *J.regia* has identified with *P.chlamydospora* for new host (Derviş et al., 2016).

Signs of die back were observed in ash trees (*Fraxinus* sp.) near the Sinop province of Türkiye and decay was observed in the roots of diseased plants. Soil samples taken from the roots of such trees were examined for *Phytophthora* and 4 out of 10 samples contained *Phytophthora* spp. and this species was later identified as *P. lacustris* (Akıllı et al., 2013b).

The pathogenicity and identification of Oomycota species leading to root rot were surveyed in forest tree nurseries in western Türkiye. Soil samples collected from the rhizosphere of diseased plants. Oomycota species were isolated by culturing on selective media. Baiting technique was used by young leaves of *Rhododendron simsii*, *R. ponticum* and *Quercus suber*. Isolates were identified by morphological methods and molecular techniques. *Pythium aphanidermatum*, *P.intermedium*, *P. ultimum*, *P. irregular*, *Phytophthora syringae*, *Phytophthora aff. cactorum*, *P. citricola sensu lato*, *P. crassamura* and *Phytopythium vexans* were common species among the isolates. *Phytophthora syringae* was detected in *Cebrus libani* in Antalya-Elmalı, Adapazarı-Hendek, İzmir-Torbalı, Isparta-Eğirdir and Denizli-Karahasanlı; *P. crassamura* was detected in *Castanea sativa* in Bursa; *P. cactorum* and *P. citricola* were detected in *Laurus nobilis* in İzmir-Torbalı; *P. citricola* was detected in *Buxus sempervirens* in Muğla-Gökova, Adapazarı-Hendek and İzmit-Sapanca. The importance of nursery infections in the introduction of potentially detrimental oomycete species into Turkish nurseries is debated (Lehtijarvi et al., 2017).

A study was conducted on the presence of *Phytophthora* species in *Alnus glutinosa* areas in Karacabey and Iğneada floodplain forests in Türkiye. Soil samples were obtained from the rhizosphere of diseased plants. Baiting techniques were used for *Phytophthora* isolation. Totally more than 300 *Phytophthora* isolates were acquired due to selective media. *Phytophthora plurivora* was the most isolated species (83%) according to morphological characteristics and the ITS sequencing. As well as *P. plurivora*, *P. gonapodyides* (9%), *P. chlamydospora* (3,8%), *P. lacustris* (2,5%) and *P. aff.*

*cactorum* (2%) were isolated from *A. glutinosa* forests. This study includes first report of *P. aff. cactorum* and *P. plurivora* obtained from the rhizosphere of *Alnus* species in Türkiye (Aday Kaya et al., 2018).

### **Phytophthora Root and Crown Rot Diseases on Other Ornamentals in Nurseries in Türkiye**

In addition to forest trees, *Phytophthora* root and crown rot diseases were also examined in other ornamental plants in nurseries in Türkiye.

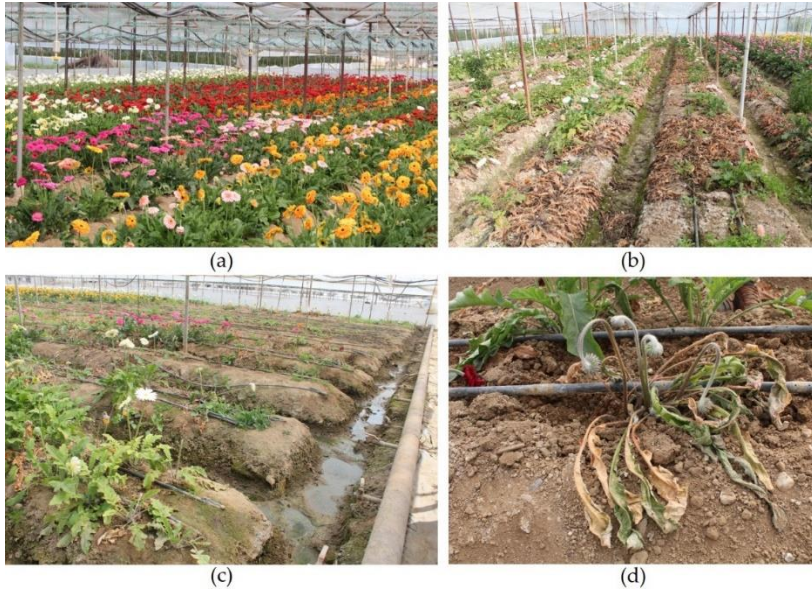
The research was carried out identify the fungi species which induce damping-off in some common sage (*Salvia officinalis*) plantation in Antalya and Izmir provinces of Türkiye. Diseased plants showed rot symptoms in root and crowns. Such symptoms were typical of *Phytophthora* species. *P. cryptogea*, new *Phytophthora* species, was isolated and identified by morphological and molecular characteristics of DNA sequencing. This research is the first report of *P. cryptogea* on *S. officinalis* in Türkiye (Çakır et al., 2017). Several *Phytophthora* species, such as *P. cryptogea*, are generally non-host specific and can affect a different plant groups.

Recently, dieback symptoms of boxwood (*Buxus sempervirens*) has been observed in many forests in Türkiye. In a study, boxwood diseases were researched in nurseries and forests in the Marmara and Black Sea regions of Türkiye. Nurseries and forests were surveyed and samples were collected from symptomatic plants tissues like soil, branch and leaves. 11 fungal genera were identified based on morphological characteristics and sequencing. *P. plurivora* was detected in two nurseries while *Phytophthora nicotianae* was detected in one nursery and *P. occultans* in only a location in forests in the Black Sea region (Akıllı et al., 2019b).

The record of *Phytophthora* in horse chestnut (*Aesculus* sp.) in Türkiye dates back to 2002. In a park in Ankara, yellowing of the leaves, shrinkage of the leaves and necrosis with dark discharge on the trunk and main branches were observed in the horse chestnut, and *P. cactorum* was isolated from the tissues surrounding these necroses (Intini et al., 2002). In another study, a new *Phytophthora* species, *P. citrophthora*, was obtained from soil and root samples taken from the rhizosphere of horse chestnut trees in Ankara. The researchers identified this species according to both morphological and molecular



characteristics (by determining the sequence of the ITS gene region) (Akıllı et al., 2012c).



**Figure 1. *Phytophthora cryptogea* infected *Gerbera jamesonii* in Türkiye:** (a) Healthy *Gerbera jamesonii* in Izmir nurseries free of *Phytophthora* infection b) nursery with gerbera plants which have died due to *Phytophthora cryptogea* (c) increase in plant losses due to excess of irrigation water in *Phytophthora* root and crown diseases (d) infected *Gerbera jamesonii* with drying of leaves, dieback, wilting

Notes: All photos taken by Çiğdem Özkan Kahraman; retrieved from Çiğdem Özkan Kahraman's Master's thesis)

Root and crown rot pathogens are also seen in cut flowers in Türkiye. Dieback symptoms of gerbera were investigated in variety of greenhouses in Izmir province of Türkiye. Discoloration, yellowing, wilting, growth deficiency and decline symptoms were observed in greenhouses. The causal pathogen was identified as *Phytophthora cryptogea* based on morphological features and DNA sequencing of ITS region. This study is the first report of *P. cryptogea* on gerbera in Izmir (Kahraman and Yıldız, 2019). As a continuation of this study, pathogen management study was carried out. Management trial was performed in order to determine the in vivo efficacy of some fungicides and biofungicides. In this study, five fungicides were tested using by soil drenching. "Azoxystrobin+difenoconazole", "mandipropamid+difenoconazole"

ole”, ”propamocarb+fosetyl-Al”, “mancozeb+metalaxyl-M”, “Ametoctradin+dimethomorph” active substances were used. Similarly, the biofungicide active ingredient such as *Bacillus amyloliquefaciens* was applied by soil drenching. In this experiment, azoxystrobin+ difenoconazole showed the highest efficacy against *P. cryptogea*. The other fungicides and biofungicides were not effective. The aim of that management trial was to indicate the fungicides and biofungicides efficieny on preventing root and crown rot disease *P. cryptogea* in gerbera in greenhouses (Özkan Kahraman and Yıldız, 2019).

**Table 2.** Coincidence of Phytophthora species associated with ornamentals in Türkiye

Species	Region	Hosts	Source
<i>Phytophthora</i> spp.	Marmara and Aegean Region	<i>Castanea sativa</i>	Erdem, 1951
	Cumalıkızık, Bursa	<i>Castanea sativa</i>	Akdoğan, 1970
<i>P.cambivora</i>	Eastern Black Sea Region Zonguldak, İstanbul Bursa	<i>Castanea sativa</i>	Çanakçıoğlu and Eliçin, 1998
	Aegean Region	<i>Castanea sativa</i>	Katırcıoğlu et al., 2017
<i>P. cactorum</i>	Marmara and Aegean Region	<i>Castanea sativa</i>	Çeliker and Onoğur, 2009
<i>P. cactorum</i> × <i>P.hedraiandra</i>	(Balıkesir, İzmir, Kütahya, Manisa)		

<i>P. cambivora</i>	Black Sea Region	<i>Castanea sativa</i>	Akıllı et al., 2012a
<i>P.cinnamomi</i>			
<i>P.plurivora (citricola)</i>			
<i>P. cinnamomi</i>	Marmara Region	<i>Castanea sativa</i>	Akıllı et al., 2012b
<i>P.cambivora</i>			
<i>P.cinnamomi</i>	Marmara and Aegean Region	<i>Castanea sativa</i>	Akıllı et al., 2019a
<i>P.plurivora(citricola)</i>			
<i>P.cryptogea</i>			
<i>P.cambivora</i>			
<i>P.plurivora(citricola)</i> <i>P. quercina</i>	Western Black Sea Region	<i>Castanea sativa</i> ,	Maden et al., 2012
		<i>Quercus sp.</i> ,	
		<i>Rhododendron sp.</i>	
<i>P.plurivora(citricola)</i> <i>P. pseudocryptogea</i>	Zonguldak	<i>Quercus sp.</i>	Akıllı et al., 2013a
<i>P.cinnamomi</i>	İstanbul	<i>Quercus robur</i>	Kurbetli et al., 2022
<i>P.plurivora (citricola)</i>			
<i>P.cryptogea</i>	51 oak stands in Türkiye	<i>Quercus sp.</i>	Balci and Halmschlager, 2003
<i>P.gonapodyides</i>			
<i>P.quercina</i>			
<i>P.sp 1</i>			
<i>P.sp 2</i>			
<i>P.lacustris</i>	Sinop	<i>Fraxinus sp.</i>	Akıllı et al., 2013b
<i>P.taxon Pgchlamydo</i>	Bingöl	<i>Juglans regia</i>	Derviş et al., 2016
<i>P.chlamydospora</i>			
<i>P. plurivora(citricola)</i>	Bursa and İğneada	<i>Alnus glutinosa</i>	Aday Kaya et al., 2018
<i>P.gonapodyides</i>			

