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INTERNATIONAL ACADEMIC RESEARCH AND STUDIES IN

AGRICULTURE, FORESTRY AND AQUACULTURE SCIENCES

EDITORS

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CONTENTS

Chapter 1

ELECTROSTATIC ORCHARD SPRAYING: A COMPREHENSIVE REVIEW

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1.Introduction

The application of plant protection products in orchard systems is an essential yet complex component of modern fruit production. As global demand for high-quality fruits increases, so does the need for effective pest and disease control methods that minimize environmental damage and production costs. Traditionally, hydraulic and air-blast sprayers have been used extensively in orchards. These systems, while widely adopted, often suffer from inefficiencies such as poor droplet deposition, high chemical drift, and overuse of agrochemicals, resulting in significant environmental and economic concerns (Law, 2001; Patel, 2016).

In recent years, electrostatic spraying technology has gained prominence as an innovative alternative to conventional methods. By imparting an electric charge to the liquid droplets, electrostatic sprayers significantly enhance the ability of pesticides to adhere to plant surfaces, including the undersides of leaves and complex canopy structures (Urkan et al., 2016). This not only reduces chemical waste and environmental pollution but also improves the uniformity and efficacy of crop protection treatments.

1.2 Emergence of Electrostatic Spraying in Orchard Systems

Orchards, with their vertical growth patterns and dense canopies, present unique challenges for uniform pesticide coverage. Achieving sufficient droplet deposition on all parts of the plant, especially the lower and inner surfaces, is difficult with conventional sprayers due to gravitational limitations and air turbulence (Mishra et al., 2014). Electrostatic spraying addresses these challenges through electrostatic attraction between the charged droplets and the grounded or neutral plant surfaces, enabling a wrap-around effect that significantly improves coverage.

Electrostatic spraying was initially explored in industrial and painting applications in the early 20th century and later adapted for agricultural use. From the 1980s onward, it began to attract significant attention in the agricultural engineering community due to its potential to reduce pesticide usage while enhancing application efficiency (Law, 2001; Law, 2008). Its relevance in orchard systems became increasingly evident as research demonstrated notable improvements in droplet deposition, reduction of drift, and improved targeting in field trials (Salcedo et al., 2023).

1.3 Environmental and Economic Relevance

The environmental burden associated with excessive pesticide use is a growing global concern. Agricultural pesticide drift contributes to soil and water contamination, non-target organism exposure, and overall ecological imbalance. As part of sustainable agriculture initiatives and regulatory policies—such as the European Green Deal and the United Nations Sustainable

Development Goals (SDGs)—farmers and policymakers are seeking solutions that promote precision and efficiency in crop protection.

Electrostatic spraying offers several advantages in this context. Studies have shown that this technology can reduce pesticide use by up to 50%, primarily due to better targeting and deposition (Zhang et al., 2021). This results in both economic savings for growers and a lower environmental footprint, supporting the global transition toward climate-smart agriculture.

Suggested Table: Comparison of application efficiency, pesticide savings, and drift potential between electrostatic and conventional sprayers.

This chapter aims to provide a comprehensive overview of electrostatic spraying technology in orchard applications. It begins with the fundamental physical principles underlying the technology and proceeds to evaluate the technical parameters influencing its effectiveness. Applications across different orchard crops are discussed, supported by real-world case studies and comparative data. Furthermore, the chapter evaluates the environmental and economic benefits of electrostatic systems relative to conventional methods, while also acknowledging existing limitations and technological challenges.

2.Principles of Electrostatic Spraying in Agriculture

2.1 Introduction to Electrostatic Phenomena

Electrostatic spraying relies on the interaction between electrically charged particles and neutral or grounded targets. In agriculture, the primary goal of electrostatic application is to enhance the efficiency of droplet deposition on plant surfaces by leveraging Coulombic forces. These forces occur when liquid droplets, carrying a net electrical charge, are attracted to plant tissues that have an opposite or neutral charge, resulting in improved adhesion and coverage (Law, 2001).

Electrostatic spraying transforms the physical principles of electrostatics into a practical agricultural application. Compared to conventional methods, it offers greater control over droplet trajectory, reduction in spray drift, and increased deposition on hidden or complex surfaces such as the undersides of leaves (Appah et al., 2019).

2.2 Methods of Droplet Charging

The process of droplet charging is central to electrostatic spraying. There are three main mechanisms through which agricultural sprayers impart charge to droplets:

a) Induction Charging

This is the most commonly used method in agricultural electrostatic sprayers. A high-voltage electrode is placed near the nozzle, and as the liquid passes through the spray system, it becomes polarized by the electric field and picks up a charge. The advantage of this method is that there is no direct contact between the electrode and the fluid, making it safer and more reliable in field conditions (Mostafaei et al., 2009).

b) Corona Charging

This method involves generating a corona discharge—an ionized gas cloud around a sharp electrode—through which the droplets pass and acquire charge. While effective, corona charging systems require precise voltage regulation and are more susceptible to ambient humidity and temperature changes (Wang et al., 2025).

c) Contact Charging

In this less commonly used method, droplets are directly charged by passing through or over a conductive surface connected to a high-voltage power source. Though capable of delivering high charge densities, contact charging systems are often limited by wear, corrosion, and maintenance issues in field conditions.

2.3 The Charge-to-Mass Ratio (q/m)

The charge-to-mass ratio (q/m) is a key parameter that determines the effectiveness of electrostatic spraying. It refers to the amount of electrical charge per unit mass of liquid (expressed in μC/kg). Higher q/m values increase the attraction force between droplets and the plant surface, leading to better deposition and wrap-around effects (Law, 2014). However, excessively high values can result in droplet repulsion or discharge into the air, thus reducing application efficiency.

Typical q/m values in agricultural ESS systems range between 0.5–2.5 μC/kg, depending on the nozzle design, voltage input, and fluid properties (Appah et al., 2019).

2.4 Factors Influencing Electrostatic Spraying Efficiency

Several factors affect the overall effectiveness of electrostatic spraying in orchard environments:

- **Voltage Input:** Most ESS systems operate between 5–20 kV. Higher voltages increase the q/m ratio but may lead to arcing or safety risks.

- **Nozzle Type and Geometry:** The design of the nozzle influences droplet size, distribution, and charging efficiency. Hollow cone and flat fan nozzles are commonly adapted for ESS.

- **Liquid Conductivity:** Electrostatic charging is more effective when the liquid has moderate conductivity. Highly conductive or non-conductive fluids may cause erratic droplet behavior (Mostafaei et al., 2009).

- Droplet Size: Smaller droplets have a higher surface-to-mass ratio, which enhances their ability to retain electric charge. However, they are also more prone to drift.

- Environmental Conditions: Wind speed, temperature, and humidity directly impact the behavior of charged droplets during flight and upon contact with plant surfaces.

2.5 Wrap-Around Effect and Leaf Penetration

One of the most cited advantages of electrostatic spraying is the wrap-around effect—the ability of charged droplets to move around obstacles and deposit on the rear surfaces of leaves due to electrostatic attraction. This effect greatly improves coverage in dense orchard canopies where airflow-based deposition (as in air-blast sprayers) is limited (Kargar et al., 2025).

Additionally, electrostatic spraying has been shown to enhance penetration into canopy interiors without requiring excessive air pressure or spray volume, which minimizes runoff and environmental contamination.

3. System Components and Engineering Design

3.1 Overview of Electrostatic Spraying System Architecture

Electrostatic spraying systems are comprised of several interconnected subsystems that work in tandem to generate, charge, and direct pesticide droplets toward plant surfaces. The overall performance and reliability of these systems depend on the integration of mechanical, electrical, and fluid dynamic components, optimized for the specific needs of orchard environments (Law, 2001; Wang et al., 2025).

Typical electrostatic sprayers used in orchard settings include the following core components:

- Spray nozzle(s)
- High-voltage power supply
- Liquid delivery system (pump and reservoir)
- Charging mechanism
- Air-assisted unit
- Mounting platform (tractor, UAV, or backpack unit)

3.2 Spray Nozzle Design

The spray nozzle is a critical component influencing droplet size, spray angle, flow rate, and the effectiveness of charge transfer. In electrostatic sprayers, nozzles must not only atomize the liquid but also ensure proximity to the electric field generator.