<i>P.chlamydospora</i>	floodplain		
<i>P.lacustris</i>	forests		
<i>P.aff.cactorum</i>			
<i>P.cactorum</i>	Ankara	<i>Aesculus sp.</i>	Intini et al., 2002
<i>P.citrophthora</i>	Ankara	<i>Aesculus sp.</i>	Akıllı et al., 2012c
		<i>Cedrus libani-</i>	
	Antalya,	<i>P.syringae</i>	
	Adapazarı,	<i>Castanea</i>	
<i>P.aff. cactorum</i>	İzmir,	<i>sativa-</i>	
<i>P.citricola sensu lata</i>	Isparta,	<i>P.crassamura</i>	Lehtijarvi et al., 2017
<i>P.crassamura</i>	Denizli,	<i>Laurus nobilis-</i>	
<i>P.syringae</i>	Bursa,	<i>P.cactorum,</i>	
	Muğla,	<i>P.citricola</i>	
	İzmit	<i>Buxus</i>	
		<i>sempervirens-</i>	
		<i>P.citricola</i>	
<i>P.cryptogea</i>	Antalya, İzmir	<i>Salvia</i> <i>officinalis</i>	Çakır et al., 2017
<i>P.plurivora (citricola)</i>	Marmara and		
<i>P.occultans</i>	Black Sea	<i>Buxus</i>	Akıllı et al., 2019b
<i>P.nicotianae</i>	Region	<i>sempervirens</i>	
<i>P.cryptogea</i>	İzmir	<i>Gerbera</i> <i>jamesonii</i>	Kahraman and Yıldız, 2019

CONCLUSIONS

Some Phytophthora root and crown rot pathogens have still not been diagnosed in many countries in worldwide. Variety of root disorders of ornamental plants have been ascribed to other pathogens, and found whereby Phytophthora species just when suitable isolation techniques such as baiting and selective media were used. However, these specific techniques are still not

widely used by many researchers today. Generally, they are unaware of the importance of these fungi like organisms that inducing severe infections, or of the peerless nature of their biology, soil ecology and pathology in relation to root systems development. It is expected that using special isolation techniques in diagnoses will result in increasing in the frequency of reports of determination of *Phytophthora* root and crown rots of ornamental plants in worldwide in the future.

While the world literature on *Phytophthora* species that cause root and crown rot is quite sufficient, studies in Türkiye are very limited and almost all of the studies have been done on forest trees and cut flowers. Most of the studies have focused on morphological and molecular identification and the control step has been missing. In addition to disease symptoms seen in other plants in nurseries and greenhouses other than forest trees, research should also be carried out on ornamental plants where problems are detected during the survey. Morphological diagnosis, which is the first step, and molecular diagnosis, which is the second step, has an important place. After diagnostic methods, basic research on control possibilities should be carried out. The results of the research will provide yield and quality increase in production areas where disease-related problems are experienced, as well as practical application, chemical control possibilities, and also environmentally friendly, biological origin preparations that do not harm the environment and human health. The increase in yield, quality and therefore income to be obtained from production will contribute to the Turkish economy by encouraging ornamental plant cultivation.

## REFERENCES

- Aday Kaya, A. G., Lehtijärvi, A., Şaşmaz, Y., Nowakowska, J. A., Oszako, T., Doğmuş Lehtijärvi, H. T. & Woodward, S. (2018). Phytophthora species detected in the rhizosphere of *Alnus glutinosa* stands in the floodplain forests of Western Turkey, *Forest Pathology*, 48.6: e12470.
- Akdoğan, S. (1970). Kestane Mürekkep Hastalığı (*Phytophthora cambivora* Petri) mücadelesi üzerine araştırmalar, *Bitki Koruma Bülteni*. 10, 121–130.
- Akıllı, S., Katircioğlu, Y. Z., Ulubaş, S., Ç., Çakar, D., Rigling, D. & Maden, S. (2019a). Phytophthora species associated with dieback of sweet chestnut in Western Turkey, *Forest Pathology*, 49(4), e12533.
- Akıllı, S., Katircioğlu, Y. Z., Çakar, D., Rigling, D. & Maden, S. (2019b). Impact of fungal diseases on common box (*Buxus sempervirens* L.) vegetation in Turkey, *European Journal of Plant Pathology*. 153, 1203–1220.
- Akıllı, S., Katircioğlu, Y. Z. & Maden, S. (2012b). Phytophthora Türlerinin Marmara Bölgesi Orman Ekosisteminin Önemli Odunsu Taksonlarından, Kestane (*Castanea sativa*) Kurumalarındaki Rollerinin Belirlenmesi, *1110494 nolu TÜBİTAK projesi sonuç raporu*. 25s. Ankara.
- Akıllı, S., Ulubaş, Serçe. Ç., Katircioğlu, Y. Z. & Maden, S. (2012a). Involvement of Phytophthora spp. in chestnut decline in the Black Sea region of Turkey, *Forest Pathology*. 42, 377- 386.
- Akıllı, S., Ulubaş, Serçe. Ç., Katircioğlu, Y.Z. & Maden, S. (2013a). Does *Pythium anandrum* contribute to the dieback of sessile oak (*Quercus petraea*) in Turkey? *Forest Pathology*. 43, 505–508.
- Akıllı, S., Ulubaş, Serçe. Ç., Katircioğlu, Y.Z. & Maden, S. (2013b). Phytophthora dieback on Narrow leaved ash in the Black Sea region of Turkey, *Forest Pathology*, 43, 252–256.
- Akıllı, S., Ulubaş, Serçe. Ç., Katircioğlu, Y.Z. & Maden, S. (2012c). *Phytophthora citrophthora*, a new pathogen causing decline on horse chestnut in Turkey, *Forest Pathology*. 42, 299–304.

- Balci, Y. & Halmschlager, E. (2003). Phytophthora species in oak ecosystems in Turkey and their association with declining oak trees, *Plant Pathology*. 52, 694–702.
- Balci, Y., Long, R. P., Mansfield, M., Balser, D. & MacDonald, W. L. (2010). Involvement of Phytophthora species in white oak (*Quercus alba*) decline in southern Ohio, *For. Pathol.* 40, 430–42.
- Beakes, G., Honda, T. & Thines, M. (2014). 3 Systematics of the Stramenipila: Labyrinthulomycota, Hyphochytridiomycota, and Oomycota. In Systematics and Evolution; McLaughlin, D., Spatafora, J., Eds.; Springer: New York, NY, USA, 39–97.
- Blair, J.E., Coffey, M.D., Park, S.-Y., Geiser, D.M. & Kang, S. A. (2008). A multilocus phylogeny for Phytophthora utilizing markers derived from complete genome sequences, *Fungal Genet. Biol.* 45, 266–277.
- Blomquist, M. (2016). Invasive Phytophthora Species Affecting Broadleaved Tree Species in Urban and Landscape Settings in Southern Sweden. Master's Thesis, Swedish University of Agricultural Sciences, Alnarp, Sweden. <https://stud.epsilon.slu.se/10072/>
- Brasier, C. M., Franceschini, S., Vettraino, A. M et al. (2012). Four phenotypically and phylogenetically distinct lineages in Phytophthora lateralis, *Fungal Biology*. 116, 1232–1249.
- Brasier, C. M. & Webber, J. (2010). Sudden larch death, *Nature*. 466, 824–825.
- Cerný, K., Tomšovský, M., Mrázková, M. & Strnadová, V. (2011). The present state of knowledge on Phytophthora spp. diversity in forest and ornamental woody plants in the Czech Republic, *New Zealand Journal of Forestry Science* (New Zealand Forest Research Institute Ltd (trading as Scion). 41.
- Cooke, D.E.L., Drenth, A., Duncan, J.M., Wagels, G. & Brasier, C.M.A. (2000). Molecular phylogeny of Phytophthora and related oomycetes, *Fungal Genet. Biol.* 2000, 30, 17–32.
- Coşkuntuna, A. & Yıldız, F. (2006). The biological control of fusarium wilt on carnation with fluorescent pseudomonads, *The Journal of Turkish Pyhtopathology*, 34.1-3, 43-56.
- Croucher, P.J.P., Mascheretti, S. & Garbelotto, M. (2013). Combining field epidemiological information and genetic data to comprehensively reconstruct the invasion history and the microevolution of the sudden oak

- death agent *Phytophthora ramorum* (Stramenopila: Oomycetes) in California, *Biol. Invasions*. 15, 2281–2297.
- Çakır, E., Bahtiyarca Bağdat, R., Katırcıoğlu, Y. Z. & Maden, S. (2017). Occurrence of root rot caused by *Phytophthora cryptogea* on common sage (*Salvia officinalis*) in Turkey, *Journal of Agricultural Science and Tecnology A*. 7, 401-406.
- Çanakçıoğlu, H. & Eliçin, G. (1998). Fitopatoloji (özel bölüm). İstanbul Üniversitesi Orman Fakültesi Yayınları. 1998, 28-31, İstanbul.
- Çeliker, M. & Onoğur, E. (2009). Preliminary Studies on the Fungal Disorders Especially on Ink Disease Causing Decline of chestnut Trees in Turkey, *Proceedings of International Workshop on Chestnut Management in Mediterranean Countries* Eds.: A. Soylu and C. Mert. *Acta Hort.* 815, 227-231.
- deCock, A. W. A. M. & Lévesque, C. A. (2004). New species of *Pythium* and *Phytophthora*. *Studies in Mycology*, 50, 481-487.
- Derviş, S., Türkölmez, Ş., Çiftçi, O. & Ulubaş, Serçe, Ç. (2016). First report of *Phytophthora chlamydospora* causing root rot on walnut (*Juglans regia*) trees in Turkey, *Plant Disease*, 100, 2336.
- Donahoo, R. S. & Lamour, K. H. (2008). Characterization of *Phytophthora* species from leaves of nursery woody ornamentals in Tennessee, *HortScience*, 43, 1833-1837.
- Erdem, R. (1951). Türkiye'deki Kestane Ölümünün Sebepleri ve Savaş, İmkanları. Tarım Bakanlığı, Orman Genel Müdürlüğü, 1951, 102, 11, Ankara.
- Erwin, D.C. & Ribeiro, O.K. (1996). *Phytophthora Diseases Worldwide*; APS Press: St. Paul, MN, USA, 562.
- Gallegly, E. M. & Hong, C. (2008). Identifying species by morphology and DNA fingerprints, *The American Phytopathology Society*, St. Paul, MN, USA, 127.
- Ginetti, B., Moricca, S., Squires, J.N., Cooke, D.E.L., Ragazzi, A. & Jung, T. (2013). *Phytophthora acerina* sp. nov., a new species causing bleeding cankers and dieback of *Acer pseudoplatanus* trees in planted forests in Northern Italy, *Plant Pathol.* 63, 858–876.
- Goheen, D. J., Mallams, K., Betlejewski, F. et al. (2012). Effectiveness of vehicle washing and roadside sanitation in decreasing spread potential of



- PortOrford-Cedar root disease, *Western Journal of Applied Forestry*. 27, 170–175.
- Goss, E. M., Larsen, M., Vercauteren, A., Werres, S., Heungens, K.& Grünwald, N. J. (2011). Phytophthora ramorum in Canada: evidence for migration within North America and from Europe, *Phytopathology*, 101, 166-171.
- Green, S., Brasier, C. M., Schlenzig, A. et al. (2013). The destructive invasive pathogen Phytophthora lateralis found on Chamaecyparis lawsoniana across the UK, *Forest Pathology*, 43, 19–28.
- Grunwald, N.J. & Flier, W.G. (2005). The biology of “ Phytophthora infestans at its center of origin, *Annu. Rev. Phytopathol.* 43,171–90.
- Grünwald, N.J., Garbelotto, M., Goss, E.M, et al. (2012). Emergence of the Sudden Oak Death pathogen Phytophthora ramorum, *Trends in Microbiology*. 20, 131–138.
- Grünwald, N.J., Goss, E.M.& Press, C. M. (2008). Phytophthora ramorum: a pathogen with a remarkably wide host range causing Sudden Oak Death on oaks and ramorum blight on woody ornamentals, *Molecular Plant Pathology*. 9, 729–740.
- Hansen, E. M., Goheen, D. J., Jules, E. S.& Ullian, B. (2000). Managing Port-Orford-cedar and the introduced pathogen Phytophthora lateralis, *Plant Disease*. 84, 4-14.
- Hansen, E. M., Reeser, P., Sutton, W.& Brasier, C. M. (2015). Redesignation of Phytophthora taxon Pgchlamydo as Phytophthora chlamydospora sp. nov., *North American Fungi*, 10, 1-14.
- Hansen, E.M., Reeser, P.W.& Sutton, W. (2017). Ecology and pathology of Phytophthora ITS clade 3 species in forests in western Oregon, USA, *Mycologia*. 109, 100–114.
- Hardham, A.R. (2005). Phytophthora cinnamomi, *Mol. Plant Pathol.* 6, 589–604.
- Harris, A.R.& Webber, J. (2016). Sporulation potential, symptom expression and detection of Phytophthora ramorum on larch needles and other foliar hosts, *Plant Pathology*. 65, 1441–1451.
- Hong, C., Gallegly, M.E., Richardson, P.A.& Kong, P. (2011). Phytophthora pini Leonian resurrected to distinct species status, *Mycologia*. 103, 351–360.

- Hulvey, J., Gobena, D., Finley, L.& Lamour, K. (2010). Co-occurrence and genotypic distribution of *Phytophthora* species recovered from watersheds and plant nurseries of eastern Tennessee, *Mycologia*. 102, 1127-1133.
- Intini, M., Gurer, M.& Ozturk, S. (2002). First Report of Bleeding Canker Caused by *Phytophthora cactorum* on Horse Chestnut in Turkey, *Plant Diseases*. 86, 697.
- Jimerson, T. M., White, D. E., Atzet, T., Park, C. S., McGee, E. A., Rose, D. L., Ulloa, M. T. (2001). Ecological factors associated with Port-Orford-cedar, *A range-wide assessment of Port-Orford-cedar (Chamaecyparis lawsoniana) on Federal lands*. BLM/OR/WA/PL-004/004-1792, 5-32.
- Jules, E.S., Kauffman, M.J., Ritts, W.D,et al. (2002). Spread of an invasive pathogen over a variable landscape: a nonnative root rot on Port Orford cedar, *Ecology*. 83, 3167–3181.
- Jung, T., Blaschke, H.& Neumann, P. (1996). Isolation, identification and pathogenicity of *Phytophthora* species from declining oak stands, *European Journal of Forest Pathology*. 26, 253-272.
- Jung, T.& Burgess, T.I. (2009). Re-evaluation of *Phytophthora citricola* isolates from multiple woody hosts in Europe and North America reveals a new species, *Phytophthora plurivora* sp. nov., *Persoonia*, 22, 95–110.
- Jung, T., Colquhoun, I.J.& Hardy, G.E.S.J. (2013). New insights into the survival strategy of the invasive soilborne pathogen *Phytophthora cinnamomi* in different natural ecosystems in Western Australia, *For. Pathol.* 43, 266–288.
- Jung, T., Orlikowski, L., Henricot, B., Abad-Campos, P., Aday, A.G., Aguin Casal, O., Bakonyi, J., Cacciola, S.O., Cech, T., Chavarriaga, D.; et al. (2016). Widespread *Phytophthora* infestations in European nurseries put forest, semi-natural and horticultural ecosystems at high risk of *Phytophthora* diseases, *For. Pathol.* 46, 134–163.
- Jung, T., Pérez-Sierra, A., Durán, A., Horta Jung, M., Balci, Y.& Scanu, B. (2018). Canker and decline diseases caused by soil- and airborne *Phytophthora* species in forests and woodlands, *Persoonia*, 40, 182–220.

- Jung, T., Stukely, M. J. C., Hardy, G. S. J., White, D., Paap, T., Dunstan, W. A. & Burgess, T. I. (2011). Multiple new Phytophthora species from ITS Clade 6 associated with natural ecosystems in Australia: evolutionary and ecological implications, *Persoonia: Molecular Phylogeny and Evolution of Fungi*. 201, 26, 13.
- Kahraman, Ç. Ö. & Yıldız, F. (2019). First Report of Crown and Root Rot Disease Caused by Phytophthora cryptogea on Gerbera in Izmir Province in Turkey, *Plant Disease*. 103, 589-590.
- Katırcıoğlu, Y. Z., Akıllı, S. & Maden, S. (2017). Ege Bölgesi kestane (Castanea sativa) alanlarında kurumlara neden olan Phytophthora türleri ve yaygınlıklarının belirlenmesi, Ankara Üniversitesi. 15B0447002 nolu Bilimsel Araştırma Projesi sonuç raporu, 22s.
- Kroon, L. P., Brouwer, H., De Cock, A. W. & Govers, F. (2012). The genus Phytophthora anno 2012, *Phytopathology*, 102, 348-364.
- Kroon, L.P.N.M., Bakker, F.T., Van Den Bosch, G.B.M., Bonants, P.J.M. & Flier, W.G. (2004). Phylogenetic analysis of Phytophthora species based on mitochondrial and nuclear DNA sequences, *Fungal Genet. Biol.* 41, 766-782.
- Kurbetli, İ., Woodward, S., Aydoğdu, M., Sülü, G. & Özben, S. (2022). Phytophthora plurivora and Phytophthora pseudocryptogea isolated from soils supporting declining oaks (Quercus robur L.) in İstanbul, Turkey, *Forest Pathology*. 52, e12782.
- Lehtijärvi, A., Aday Kaya, A. G., Woodward, S., Jung, T. & Doğmuş Lehtijärvi, H. T. (2017). Oomycota species associated with deciduous and coniferous seedlings in forest tree nurseries of Western Turkey, *Forest Pathology*. 47, e12363.
- Maden, S., Akıllı, S. & Katırcıoğlu, Y. Z. (2012). Phytophthora türlerinin Karadeniz Bölgesi orman ekosisteminin önemli odunsu taksonlarından Meşe (Quercus spp.), Kestane (Castanea sativa) ve Orman gülü (Rhododendron spp.) kurumalarındaki rollerinin belirlenmesi, TÜBİTAK 108O888 nolu proje sonuç raporu.
- Matsiakh, I. & Menkis, A. (2023). An Overview of Phytophthora Species on Woody Plants in Sweden and Other Nordic Countries, *Microorganisms*. 11, 1309.

- Matsiakh, I., Kramarets, V. & Cleary, M. (2021). Occurrence and diversity of *Phytophthora* species in declining broadleaf forests in western Ukraine, *For. Pathol.* 51, e12662.
- Meadows, I. M.& Jeffers, S.N. (2011). Distribution and recovery of *Phytophthora cinnamomi* in soils of mixed hardwood-pine forests of the south-eastern USA. *N. Z. J. For. Sci.* 41, 39–47.
- Migliorini, D., Ghelardini, L., Tondine, E., Luchi, N.& Santini, A. (2015). The potential of symptomless potted plants for carrying invasive soilborne plant pathogens, *Divers. Distrib.* 21, 1218–1229.
- Moralejo, E., Pérez-Sierra, A. M., Álvarez, L. A., Belbahri, L., Lefort, F.& Descals, E. (2009). Multiple alien *Phytophthora* taxa discovered on diseased ornamental plants in Spain, *Plant Pathology*. 58, 100-110.
- Özkan, Kahraman, Ç.& Yıldız, F. (2019). The effect of chemical and biological treatment on root and crown rot disease caused by *Phytophthora cryptogea* Pethybr. & Lafferty in *Gerbera*, *Journal of Phytopathology*. 167, 240-247.
- Pérez-Sierra, A.& Jung, T. (2013). *Phytophthora* in woody ornamental nurseries. In *Phytophthora: A Global Perspective*; Lamour, K., Ed.; CABI: Wallingford, UK, 166–177.
- Prigigallo, M. I., Mosca, S., Cacciola, S. O., Cooke, D. E. L.& Schena, L. (2015). Molecular analysis of *Phytophthora* diversity in nursery-grown ornamental and fruit plants, *Plant pathology*. 64, 1308-1319.
- Redonto, M.A. (2018). Invasion Biology of Forest *Phytophthora* Species in Sweden: Pathways, Traits, Climate and Host Adaptation. Ph.D. Thesis, Swedish University of Agricultural Sciences, Uppsala, Sweden.
- Rizzo, D.M., Garbelotto, M. & Hansen. E.M. (2005). *Phytophthora ramorum*: integrative research and management of an emerging pathogen in California and Oregon forests, *Annu. Rev. Phytopathol.* 43:309.
- Robin, C., Piou, D., Feau, N., Douzon, G., Schenck, N., & Hansen, E. M. (2011). Root and aerial infections of *Chamaecyparis lawsoniana* by *Phytophthora lateralis*: a new threat for European countries, *Forest Pathology*, 41(5), 417-424.
- Robin. C., Brasier, C.M., Reeser, P. et al. (2015). Pathogenicity of *Phytophthora lateralis* lineages on resistant and susceptible selections of *Chamaecyparis lawsoniana*, *Plant Disease*. 99, 1133–1139.