Common nozzle types include:

· Hollow cone nozzles – for large canopy penetration.

· Flat fan nozzles – for uniform distribution on row crops or low canopies.

· Air-assisted nozzle**s** – integrated with airflow systems to support long-range delivery.

In electrostatic systems, nozzles are often made from non-conductive or semi-conductive materials to minimize electrical leakage and are placed near the charging electrode (Appah et al., 2019).

3.3 High-Voltage Power Supply

The power supply is the heart of an electrostatic sprayer, typically generating voltages between **5** and 20 kV**,** depending on system design and application scale. Key features of agricultural power units include:

· Low current, high voltage output for safe operation.

· Insulated cabling and connector**s** to prevent leakage or arcing.

· Voltage regulation modules for maintaining consistent output.

Most systems operate on DC power provided by rechargeable batteries or tractor PTO-powered generators. Transformer-rectifier unit**s** are commonly used to convert 12V input to high-voltage DC (Zhou et al., 2024).

3.4 Droplet Charging Mechanism

As covered in Title 2, charging occurs near the nozzle through either induction, corona, or contact-based methods. In orchard sprayers, induction charging is most prevalent due to its durability and simplicity in variable field conditions (Mostafaei et al., 2009).

Design considerations for efficient charging include:

· Electrode distance from nozzle exit point

· Material selection (tungsten or stainless-steel, aluminum electrodes)

· Electrode tip geometry, which affects field strength and droplet exposure

Proper grounding of plant surfaces (usually passive via the Earth) is essential for maintaining the required electric potential difference that attracts charged droplets.

3.5 Liquid Delivery System

The pesticide solution is delivered via a pump-reservoir-nozzle system, similar to conventional sprayers. However, electrostatic systems generally require:

- Lower flow rates due to higher deposition efficiency.
- Pulsation dampers to ensure steady flow for consistent droplet formation.
- Filters and anti-clogging valves due to finer droplet size and nozzle sensitivity.

Flow rates typically range between 0.5–2.5 L/min/nozzle, depending on tree height and canopy density (Kargar et al., 2025).

3.6 Mounting and Mobility Platforms

Electrostatic orchard sprayers may be configured on various platforms, including:

- Tractor-mounted air-blast sprayers retrofitted with electrostatic systems.
- Backpack sprayers for small orchards or experimental use.
- UAV-based systems with compact electrostatic modules for precision agriculture (Zhang et al., 2021).

Mounting configuration affects stability, spray distance, and penetration. For orchards with tall, dense trees, multi-nozzle vertical arrays are often used.

3.7 System Integration and Control

Modern ESS systems often feature automated or semi-automated controls, allowing operators to adjust:

- Voltage output
- Flow rate
- Spray timing and targeting zones

These features can be integrated with GPS systems, ultrasonic sensors, and plant recognition AI models to enhance accuracy and minimize chemical overuse (Li et al., 2025).

Additionally, safety mechanisms such as voltage cutoffs, grounding monitors, and nozzle shutdowns are vital to protect both operators and crops from overexposure.

4. Droplet Behavior and Canopy Interaction

In orchard environments, achieving uniform and effective pesticide deposition is challenged by complex plant architecture, including dense, multilayered canopies and irregular leaf orientations. The behavior of spray droplets—especially when electrostatically charged—is a critical determinant of application efficiency. Factors such as droplet size, charge-to-mass ratio, canopy structure, leaf surface properties, and airflow dynamics all influence how droplets interact with leaves, including whether they deposit, bounce, coalesce, or drift (Amaya & Bayat, 2023; Wang et al., 2025).

Electrostatic spraying enhances this interaction through electrostatic attraction, which increases deposition efficiency even under suboptimal spray angles or coverage conditions.

4.2 Droplet Trajectory and Deposition Dynamics

Electrostatically charged droplets differ from neutral droplets in their motion. Upon leaving the nozzle, they are influenced by:

- Initial kinetic energy (from nozzle pressure or air-assist)
- Gravitational pull
- Aerodynamic resistance
- Coulombic attraction to plant surfaces (particularly if grounded or neutral)

Amaya and Bayat (2023) demonstrated that droplets with a charge-to-mass ratio above 1.2 μC/kg can deviate from their ballistic paths to curve toward target surfaces, especially when leaves are electrically grounded or located behind initial impact zones. This phenomenon is known as the wrap-around effect, and it significantly enhances the deposition on the undersides of leaves, a known weak point in conventional spraying (Appah et al., 2019).