- Santini, A., Ghelardini, L., De Pace, C., Desprez-Loustau, M. L., Capretti, P., Chandelier, A., & Stenlid, J. (2013). Biogeographical patterns and determinants of invasion by forest pathogens in Europe, *New Phytologist*, 197(1), 238-250.
- Santini, A., Liebhold, A., Migliorini, D. & Woodward, S. (2018). Tracing the role of human civilization in the globalization of plant pathogens, *ISME J.* 2018, 12, 647–652.
- Schlenzig, A., Campbell, R. & Mulholland, V. (2011). Thuja occidentalis: a new host for Phytophthora lateralis, *New Disease Reports*. 24, 8.
- Schwingle, B. W., Smith, J. A. & Blanchette, R. A. (2007). Phytophthora species associated with diseased woody ornamentals in Minnesota nurseries, *Plant disease*. 91, 97-102.
- Scott, P., Bader, M. K. F., Burgess, T., Hardy, G., & Williams, N. (2019). Global biogeography and invasion risk of the plant pathogen genus Phytophthora, *Environmental Science & Policy*, 101, 175-182.
- Scott, P.M., Burgess, T.I., Barber, P.A., Shearer, B.L., Stukely, M.J.C., Hardy, G.E.S.J. & Jung, T. (2009). Phytophthora multivora sp nov., a new species recovered from declining Eucalyptus, Banksia, Agonis and other plant species in Western Australia, *Persoonia*. 22, 1–13.
- Shearer, B.L., Crane, C.E. & Cochrane, A. (2004). Quantification of the susceptibility of the native flora of the South-West Botanical Province, Western Australia, to Phytophthora cinnamomi, *Australian Journal of Botany*. 52, 435–443.
- Themann, K., Werres, S., Lüttmann, R. & Diener, H. A. (2002). Observations of Phytophthora spp. in water recirculation systems in commercial hardy ornamental nursery stock, *European Journal of Plant Pathology*. 108, 337-343.
- Thines, M. & Choi, Y.J. (2016). Evolution, diversity and taxonomy of the Peronosporaceae, with focus on the genus Peronospora, *Phytopathology*. 106, 6–18.
- Tremblay, É.D., Duceppe, M.O., Bérubé, J.A., Kimoto, T., Lemieux, C. & Bilodeau, G.J. (2018). Screening for exotic forest pathogens to increase survey capacity using metagenomics, *Phytopathology*. 108, 1509–1521.

- Tyler, B.M., Tripathy, S., Zhang, X.M., Dehal, P., Jiang, R.H.Y., Aerts, A., Arredondo, F.D., Baxter, L., Bensasson, D., Beynon, J.L. et al. (2006). Phytophthora genome sequences uncover evolutionary origins and mechanisms of pathogenesis, *Science*. 313, 1261–1266.
- Ufer, T., Werres, S., Posner, M. & Wessels, H. P. (2008). Filtration to eliminate Phytophthora spp. from recirculating water systems in commercial nurseries, *Plant health progress*. 9, 22.
- Vettraino, A. M., Barzanti, G. P., Bianco, M. C., Ragazzi, A., Capretti, P., Paoletti, E., Luisi, N., Anselmi, N. & Vannini, A. (2002). Occurrence of phytophthora species in oak stands in Italy and their association with declining oak trees, *Forest Pathology*. 32, 19–28.
- Webber, J.F., Mullett, M. & Brasier, C.M. (2010). Dieback and mortality of plantation Japanese larch (*Larix kaempferi*) associated with infection by Phytophthora ramorum, *New Disease Reports*. 22, 19.
- Werres, S., Marwitz, R., Man in 't Veld, W.A.M., De Cock, A. W., Bonants, P. J., De Weerd, M. & Baayen, R. P. (2001). Phytophthora ramorum sp. nov., a new pathogen on Rhododendron and Viburnum, *Mycological Research*, 105, 1155–1165.
- Wingfield, M.J., Slippers, B., Wingfield, B.D. & Barnes, I. (2017). The unified framework for biological invasions: A forest fungal pathogen perspective, *Biol. Invasions*. 19, 3201–3214.
- Yang, X., Tyler, B. M. & Hong, C. (2017). An expanded phylogeny for the genus Phytophthora, *IMA Fungus*. 8, 355–38.



## **CHAPTER 9**

### **BIOACTIVE COMPOUND LYCOPENE IN TOMATO**

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## INTRODUCTION

Natural antioxidants play an important role in maintaining our health and preventing diseases because of their therapeutic effect. Antioxidants (glutathione, arginine, selenium, zinc, vitamin E, vitamin C, vitamin A, lycopene, beta-carotene, etc.) are crucial effect for cleaning free radicals. If free radicals are not well controlled, they attack lipids, sugars, proteins and DNA to induce oxidative damage to these molecules and eventually cause various diseases; cancer, aging, etc. In this part of the study, one of the most important antioxidant compounds lycopene will be evaluated in detail.

Lycopene is the most abundant antioxidant in human blood. Lycopene is the red carotenoid found predominantly in tomatoes and in a few other fruits and vegetables (Joseph et al., 2004).

### Tomato Nutrition Glossary

Tomato is a very important nutrition in our diet. Tomato contains not only lycopene but also gallic acid, ferulic acid, quercetin, caffeic acid, chlorogenic acid, malic acid, vitamins (mainly vitamin A, vitamin E, and vitamin C), and various minerals (Ca, P, Fe, Na, K, etc.).

*Gallic acid:* Gallic acid (also known as gallate) is a benzoic acid that is thought to be one of the main phenolic acids. It is crucial for the creation of a category of tannins known as galatotanin-hydrolyzable tannins, which is made up of a unit of sugar and a variable number of phenol acid molecules (Fernandes and Salgado, 2016).

*Malic acid:* Malic acid, fumaric acid, itaconic acid, and succinic acid are examples of compounds that have a variety of potential uses as platform chemicals. Malic acid is an organic acid that is a crucial cell metabolism step and a member of the C<sub>4</sub> dicarboxylic acid group (Iyyappan et al., 2019).

*Citric acid;* Both plants and animals frequently metabolize citric acid, a tricarboxylic acid (C<sub>6</sub>H<sub>8</sub>O<sub>7</sub>·H<sub>2</sub>O), which is found in pineapple and citrus fruit juice. The molecular weight of pure citric acid is 210.14 g/mol, and it is colorless and easily soluble in water. In addition to being a multifunctional chemical for sequestering, buffering, wetting, cleaning, and dispersing, it is also biodegradable, environmentally friendly, cost-effective, and safe (Angumeenal and Venkappayya 2013).

*Oxalic acid*; With a molecular weight of 90 kg/kmol and the chemical formula  $C_2H_2O_4$ , oxalic acid is a naturally occurring dicarboxylic acid that is vital to many plant, animal, and microbiological species. Oxalic acid plays a crucial role in ion homeostasis, heavy metal detoxification, calcium control, and plant defense in plants (Amenaghawon et al., 2024).

*Quercetin*; The dietary flavonoid quercetin (3,5,7-trihydroxy-2-(3,4-dihydroxyphenyl)-4Hchromen-4-one) is found in fruit peels, leafy vegetables, strawberries, onions, cranberries, blueberries, black tea, lettuce, tomatoes, black chokeberries, capers, etc. (Dinç et al., 2023; Wang et al., 2016). Quercetin is typically found in plants attached to ethers, sugars, phenolic acids, and other substances. The rate at which quercetin derivatives are absorbed in the stomach and small intestine appears to vary depending on their shape (Wang et al., 2016). The amount of quercetin a person takes daily is approximately 16-25 mg (Dinç et al., 2023).

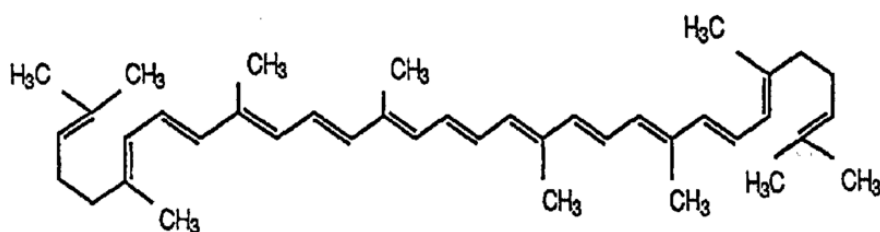
*Naringenin*; Mostly present in citrus fruits and some edible fruits like tomatoes and figs from the smyrna variety *Ficus carica*, naringenin is one of the most significant naturally occurring flavonoids. Naringenin, a flavonone in the flavonoid class, is produced by hydrolyzing naringin or narirutin, the glycone precursor. In addition to lowering protein carbonylation and lipid peroxidation biomarkers, naringenin promotes carbohydrate metabolism, boosts antioxidant defenses, scavenges reactive oxygen species, controls immune system activity, and has anti-inflammatory and anti-atherogenic properties (Salehi et al., 2019).

*Caffeic acid*; Caffeic acid (CA) is a metabolite of hydroxycinnamate and phenylpropanoid, widely synthesized by all plant species. This polyphenol can be found in a wide variety of foods, including propolis, coffee, tea, wine, blueberries, apples, cider, and honey. Potential antibacterial, antidiabetic, antioxidant, anti-inflammatory, antineoplastic, and cardioprotective properties have been described for CA and its main derivatives, such as caffeic acid phenethyl ester (CAPE) and caffeic acid 3,4-dihydroxy-phenethyl ester (CADPE). Caffeic acid phenethyl ester (CAPE) and caffeic acid 3,4-dihydroxy-phenethyl ester (CADPE), two of CA's main derivatives, have been shown to have potential antibacterial, antidiabetic, antioxidant, anti-inflammatory, antineoplastic, and cardioprotective properties (Ekeuku et al., 2021).

*Ferulic acid*; A phenolic molecule that is frequently present in plant tissues, ferulic acid (4-hydroxy-3-methoxycinnamic acid) is a bioactive

ingredient in a variety of foods (Zhao and Moghadasian 2008). The dietary antioxidant ferulic acid (FA) is plentiful and may have protective effects against Alzheimer's disease, diabetes, heart disease, and cancer (Li et al., 2021).

Lycopene is an acyclic isomer of beta carotene (Lowe et al., 2018). Since lycopene does not have the beta-ionone ring structure, it cannot form vitamin A (Helmenstine, 2004). Lycopene, which has the molecular formula of  $C_{40}H_{56}$  (Figure 1), was first studied by Willstätter and Escher (1910) who showed that lycopene is an isomer of carotenes. Karrer et al. (1930) published the chemical structure of lycopene. It was later isolated as a dark red crystalline pigment from *Tamus communis* L. Berries by Hartsen (1873). Millardet (1875) obtained a mixture containing lycopene from tomatoes and named it solanorubin. Schunck (1903) gave the name lycopene after showing that this pigment obtained from tomatoes had an absorption spectrum different from that of carotenes obtained from carrots (Nguyen and Schwartz, 1999).