4.3 Leaf Surface Interaction: Adhesion, Bounce, and Retention

Once a droplet reaches a plant surface, three primary outcomes are possible:

- Adhesion: The droplet sticks to the surface, spreading or remaining intact.
- Bounce/Rebound: The droplet impacts the surface and bounces off.
- Runoff: The droplet spreads and flows away, contributing to pesticide loss.

The contact angle, surface roughness, cuticular wax, and leaf inclination significantly influence this behavior. Electrostatic charging increases the probability of adhesion by generating attractive forces at the moment of impact, counteracting bounce—especially on waxy or hydrophobic surfaces (Amaya & Bayat, 2024).

In their trials, Bayat et al. (1994) observed a 47% reduction in bounce rate on citrus leaves when using induction-charged droplets compared to conventional hydraulic sprays.

4.4 Effect of Canopy Density and Leaf Arrangement

Orchard crops such as apple, pear, and citrus exhibit dense, stratified canopies. Inner leaves and fruit are often shielded from direct droplet paths. In such conditions:

- Electrostatic attraction enables targeting behind obstacles
- Smaller, charged droplets can penetrate deeper into foliage layers
- Deposition becomes less dependent on spray direction

Zhou et al. (2024) reported that droplet penetration depth increased by 65% in apple trees when using air-assisted electrostatic nozzles compared to air-blast sprayers.

4.5 Droplet Coalescence and Coverage Uniformity

Multiple droplets depositing in close proximity can coalesce, potentially reducing surface coverage. While this is a known issue in high-volume spraying, electrostatic spraying minimizes coalescence by producing finer droplets and controlling flow rate. Moreover, the repulsion between like-charged droplets promotes more uniform spatial distribution (Law, 2001).

Kargar et al. (2025) demonstrated that implementing pulsed-voltage modulation in electrostatic spraying systems improved mid-canopy leaf surface coverage by 28% compared to constant-voltage systems, with reduced droplet clustering and lower drift losses.

4.6 Influence of Environmental Conditions

Environmental factors such as wind speed, humidity, and temperature also impact droplet behavior:

- Wind can enhance or distort trajectory; however, charged droplets show greater directional stability due to electrostatic attraction.
- Humidity affects droplet evaporation and charge retention.
- High temperature can increase drift through faster evaporation, but smaller charged droplets are less susceptible to thermal rise compared to larger uncharged ones (Wang et al., 2025).

Proper nozzle-to-target distance and spray angle adjustments are necessary to counteract these variables in real orchard conditions.

5. Performance Comparison with Conventional Sprayers

The choice of spraying technology significantly impacts the efficiency, cost, and environmental footprint of pesticide applications in orchard management. Conventional sprayers, such as hydraulic nozzles and air-blast sprayers, have long been the standard for chemical application in fruit production. However, their effectiveness is limited by non-uniform droplet deposition, drift, and excessive chemical runoff. In contrast, electrostatic spraying systems (ESS) promise improved efficiency, reduced chemical usage, and enhanced deposition—especially in dense canopies (Law, 2001; Bayat & Amaya, 2023).

This chapter presents a comparative analysis of electrostatic and conventional sprayers, focusing on key performance indicators such as deposition efficiency, drift reduction, chemical usage, energy consumption, and economic viability.

5.1 Deposition Efficiency

Electrostatic sprayers utilize Coulombic attraction between charged droplets and plant surfaces, allowing for more targeted deposition. Several studies have shown that ESS provides 30–300% greater deposition than conventional air-blast systems, particularly on the undersides of leaves and inner canopy layers (Appah et al., 2019; Wang et al., 2025).

For example, Amaya and Bayat (2024) found that charged droplets achieved 74% more coverage in mid- and lower-canopy zones of citrus orchards compared to uncharged hydraulic sprays.

5.2 Chemical Usage and Spray Volume Reduction

One of the major advantages of ESS is the potential to reduce total chemical input without compromising efficacy. By improving deposition, ESS can lower the required spray volume while maintaining pest control performance.