**Figure 1.** Chemical structure of lycopene

Lycopene is an aliphatic hydrocarbon with 11 conjugated carbon-carbon double bonds, making it soluble in fats and lipids and red in color.

While beta carotene and lutein are found in many different kinds of fruits and vegetables, only a few products contain important other carotenoids such as lycopene (Kumpulainen and Salonen, 1999). Foods containing lycopene are given in Table 1.

Lycopene is found predominantly in the chromoplast of plant tissues. Human bodies are unable to synthesize lycopene. The liver, adrenal glands, and prostate store the majority of the lycopene that is stored. Furthermore, it is present in other bodily areas (such as the skin and brain) in smaller amounts. The bioavailability of lycopene can be reduced by age and certain clinical conditions, including heart disease (Imran et al., 2020). In tomatoes, lycopene

biosynthesis increases dramatically during the ripening process as chromoplasts undergo transformation to chromoplasts (Nguyen and Schwartz, 1999).

**Table 1.** Common food sources of lycopene

Food source	Type	Amount (mg/100 g wet weight)	Amount per serving	
			mg	Serving size
Apricots	Fresh	0.005	0.007	140 g
Apricots	Canned, drained	0.065	0.091	140 g
Apricots	Dried	0.86	0.34	40 g
Chilli	Processed	1.08 to 2.62	1.40 to 3.41	130 g
Grapfruit	Pink, fresh	3.36	4.70	140 g
Guava	Pink, fresh	5.40	7.56	140 g
Guava juice	Pink, processed	3.34	8.35	240 mL (250 g)
Ketchup	Processed	16.60	3.32	1 tbsp (20 g)
Papaya	Red, fresh	2.00 to 5.30	2.8 to 7.42	140 g
Pizza sauce	Canned	12.71	15.89	125 g
Pizza sauce	From pizza	32.89	9.867	125 g
Salsa	Processed	9.28	3.71	2 tbsp (40 g)
Spaghetti sauce	Processed	17.50	21.88	125 g
Tomatoes	Red, fresh	3.1 to 7.74	4.03 to 10.06	130 g
Tomatoes	Whole, peeled, processed	11.21	14.01	125 g
Tomato Juice	Processed	7.83	19.58	240 mL (250 g)
Tomato soup	Canned, condensed	3.99	9.77	245 g
Tomato paste	Canned	30.07	9.02	30 g
Watermelon	Red, fresh	4.10	11.48	280 g
Vegetable juice	Processed	7.28	17.47	240 mL (250 g)

(Singh and Goyal, 2008)

It has been demonstrated that lycopene cis-isomers are more bioavailable and bioactive than the naturally found all trans-isomers. Cis isomers of lycopene can be formed from the all trans forms of it by light, heat, and metabolic processes. Therefore, during the processing of foods, lycopene structure will be changed and as a result, increasing the proportion of cis-isomers. The stability, bioavailability, health effect, and distribution of lycopene isomers are different from each other (Honest et al., 2011). Lycopene's configuration enables it to inactivate free radicals. Because free radicals are electrochemically imbalanced molecules, they are highly aggressive, ready to react with cell components, and cause permanent damage. These toxic chemicals are formed naturally as by-products during oxidative cellular metabolism. As an antioxidant, lycopene has a singlet-oxygen-quenching ability twice as high as that of beta-carotene and ten times higher than that of alpha-tocopherol. Lycopene is fat-soluble, and absorption into tissues is improved when oil is added to the diet. (Helmenstine, 2004).

There are a lot of studies for lycopene some of them are given below;

In their study conducted in 2003, Kana et al. Total lycopene concentration and the concentrations of the cis- and trans-lycopene isomers were measured by HPLC in plasma samples taken 3-4 y apart from 144 mostly

nonsmoking male participants in the Health Professionals Follow-up Study. Results suggest that measuring specific lycopene isomers in epidemiologic studies may not provide additional information beyond that provided by total lycopene concentration. Single plasma samples quantitating plasma lycopene are a valid predictor of long-term exposure for epidemiologic studies. (Kana et al., 2003).

In a study conducted in 2004, Different crystalline lycopene samples obtained from the fermentation process and recrystallized lycopene were analyzed. Structural properties (NMR, mass spectrometry, and powder X-ray diffraction) of lycopene were clarified with recent techniques. High-purity sample analysis by differential scanning calorimetry was used to study the thermal behavior of pure lycopene with traces of isomers. But also this was correlated with the HPLC method for determining lycopene purity and isomers in low proportion. (Estrella et al., 2004).

According to Yang et al., in recent years, the food industry and pharmaceutical industries have expressed a strong interest in the industrial synthesis of lycopene and beta-carotene from tomatoes for the creation of functional meals. First, a new neuro-fuzzy model was presented to model the supercritical CO<sub>2</sub> extraction of lycopene and beta-carotene from tomato paste waste, taking into account many process factors. It can aid in the development of a quality assurance simulation and self-control system, as well as achieving optimal control in industrial production. A simulation analysis demonstrated the efficiency of the proposed model (Yang et al., 2004).

In the study by Hyman et al., product development for higher fruit lycopene content requires a rapid and efficient method for lycopene quantification. Among the available procedures, high-performance liquid chromatography (HPLC) may be accurate; however, it is time-consuming and requires the use of specialized personnel and highly hazardous solvents. Similarly, spectrophotometric procedures, although simpler than HPLC, require time-consuming extractions and may not be as reliable as they often overestimate fruit lycopene levels. Colorimetric assessment of fruit lycopene using chromaticity values has been presented as a faster method. The results showed that fruit lycopene content can be assessed simply and accurately in a wide range of tomato genotypes using chromaticity values obtained from fruit puree (Hyman et al. 2004).

Periago et al. used a simple mixture process design based on the comparison of both quadratic and special cubic models, including three mixture components (hexane/acetone/ethanol), to extract lycopene from raw tomatoes, tomato sauce, and tomato paste, and to test the hypothesis that lycopene extraction rates are a function of the solvent used during the extraction process. Conventional criteria (0.15 or less) were employed to assess the influencing effects in each model. Although hexane was the primary component utilized in lycopene extraction, it exhibited a favorable secondary synergistic interaction with ethanol (all sample types) and acetone (tomato paste samples), showing that a combination of all three components is required to enhance the extraction process. The partial special cubic model yielded three fixed points indicating the hexane, acetone, and ethanol concentrations required for optimal lycopene extraction in raw tomatoes, tomato sauce, and tomato paste (Periago et al., 2004).

The aim of the study by Chonn et al. was to examine the plasma concentration responses of total lycopene and its primary isomers to carotenoid dosing as tomato juice, tomato soup, or synthetic lycopene pills. The findings of this study indicate that the systemic availability of synthetic lycopene from the tablet formulation is similar to that of processed tomatoes (soup from tomato paste) and superior to tomato juice. There was no change in the elimination kinetics of natural and synthesized lycopene. The synthetic lycopene pill formulation used in this study may be useful for future clinical studies (Chohn et al., 2004).

Giuseppe et al. report a new method for extracting lycopene from tomatoes utilizing supercritical carbon dioxide and vegetable oil as a co-solvent. The co-solvent increases the yield of the lycopene extract and improves the pigment's stability. A comprehensive description of the extraction method is also provided. Experiments performed with and without co-solvent at pressures and temperatures ranging from 335 to 450 bar and 45 to 70 °C, respectively, showed that the amount of extractable lycopene depends on the experimental conditions. Furthermore, the maximum amount of extractable lycopene from dried tomatoes (6% moisture, average particle size about 1 mm) was 60% at 450 bar and 66 °C in the presence of co-solvent and using a flow rate of about 20 kg CO<sub>2</sub>/h. The extracts were analyzed by high-performance liquid chromatography and UV-vis spectra (Giuseppe et al., 2004).

## CONCLUSION

Lycopene, a natural carotenoid, stands out as a molecule that has significant biological impacts on human health. It helps to prevent chronic diseases caused by oxidative stress by neutralizing free radicals, thanks to its powerful antioxidant qualities. Lycopene has been shown in studies to lessen the chance of acquiring a variety of health conditions, including cardiovascular disease, cancer, diabetes, and neurological illnesses. However, in vivo and in vitro research to understand the mechanisms of these effects has revealed that a wide range of complex processes are involved, including cellular gene expression regulation, inflammatory modulation, and cellular proliferation control. Lycopene's bioavailability and bioeffectiveness vary according to ingestion type, dietary matrix, processing methods, and individual metabolic variations. It is stressed that consuming lycopene from dietary sources such as tomatoes is more effective, although this effectiveness can be enhanced by using various formulations and nanotechnological transport systems.

As a result, lycopene is being studied as a potential therapeutic agent in modern medicine and nutritional science, as well as a key component in the development of functional foods. However, comprehensive randomized controlled studies and long-term human trials are required to further understand lycopene's biological effects and translate them into clinical applications. In this setting, multidisciplinary approaches to lycopene's effects on health will provide novel perspectives in both science and industry.



## REFERENCES

- Amenaghawon, A. N., Ayere, J. E., Amune, U. O., Otuya, I. C., Abuga, E. C., Anyalewechi, C. L., ... & Darmokoesoemo, H. 2024. A comprehensive review of recent advances in the applications and biosynthesis of oxalic acid from bio-derived substrates. *Environmental Research*, 118703.
- Angumeenal, A. R., & Venkappayya, D. 2013. An overview of citric acid production. *LWT-Food Science and Technology*, 50(2), 367-370.
- Cohn, W et al. 2004. Comparative multiple dose plasma kinetics of lycopene administered in tomato juice, tomato soup or lycopene tablets. *European Journal of Nutrition*. 43: 304-312.
- Dinç, E., Üçer, A., & Ünal, N. 2023. Three-dimensional strategies in the quantitative resolution of kinetic UV absorbance measurements for monitoring the oxidation of quercetin by oxidant agents and analyzing dietary supplement product. *Journal of Food and Drug Analysis*, 31(2), 326.
- Ekeuku, S. O., Pang, K. L., & Chin, K. Y. 2021. Effects of caffeic acid and its derivatives on bone: A systematic review. *Drug design, development and therapy*, 259-275.
- Estrella, A., López-Ortiz, J. F., Cabri, W., Rodríguez-Otero, C., Fraile, N., Erbez, A. J., ... & Muñoz-Ruiz, A. (2004). Natural lycopene from *Blakeslea trispora*: all-trans lycopene thermochemical and structural properties. *Thermochimica acta*, 417(1), 157-161.
- Fernandes, F. H. A., & Salgado, H. R. N. 2016. Gallic acid: review of the methods of determination and quantification. *Critical reviews in analytical chemistry*, 46(3), 257-265.
- Helmenstine, Anne Marine. (2004). *Biochemistry of Lycopene*.
- Honest, K. N., Zhang, H. W., & Zhang, L. 2011. Lycopene: Isomerization effects on bioavailability and bioactivity properties. *Food Reviews International*, 27(3), 248-258.
- Hyman, J. R., Gaus, J., & Foolad, M. R. 2004. A rapid and accurate method for estimating tomato lycopene content by measuring chromaticity values of fruit puree. *Journal of the American Society for Horticultural Science*, 129(5), 717-723.

- Imran, M., Ghorat, F., Ul-Haq, I., Ur-Rehman, H., Aslam, F., Heydari, M., ... & Rebezov, M. 2020. Lycopene as a natural antioxidant used to prevent human health disorders. *Antioxidants*, 9(8), 706.
- Iyyappan, J., Baskar, G., Gnansounou, E., Pandey, A., Raaman, J. K., Bharathiraja, B., & Praveenkumar, R. 2019. Recent advances in microbial production of malic acid from renewable byproducts. *Reviews in Environmental Science and Bio/Technology*, 18, 579-595.
- Kumpulainen, J. T., & Salonen, J. T. 1999. Natural antioxidants and anticarcinogens in nutrition, health and disease (No. 240). Elsevier.
- Levy, J., & Sharoni, Y. 2004. The functions of tomato lycopene and its role in human health. *HerbalGram*, (62).
- Li, D., Rui, Y. X., Guo, S. D., Luan, F., Liu, R., & Zeng, N. 2021. Ferulic acid: A review of its pharmacology, pharmacokinetics and derivatives. *Life sciences*, 284, 119921.
- Lowe, G. M., Graham, D. L., & Young, A. J. 2018. Lycopene: Chemistry, metabolism, and bioavailability. In *Lycopene and Tomatoes in Human Nutrition and Health* (pp. 1-20). CRC Press.
- Nguyen M & Schwartz, S. 1999. Lycopene: Chemical and Biological Properties. *Food Technology*. 53(2): 38-45.
- Periago, M. J., Rincon, F., Agüera, M. D., & Ros, G. 2004. Mixture approach for optimizing lycopene extraction from tomato and tomato products. *Journal of Agricultural and Food Chemistry*, 52(19), 5796-5802.
- Salehi, B., Fokou, P. V. T., Sharifi-Rad, M., Zucca, P., Pezzani, R., Martins, N., & Sharifi-Rad, J. 2019. The therapeutic potential of naringenin: A review of clinical trials. *Pharmaceuticals*, 12(1), 11.
- Singh, P., & Goyal, G. K. 2008. Dietary lycopene: Its properties and anticarcinogenic effects. *Comprehensive Reviews in Food Science and Food Safety*, 7(3), 255-270.
- Vasapollo, G., Longo, L., Rescio, L., & Ciurlia, L. 2004. Innovative supercritical CO<sub>2</sub> extraction of lycopene from tomato in the presence of vegetable oil as co-solvent. *The Journal of Supercritical Fluids*, 29(1-2), 87-96.
- Wang, W., Sun, C., Mao, L., Ma, P., Liu, F., Yang, J., & Gao, Y. 2016. The biological activities, chemical stability, metabolism and delivery systems of quercetin: A review. *Trends in food science & technology*, 56, 21-38.

- Wu, K., Schwartz, S. J., Platz, E. A., Clinton, S. K., Erdman Jr, J. W., Ferruzzi, M. G., ... & Giovannucci, E. L. (2003). Variations in plasma lycopene and specific isomers over time in a cohort of US men. *The Journal of nutrition*, 133(6), 1930-1936.
- Yang, S. X., Shi, W., & Zeng, J. (2004). Modelling the supercritical fluid extraction of lycopene from tomato paste waste using neuro-fuzzy approaches. In *Advances in Neural Networks-ISNN 2004: International Symposium on Neural Networks, Dalian, China, August 19-21, Proceedings, Part II 1* (pp. 880-885). Springer Berlin Heidelberg.
- Zhao, Z., & Moghadasian, M. H. 2008. Chemistry, natural sources, dietary intake and pharmacokinetic properties of ferulic acid: A review. *Food Chemistry*, 109(4), 691-702.

## **CHAPTER 10**

### **GREEN FINANCE AND AGRICULTURE**

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## INTRODUCTION

Globally, the increasing prevalence of environmental issues and their growing impact on the agricultural sector highlight the importance of the concept of sustainable development. In economic transformations, the phenomenon of growth was initially followed by development and subsequently by sustainable development. The concept of sustainable development emerged when economic development proved insufficient. The green economy, on the other hand, is not an alternative to sustainable development but a concept that explains the responsibilities of the public and private sectors (Horasan, 2022). In recent years, global “green finance” practices have accelerated to promote environmental sustainability. The term green finance refers to financing environmentally friendly, beneficial, or less harmful products and projects through opportunities provided by financial institutions. This includes offering low-interest rates, reduced banking fees, and donations to environmental organizations to encourage customers to use “green” financial products (Kuloğlu and Öncel, 2015). Green finance practices aim to reduce environmental harm, ensure sustainable economic growth, and promote green transformation.

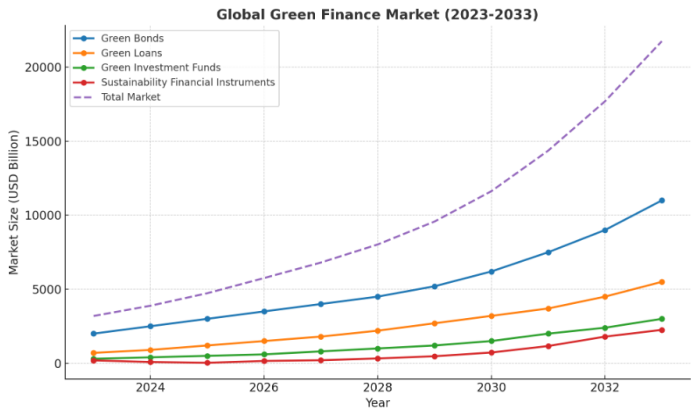
Sustainable development is a method of achieving economic growth and enhancing welfare levels while preserving the environment and the quality of life for all people on Earth (Yücel Engindeniz, 2022). It is known that approximately 25-30% of crop losses occur globally from field to table. Some of these losses are caused by environmental issues. Environmental stress in agricultural production, exacerbated by global warming, affects various physiological processes in crops, potentially leading to quality deterioration and significant losses (Oğurlu et al., 2024a). Environmentally friendly products and technologies used in the agricultural sector play a critical role in preventing product losses (Eroğul et al., 2024; Küçükler et al., 2024a). These practices should be considered integral parts of the entire process, from pre-harvest to harvest and the delivery of products to the consumer. In addition to pre-harvest practices, many post-harvest, human-, and eco-friendly applications can extend the shelf life of products. For example, the use of growth regulators such as aloe vera (Oğurlu et al., 2024b), putrescine (Küçükler et al., 2023), and melatonin (Küçükler et al., 2024b) is now widespread. Reducing the effects of global warming, controlling residue levels, which currently pose significant

challenges in global markets, and promoting environmentally friendly agricultural systems are crucial for sustainable development. Sustainable agriculture falls under the umbrella of sustainable development goals. The greatest success in 21st-century agriculture will be achieving the desired production increase while minimizing adverse environmental conditions. This can only be achieved through the implementation of sustainable methods and permanent solutions in agriculture, the diversification and renewability of resources, and the targeting of long-term stability and efficiency (Yılmaz and Yücel, 2017). At this point, green finance plays a significant role in achieving sustainable development goals in the agricultural sector and reducing environmental impacts.

This study examines developments in global green finance practices, emphasizes the importance of green finance for the agricultural sector, and evaluates various applications within this sector. The primary materials of the study consist of data collected from relevant institutions and the results of previous studies on the topic.

### **GLOBAL GREEN FINANCE MARKET**

The size of the Global Green Finance Market was \$3,192.61 billion in 2023. It is expected to grow by 21.7% annually, reaching approximately \$22,754 billion by 2033 (Figure 1). The green finance market focuses on funding initiatives that have positive environmental impacts. These include investments in renewable energy, sustainable agriculture, and projects aimed at reducing carbon emissions. Green finance encompasses various financial products used to fund environmentally friendly projects, such as green bonds, loans, and equities.



**Figure 1.** Development of Global Green Finance Market  
Source: Market.U.S, 2024.

Europe holds a 35% share of the global green finance market. This leadership stems from strong regulatory frameworks that support sustainable practices and financial incentives for green projects. European governments and institutions prioritize investments in renewable energy and environmentally friendly technologies, driving significant market growth.

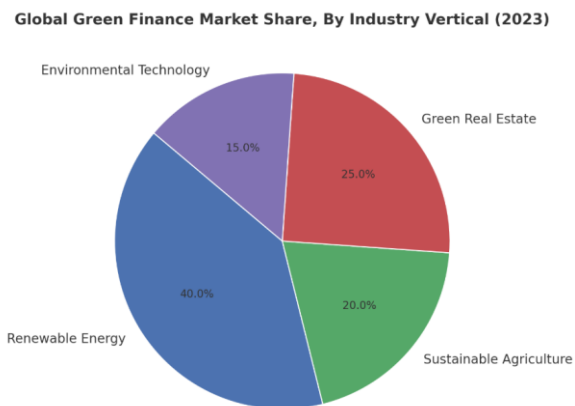
As global awareness of climate change increases, the demand for green finance is also rising. Governments, corporations, and investors play a key role in shaping this market. Green finance is not just about generating profit but also about contributing to a sustainable future. As more organizations commit to reducing their carbon footprints and embracing sustainability, the market is expected to expand further.

Governments and private sectors in various countries recognize the importance of green finance in achieving environmental goals. For instance, the U.S. Department of Energy’s Loan Programs Office has committed over \$40 billion in loans to support renewable energy projects and emerging technologies like carbon capture and hydrogen. In Europe, the EU Green Deal is another major driver of green finance. The EU plans to fund policies outlined in the Green Deal through the InvestEU program, which envisions investments of at least €1 trillion. To meet the ambitious targets of the Green Deal, it is estimated that approximately €260 billion annually will be required by 2030.



Companies issuing green bonds have seen significant improvements in their environmental performance. For example, corporate green bond issuances reached a record \$500 billion in 2021. Renewable energy projects remain crucial for green finance, particularly in the U.S. and Europe. As both public and private sectors commit to large-scale investments, the green finance market is poised for substantial growth. In the U.S., renewable energy accounted for 23% of electricity generation in 2021, and this figure is expected to rise significantly with ongoing investments. The focus on renewable energy, supported by major government programs and corporate initiatives, is expected to continue driving the market forward.