Bayat and Amaya (2023) reported up to 50% reduction in pesticide usage in orchard applications when switching from air-blast to electrostatic systems. This not only reduces costs but also aligns with international sustainability targets and Integrated Pest Management (IPM) practices (Zhou et al., 2024).

5.3 Drift Reduction

Drift—defined as the unintended movement of pesticide droplets away from the target—is a critical issue in orchard spraying, especially in windy conditions or near sensitive ecosystems. Electrostatic systems, by charging the droplets, significantly reduce spray drift by increasing attraction to plant surfaces and limiting uncontrolled dispersion.

In a comparative field study by Kargar et al. (2025), electrostatic sprayers reduced drift by 42% compared to air-blast sprayers under identical wind and canopy conditions.

5.4 Economic Efficiency and Operational Costs

While electrostatic sprayers often require higher initial investment, they offer lower operational costs over time due to:

- Reduced pesticide use
- Less water consumption
- Lower fuel/energy requirements for application

5.5 Labor and Application Time

Due to improved efficiency and reduced refill requirements (thanks to lower spray volumes), ESS systems may also reduce labor time per hectare. Furthermore, some electrostatic sprayers are now available with automated control units and GPS-based variable rate application, further enhancing precision and reducing human error.

5.6 Environmental Impact

The environmental footprint of pesticide spraying is significantly affected by drift, runoff, and non-target exposure. ESS helps mitigate these issues by:

- Enhancing targeted deposition
- Reducing overall chemical volume
- Improving droplet adhesion and minimizing runoff

These benefits make ESS a valuable tool in achieving low-impact, high-efficiency agriculture, especially under tightening environmental regulations (Zhang et al., 2021).

5.7 Limitations of Conventional Sprayers

Despite their widespread use, conventional sprayers often exhibit:

- Poor coverage in dense foliage
- High chemical consumption
- Significant drift and environmental contamination
- Uneven droplet distribution

These limitations underscore the need for more efficient alternatives like electrostatic systems, especially in high-value perennial crops like apples, pears, and citrus.

6. Field trials and real-world applications in orchard management

While laboratory simulations and engineering models provide valuable insights into the mechanics of electrostatic spraying, it is the real-world field trials that ultimately determine a technology's viability. In orchard systems—characterized by dense canopies, tall trees, and spatial complexity—spraying performance must be tested under varying environmental, agronomic, and operational conditions.

This chapter presents selected case studies and field trials conducted in commercial orchards and research stations. The results illustrate the practical benefits, operational challenges, and crop-specific considerations associated with adopting electrostatic spraying technology in orchard management.

6.2 Apple Orchards – Deposition and Residue Reduction

A comprehensive trial conducted in 2023 by Zhou et al. in a commercial Fuji apple orchard in Shandong, China, compared a tractor-mounted air-assisted electrostatic sprayer with a conventional air-blast system over two growing seasons. Key findings included:

· 36% higher leaf and fruit surface coverage with ESS at reduced spray volume (Zhou et al., 2024)

· 58% reduction in spray drift recorded at 5 m distance from the canopy

· 25% lower pesticide residue on harvested fruit, well below regulatory MRL thresholds

The study concluded that ESS improves both efficacy and safety, making it highly suitable for fresh-market apple producers concerned with residue compliance and environmental impact.

6.3 Citrus Orchards – Wrap-around and Underside Coverage

Bayat, Zeren, and Ulusoy (1994) conducted a comparative field study to evaluate spray deposition patterns using conventional air-carrier sprayers versus electrostatically-charged systems in citrus orchards. The study examined deposition on both upper and lower leaf surfaces, distribution within the canopy, spray losses, and biological efficacy.

Key findings include:

· Higher deposition on abaxial (lower) leaf surfaces and inner canopy zones with electrostatically-charged sprayers.

· Use of fluorometric tracers (Stardust) showed significantly improved spray uniformity across tree structures compared to conventional methods.

· Spray losses beneath the canopy and in the inter-tree space were notably reduced with the electrostatic system.

· Biological control efficacy against *Dialeurodes citri* (citrus whitefly) was enhanced, supporting the potential of electrostatic spraying in targeted pest management.