In the green finance market, the renewable energy sector leads with a 45% market share, making it the dominant vertical. This dominance is driven by the global shift toward sustainable energy sources to combat climate change and reduce greenhouse gas emissions. Other key sectors include sustainable agriculture, green real estate, and environmental technology (Figure 2). Each of these sectors utilizes green finance to implement sustainable practices and technologies.



**Figure 2.** Share of Vertical Sectors in the Global Green Finance Market

Source: MarketResearch, 2024.

In Türkiye, banks began providing financial support for eco-friendly projects starting in 2012. Banks utilizing European-sourced funds have offered monthly interest rates starting from 1% and extended loan maturities up to 15 years to support green finance for environmentally friendly projects. Various

foreign banks and funds also provide long-term, low-interest financial support for eco-friendly initiatives through Turkish banks. These include the European Investment Bank, the Council of Europe Development Bank, the European Bank for Reconstruction and Development, the French Development Agency (Proparco), JBIC, and the German Industrialization Fund.

One of the organizations that secures financial support for renewable energy projects from multiple foreign sources is the Türkiye Sustainable Energy Financing Program (TURSEFF). This program offers financial support for eco-friendly projects with interest rates starting from 1% and terms of up to 60 months. In addition to TURSEFF, several other institutions have provided support in the renewable energy sector. These include Vakıfbank, the Industrial Development Bank of Türkiye (TSKB), the Turkish Economy Bank (TEB), Denizbank, and İş Bank.

## **THE IMPORTANCE OF GREEN FINANCE IN THE AGRICULTURAL SECTOR**

Agricultural production activities and the agriculture sector are among the significant contributors to greenhouse gas emissions, which exacerbate global warming. Since 1970, global agricultural output has more than doubled. Emissions from agricultural ecosystems account for 7-20% of the world's total greenhouse gas emissions (Mo et al., 2023).

Green finance plays a critical role in supporting sustainable development in the agricultural sector and reducing environmental impacts. This type of financing promotes environmental sustainability through various means, such as reducing carbon emissions from agricultural activities, preventing pollution, and optimizing agricultural structures. It also plays a vital role in reducing carbon emissions in the agricultural sector. Research conducted in China has shown that green finance can significantly reduce agricultural carbon emission intensity. This financing contributes directly and indirectly to reducing carbon emissions by optimizing the agricultural industrial structure and driving technological advancements in agriculture (Mo et al., 2023).

Additionally, green finance is essential for enhancing the resilience of rural economies. Rural economies, being dependent on natural resources, are particularly vulnerable to climate change and environmental degradation. Green finance helps rural areas invest in sustainable agricultural practices,

renew aging infrastructure, implement resource conservation projects, and adopt clean energy and energy efficiency technologies (Liu, 2024).

Green finance also creates new opportunities for businesses engaged in agricultural product imports and exports. It has become a fundamental means of providing funds to import and export businesses. Specifically, green finance enables businesses to make environmental improvements and technological upgrades in their production processes, effectively reducing pollution (Huang and Zhang, 2021; Yinghan et al., 2023).

In terms of optimizing agricultural structures, green finance is a critical element. Research in China has revealed that green finance can effectively contribute to improving the agricultural industrial structure. This process highlights the importance of innovative green financial services, enhanced efficiency, and regional approaches. The robust support provided by green finance allows for the restructuring of the agricultural industrial framework through sufficient funding. It facilitates the large-scale and professional development of agriculture, modernizes production and business models, creates economies of scale, and promotes the optimization of the agricultural industrial structure. This optimization makes agricultural production processes more sustainable while also contributing to the reduction of environmental impacts (Zhu et al., 2023).

On the other hand, green finance emerges as an effective tool for reducing agricultural pollution. A study conducted in China demonstrated that green finance significantly reduces agricultural non-point source pollution (ANSP) and that its effectiveness varies regionally. Green finance contributes to reducing agricultural pollution by facilitating agricultural scaling and promoting the adoption of green technologies (Geng et al., 2024).

## **GREEN FINANCE APPLICATIONS IN THE AGRICULTURAL SECTOR**

### **Green Bonds**

Green bonds are debt instruments issued by the private sector, public sector, or multilateral organizations to finance environmentally friendly and climate-conscious projects in compliance with the four core principles of green bonds (Özkan, 2019).

These principles are briefly explained below:

- Funds raised through the issuance of green bonds must be used exclusively for green projects, and this must be explicitly stated in writing during the issuance process.
- The green bond issuer must clearly define how green projects will be selected and evaluated.
- Transparent management must provide information regarding the management of the funds, and it is even recommended to seek support from an external auditor in this regard.
- The green bond issuer must prepare and publish regular reports on the management of bond funds (Özkan, 2019).

Green bonds are financial instruments that can be utilized in the agricultural sector to promote sustainable agricultural practices, adapt to climate change, and reduce environmental impacts. Agricultural enterprises can issue green bonds to finance environmentally friendly projects. While the issuance of green bonds in Türkiye is limited, it has begun. However, there has not yet been a direct issuance of green bonds specifically targeted at the agricultural sector. Most of the green bonds issued so far have been used to finance energy and infrastructure projects, which indirectly affect the agricultural sector.

In 2016, the Industrial Development Bank of Türkiye (TSKB) was the first to issue a green bond in Türkiye. TSKB, under the coordination of seven banks, issued a \$300 million, five-year Green/Sustainable Bond. The issuance received significant demand in international markets, with approximately \$4 billion in orders from 317 institutional investors (URL 1). In 2022, Yapı Kredi Bank issued a \$50 million, five-year green bond to finance renewable energy projects (URL 2). In 2017, Garanti Bank issued a \$150 million green bond under the Mortgage-Backed Securities Program (ITMK) in collaboration with the International Finance Corporation (IFC). This bond contributed to financing environmentally friendly projects, including energy-efficient buildings. In 2019, under the GMTN (Global Medium Term Notes) program, a five-year \$50 million green bond was issued, with the funds aimed at supporting new or ongoing projects addressing climate change (URL 3). On August 21, 2019, İş Bank issued its first green bond. This issuance also marked the first 100%

Green Eurobond transaction conducted by a Turkish bank. The issuance amount was \$50 million, and the bond had a maturity of 10 years (URL 4).

### **Carbon Credits**

A Carbon Credit is a certificate obtained from projects that prevent greenhouse gas emissions or reduce them, corresponding to 1 ton of carbon dioxide (CO<sub>2</sub>). Carbon Credits can also be defined as assets traded on voluntary carbon markets and used in carbon trading. These credits are generated through various projects and are approved and listed by internationally authorized non-profit organizations (URL 5).

In the agricultural sector, practices such as compost use, green fertilization, the use of agricultural waste for biogas production, energy-efficient irrigation systems, rainwater harvesting, organic farming, good agricultural practices, and no-tillage farming are examples of methods that reduce carbon footprints. Agricultural enterprises can generate revenue from carbon markets by adopting practices that reduce their carbon footprint.

In Türkiye, carbon pricing efforts began in 2013 with the Partnership for Market Readiness (PMR) Project. This project, which lasted approximately seven years, examined the impact of carbon pricing mechanisms on the national economy, budget, and sectors. It concluded that the most suitable carbon pricing mechanism for Türkiye is the Emissions Trading System (ETS). In 2021, the Paris Climate Agreement was ratified by the Turkish Grand National Assembly, and the country announced its net-zero carbon target for 2053. During Türkiye's first Climate Council held in Konya from February 21 to 25, 2022, the "Green Finance and Carbon Pricing" commission was established. Under this main commission, "Carbon Pricing and Emissions Trading System" was also discussed (Ministry of Environment, Urbanization, and Climate Change, 2024). The Energy Market Regulatory Authority (EPDK) prepared a draft regulation titled "Regulation on the Operation of Carbon Markets" to establish and operate carbon markets aimed at encouraging the reduction of greenhouse gas emissions under the emissions trading system. This draft regulation was submitted for public consultation on November 13, 2023 (EPDK, 2023). The official launch of the "Türkiye Carbon Market Development Project," part of the World Bank's Partnership for Market Implementation (PMI) program, took place on April 30, 2024. The project aims

to contribute to achieving the 2053 Net Zero Emission Target and utilizing carbon markets in line with climate objectives. Additionally, it seeks to establish a national ETS, thereby creating a strong connection with the Draft Regulation (Ministry of Environment, Urbanization, and Climate Change, 2024).

### **Green Loans**

Green loans are loans provided to finance environmentally friendly projects. In Türkiye, green loans in the agricultural sector are offered by banks for purposes such as improving water efficiency, achieving energy savings, and promoting eco-friendly farming practices. For example, Ziraat Bank offers a renewable energy investment loan for businesses to meet their energy needs through renewable energy systems. Additionally, the bank provides Energy Efficiency Investment Loans to upgrade machinery and equipment in existing facilities to energy-efficient technologies. It also offers loan support for investments under the European Union's "Instrument for Pre-Accession Assistance - Rural Development Component" (IPARD) Program (Ziraat Bank, 2024). Garanti Bank supports sustainable agriculture by offering projects such as organic farming, more efficient water usage, direct seeding, and energy efficiency in agriculture (e.g., Agricultural Solar Power Plants) at low-interest rates (Garanti Bank, 2024). İş Bank provides green loan products and financing options for eco-friendly investments, including energy efficiency loans and rooftop solar power plant loans (Türkiye İş Bank, 2024).

### **Green Project Financing Loans**

Türkiye also receives financial support from international organizations under the framework of sustainable agriculture. On March 30, 2022, the World Bank approved a loan worth USD 341.27 million to support sustainable and competitive agricultural growth in Türkiye. This loan aims to ensure the more efficient use of approximately 14 million hectares of agricultural land, improve the diagnosis of animal diseases, increase resource efficiency, and implement environmentally friendly technologies in agriculture to reduce carbon emissions. Over 80,000 farmers, service providers, and veterinarians are expected to benefit directly from the project. The approval of this loan is anticipated to contribute to Türkiye's efforts to achieve its 2053 net-zero emissions target (Ada, 2022).

## Grants and Incentives

The agricultural sector is supported by various grant and incentive programs in all countries. Organic farming is one of the sustainable agricultural practices. It is defined as a type of farming that aims to conduct plant or animal production without disrupting the balance of nature, using suitable ecologies, and relying only on cultural measures, biological control, and organic inputs instead of synthetic chemical inputs (Kızılaslan and Olgun, 2012). Support payments are provided to encourage producers to adopt organic farming systems and continue production. For 2024, individual producers registered in the Farmer Registration System are eligible for payments of 270 TL per decare for first-category products, 110 TL per decare for second-category products, 135 TL per decare for first-category products for producer groups, 55 TL per decare for second-category products, and 50 TL per decare for third-category products for both individual producers and producer groups (TOB, 2024).