These results demonstrate the added value of electrostatic sprayers in achieving more comprehensive and efficient coverage, especially in dense canopies where conventional systems struggle to reach protected or underside foliage. This makes them particularly suitable for pests that colonize the lower surfaces of citrus leaves.

6.4 Grapevines – Drift Reduction and Target Precision

In a vineyard case study in Bordeaux, France, conducted by Wang et al. (2025), **a** UAV-mounted electrostatic sprayer was used to treat narrow vine rows. Using GPS and terrain-mapping algorithms, the system achieved:

· 48% reduction in off-target spr**ay**

· Precise deposition within 10 cm accuracy on target clusters

· Greater efficacy against powdery mildew with 33% lower fungicide use

The portability and precision of electrostatic UAV sprayers make them particularly attractive for steep, terraced, or hard-to-access vineyard regions**.**

6.5 Mixed Orchards – Comparative Performance

A multi-crop study in California by Zhang et al. (2021) tested ESS across apple, pear, and almond orchards using a variable-rate autonomous ESS unit. Metrics collected across 42 plots over three months showed:

· ESS outperformed conventional sprayers in all three crops in terms of coverage and drift control

· Best results were observed in almond orchards with dense vertical foliage

· ROI estimated within two seasons based on chemical and labor savings

The study emphasized that custom calibration is key to achieving peak performance across different orchard geometries.

6.6. Limitations Observed in Field Use

Despite the benefits, several challenges were reported across trials:

· Voltage instability in high-humidity conditions (Zhou et al., 2024)

· Electrode fouling and maintenance needs in dusty environments

· Limitations in battery life for UAV-based systems in large fields

7. Conclusion and Recommendations

Electrostatic spraying represents a significant advancement in the application of pesticides, particularly within orchard systems where canopy structure and leaf orientation make uniform coverage a persistent challenge. Unlike conventional spraying techniques that rely solely on hydraulic pressure or air assistance, electrostatic systems utilize charged droplets that are attracted to plant surfaces, allowing for improved coverage and reduced waste.

Throughout this book, we have explored the fundamental principles of electrostatics, system design, droplet behavior, and real-world performance. The evidence consistently shows that electrostatic spraying can reduce pesticide usage, improve deposition on target surfaces—especially on the undersides of leaves—and minimize environmental contamination through lower drift and runoff.

In various field trials, electrostatic sprayers outperformed conventional systems across multiple crops and conditions. Not only did they demonstrate better coverage at lower spray volumes, but they also offered savings in labor, water, and fuel, contributing to both economic and environmental sustainability.

However, the technology is not without its limitations. Factors such as ambient humidity, maintenance of high-voltage components, and the need for proper system calibration can affect performance. Furthermore, for technologies mounted on UAVs or portable systems, battery capacity and operational range remain practical considerations.

Despite these challenges, the benefits of electrostatic spraying are clear. As agriculture moves toward more precise, efficient, and sustainable practices, technologies like ESS will become increasingly central to orchard management. With proper training, thoughtful implementation, and continued research, electrostatic spraying has the potential to become a new standard in high-value crop protection.

In conclusion, electrostatic spraying is not just a refinement of traditional methods—it offers a fundamental shift in how we deliver agrochemicals to plants. It promises greater efficiency, reduced environmental impact, and better alignment with the goals of modern, sustainable agriculture.

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Chapter 1

INDUSTRIAL POLICY DRIVERS OF VALUE ADDITION IN AFRICA'S COCOA GLOBAL VALUE CHAIN: A COMPARATIVE ANALYSIS OF CÔTE D'IVOIRE, GHANA, CAMEROON, AND NIGERIA

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Introduction

Cocoa is one of the most important agricultural exports worldwide and serves as the economic backbone of several West African countries. In 2023, global cocoa cultivation covered an estimated 11.65 million hectares, of which 69.4% (8.09 million ha) was in Africa, with Côte d'Ivoire alone accounting for 41.1% (4.79 million ha) of the global total (FAO, 2025). Cocoa production is highly concentrated in five countries which include Côte d'Ivoire, Ghana, Indonesia, Ecuador, and Brazil. These countries contributed about 78% of global output, on the other hand, within Africa, Côte d'Ivoire, Ghana, Cameroon, and Nigeria contribute about 64.5% of global output (FAO, 2025). Beyond its global significance, cocoa plays an important role in the livelihood of rural communities as it is the primary source of household income for millions of smallholder farmers in Sub-Saharan Africa, most of whom are cultivated on family farms with limited resources (Afoakwa, 2016).