Integrated pest management (IPM) is an approach developed to promote sustainable agriculture. It is described as the safe, cost-effective, and environmentally friendly combination of existing pest control methods (cultural, mechanical, biological, chemical, etc.) to suppress pests (Inak et al., 2019). Producers applying biological and biotechnical pest control are provided with support payments covering approximately half of the control costs.

In agricultural production, systems such as drip irrigation and sprinkler irrigation ensure the efficient and effective use of water. Under the Individual Irrigation Systems Support Program, grants of up to 50% are provided for investments related to the installation of in-field drip irrigation systems, sprinkler irrigation systems, micro-sprinkler irrigation systems, subsurface drip irrigation systems, linear or center pivot irrigation systems, reel irrigation systems, solar-powered irrigation systems, and agricultural irrigation solar energy systems, as well as smart irrigation systems (TOB, 2024).

In Türkiye, the Renewable Energy Sources Support Mechanism (YEKDEM) was initiated under Law No. 5346 on the Use of Renewable Energy Sources for the Purpose of Generating Electrical Energy (YEK Law), enacted on 18/05/2005. Within this framework, facilities based on renewable energy that commenced production by 31/12/2021 were provided with incentives for 10 years (Ada, 2022).

## **Agricultural Insurance**

In Türkiye, various insurance products provide risk management, especially against environmental factors such as climate change, drought, and natural disasters. The Agricultural Insurance Pool (TARSİM) offers insurance coverage against natural disasters in the agricultural sector. This type of insurance provides financial security against adverse environmental events such as drought, hail, frost, storms, and floods. Additionally, insurance products promoting eco-friendly farming practices, such as water management, soil conservation, and carbon emission reduction, have been developed.

## **CONCLUSION**

Green finance is a critical tool for supporting sustainable development in the agricultural sector. It promotes environmental sustainability through various means, such as reducing carbon emissions, optimizing agricultural structures, minimizing pollution, improving agricultural trade, and enhancing the resilience of rural economies. Therefore, the broader adoption of green finance in the agricultural sector will significantly contribute to the widespread implementation of sustainable farming practices and the reduction of environmental impacts.

Particularly in developing countries, it is necessary to disseminate and enhance expertise in green finance among stakeholders in the financial system. Market regulators, banks, portfolio management companies, capital market supervisory authorities, as well as policymakers and industries outside the financial services sector, need to incorporate green finance specialists. The lack of expertise in green finance, as is the case globally, will pose a significant challenge in the future.

Awareness of green finance must be increased. Companies should be better informed about the concept of green finance and the opportunities it offers. By organizing seminars and training programs, firms' knowledge and understanding of this field can be enhanced.

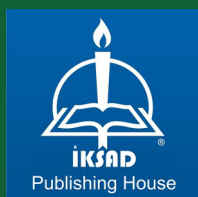


## REFERENCES

- Ada, S. 2022. Sürdürülebilir Finans Yaklaşımı Çerçevesinde Yeşil Bankacılık ve Yeşil Finansman Araçları. Yüksek Lisans Tezi, Trakya Üniversitesi, Sosyal Bilimler Enstitüsü, Edirne.
- Anonymous, 2024. Green Finance: Definition, Types, Benefits and Situation in Türkiye, <https://www.quickcarbon.com/tr/blog/yesil-finansman-tanimi-turleri-faydalari-ve-turkiyedeki-durumu/>, Access date: December 2024.
- Eroğul, D., Gündoğdu, M., Şen, F., Taş, A. 2024. Impact of Postharvest Calcium Chloride Treatments on Decay Rate And Physicochemical Quality Properties in Strawberry Fruit. BMC Plant Biology, 24(1), 1088.
- Garanti Bank, 2024. <https://www.garantibbva.com.tr/>, Access date: October 2024.
- Geng, G., Shen, Y., & Dong, C. 2024. The Impact of Green Finance on Agricultural Non-Point Source Pollution: Analysis of the Role of Environmental Regulation and Rural Land Transfer. Land, 13(9), 1516. <https://doi.org/10.3390/land13091516>
- Huang, H., Zhang, J. 2021, Research on the Environmental Effect of Green Finance Policy Based on the Analysis of Pilot Zones for Green Finance Reform and Innovations. Sustainability, 13, 3754, <https://doi.org/10.3390/su13073754>
- Horasan, M. 2022. Yeşil Finansı Anlamak, İktisadi ve İdari Bilimlerde Güncel Araştırmalar, Editör: Mete, M., Toptaş, A., Gece Kitaplığı, Ankara, ss.221-235.
- Inak, E., Özdemir, E., Alpkent, Y.N., Inak, A., Özkan, C. 2019. Entegre Zararlı Yönetimi ve Gelişmekte Olan Ülkelerdeki Durumu. Harran Tarım ve Gıda Bilimleri Dergisi, 23(1):120-130.
- Kızılaslan, H., Olgun, A. 2012. Türkiye’de Organik Tarım ve Organik Tarıma Verilen Desteklemeler. GOÜ Ziraat Fakültesi Dergisi, 29 (1): 1-12.
- Kuloğlu, E., Öncel, M. 2015. Yeşil Finans Uygulaması ve Türkiye’de Uygulanabilirliği. Gazi Üniversitesi Sosyal Bilimler Dergisi, 2(2): 2-19.
- Küçükler, E., Ağlar, E., Sakaldaş, M., Şen, F., Gündoğdu, M. 2023. Impact of Postharvest Putrescine Treatments on Phenolic Compounds, Antioxidant Capacity, Organic Acid Contents and Some Quality Characteristics of Fresh Fig Fruits During Cold Storage. Plants, 12(6): 1291.

- Küçüker, E., Kuru Berk, S., Melda Çolak, A., Gündoğdu, M. 2024a. Melatonin Use in Post-harvest Fruit Physiology: Effect of Melatonin Treatments on Quality Properties, Primer and Seconder Metabolites Contents of Hawthorn Fruit During Cold Storage. *Journal of Plant Growth Regulation*, 1-14.
- Küçüker, E., Gündoğdu, M., Ağlar, E., Oğurlu, F., Arslan, T., Özcengiz, C. K., Tekin, O. 2024b. Physiological Effects of Melatonin on Polyphenols, Phenolic Compounds, Organic Acids and Some Quality Properties of Peach Fruit During Cold Storage. *Journal of Food Measurement and Characterization*, 18(1): 823-833.
- Liu, Z. 2024. Assessing the Role of Green Finance in Enhancing Rural Economic Resilience and Environmental Sustainability. *Frontiers in Management Science* 3(1):82-89.
- Market.Us, 2024. Global Green Finance Market Report, <https://market.us/report/green-finance-market/#overview>, Access date: December 2024.
- MarketResearch, 2024. Global Green Finance Market Report, <https://marketresearch.biz/report/green-finance-market/>, Access date: December 2024.
- Mo Y, Sun D, Zhang Y. 2023, Green Finance Assists Agricultural Sustainable Development: Evidence from China. *Sustainability*. 15(3):2056. <https://doi.org/10.3390/su15032056>.
- Oğurlu, F., Küçüker, E., Ağlar, E., Kızgın Özcengiz, C., Uyak, C. (2024a). New Approaches in Pear Preservation: Putrescine and Modified Atmosphere Packaging Applications to Maintain Fruit Quality During Cold Storage. *Food Science and Nutrition*, 12(9), 6627-6636.
- Oğurlu, F., Küçüker, E., Ağlar, E. 2024b. Effects of Aloe vera and Modified Atmosphere Packaging on the Quality and Biochemical Properties of Pear Fruit During Cold Storage. *Applied Fruit Science*, 6:823-832.
- Özkan, T. 2019. Yeşil Tahvil Piyasaları: Türkiye Örneği. *PAP-IFC- 10(14):73-75*.
- Tarım ve Orman Bakanlığı (TOB), 2024. Tarımsal Destekler. <https://www.tarimorman.gov.tr/>, Erişim Tarihi: Kasım 2024.
- T.C. Çevre, Şehircilik ve İklim Değişikliği Bakanlığı, 2024. <https://csb.gov.tr/>, Erişim Tarihi: Kasım 2024.

- T.C. Enerji Piyasası Düzenleme Kurumu (EPDK), 2023. <https://www.epdk.gov.tr/>, Erişim Tarihi: Kasım 2024.
- T.C. Ziraat Bank, 2024. <https://www.ziraatbank.com.tr/tr>, Erişim Tarihi: Kasım 2024.
- Türkiye İş Bank, 2024. <https://www.isbank.com.tr/>, Access date: October, 2024.
- URL 1. <https://www.tskb.com.tr/hakimizda/bizi-taniyin/haberler/turkiyenin-ilk-yesil-tahvili-tskbden>, Access date: December, 2024.
- URL 2. <https://www.yapikredi.com.tr/blog/surdurulebilirlik/finansal-okuryazarlik/detay/surdurulebilir-ekonomide-yesil-tahvil>, Access date: December, 2024.
- URL 3. <https://www.garantibbva.com.tr/blog/yesil-tahvil-ve-surdurulebilir-ekonomi>, Access date: December, 2024.
- URL 4. <https://www.isbank.com.tr/bankamizi-taniyin/yesil-ekonomiye-katki-saglayan-urunler>, Access date: December, 2024.
- URL 5. <https://www.casem.com.tr/karbon-kredisi-nedir/>, Access date: December, 2024.
- Wang, Y., Liu, H., Zhou, J., Zang, D., Shen, Q. 2023. The Impact of Green Finance on China's Agricultural Trade, Sustainability 15(9):7688. <https://doi.org/10.3390/su15097688>
- Yılmaz, Ö., Yücel, G.E. 2017. Sürdürülebilir Kalkınma Sürecinde Türkiye'nin Tarımda Yaşadığı Dönüşüm. Süleyman Demirel Üniversitesi İktisadi ve İdari Bilimler Fakültesi Dergisi, 22(1):179-199.
- Yücel Engindeniz, D., 2022. Sosyal Inovasyonun Kırsal Kalkınma Açısından Değerlendirilmesi, Tarım Bilimleri Alanında Multidisipliner Güncel Yaklaşımlar, Editör: Yazıcı, K., Doğan, H., Iksad Yayınevi, Ankara, ss.47-71.
- Zhu, M., Sun, M., Elahi, E., Li, Y., Khalid, Z. 2023. Analyzing the Relationship between Green Finance and Agricultural Industrial Upgrading: A Panel Data Study of 31 Provinces in China. Sustainability. <https://doi.org/10.3390/su15129813>.



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