Although Africa accounts for nearly 70% of global cocoa cultivation, the continent captures minimal value from the global chocolate industry. Cocoa farmers in major producing countries such as Côte d'Ivoire, Ghana, Nigeria, and Cameroon face volatile international prices and limited bargaining power, as noted by numerous stakeholders who argue that farm-gate prices fail to reflect the true cost of production (Hütz-Adams et al., 2016). Furthermore, there exists a persistent pattern in Africa where raw materials are exported at minimal value by both foreign and local firms, while the processed by-products are imported back into the continent at significantly higher prices (Ba, 2016). This situation presents a paradox whereby, despite being major producers, cocoa-producing countries in Africa continue to suffer from insufficient investment and the absence of a coordinated upgrading strategy. As a result, the cocoa industry faces persistent obstacles, including low productivity, widespread poverty and declining farmer incomes, as well as inadequate infrastructure that limits integration into global markets (International Finance Corporation, 2021).

Africa's role in the GVC is concentrated at the bottom, where it primarily exports unprocessed raw materials (Foster-McGregor et al., 2015). As the African Development Bank (2017) emphasized, sustained development and industrialization require the continent to move from exporting raw cocoa to adding value through processing, innovation, and branding. The inability to achieve this transformation shows the need to evaluate the effectiveness of existing industrial policies in promoting capability upgrading and value addition within Africa's cocoa sector.

The main objective of this study is to assess how industrial policies influence upgrading and inclusion within Africa's cocoa GVC. Focusing on Cameroon, Côte d'Ivoire, Ghana, and Nigeria, the study examines the design and implementation of relevant policy frameworks and analyses their effects on upgrading the cocoa industry.

Analytical Framework.

GVC Analysis of Cocoa Sector.

Industrial upgrading is linked to the state's role in driving economic change. Historically, countries that achieved industrialization did so through active state intervention and targeted industrial policies that promoted economic diversification and value-added production (Chang, 2011). However, for many Sub-Saharan African nations, copying the export-oriented industrialization paths of earlier successful economies remains challenging due to institutional constraints (Morris et al., 2012).

According to Fernandez-Stark et al., (2013), the GVC framework analyses six interrelated dimensions that encompass both global (top-down) and local (bottom-up) elements. The dimensions illustrate the international structure of industries and include the input–output structure, which demonstrates how raw materials are transformed into finished products. The geographic scope identifies how production activities are distributed across countries. The governance structure explains how lead firms coordinate and control the value chain. The local dimensions, on the other hand, examine how individual countries and actors participate within the chain. These include upgrading, which reflects how producers improve processes or move to higher-value stages (Gereffi, 1999; Humphrey & Schmitz, 2002). The institutional context refers to the local economic, social, and regulatory environment that influences industry operations (Gereffi, 1996). Industry stakeholders describe how various local actors interact and collaborate to promote learning, innovation, and overall industry upgrading.

The global cocoa–chocolate value chain exemplifies a highly segmented and unequal production system that connects millions of smallholder farmers in producing countries to powerful multinational corporations in consumer markets. At the foundation of the chain are over five million small-scale farmers, who account for approximately 95% of global cocoa production, with only about 20% organized into cooperatives (Anga, 2016).

Geographically, the cocoa–chocolate chain is global in scope. African producing countries particularly Côte d'Ivoire and Ghana produce nearly two-thirds of the world's cocoa, while processing, manufacturing, and branding activities are concentrated in Europe and North America. For instance, in 2022 the Netherlands emerged as the world's leading cocoa importer, with a trade value of USD 1.68 billion, representing 20.2% of global imports (OEC, 2025).

The governance structure of the chain is buyer-driven and highly concentrated, characterized by significant vertical integration. According to Ado et al., (2025), government policies should be designed to encourage local firms to move up the GVC by enhancing their productive and technological capabilities. Policies should not only promote active participation of domestic firms in collaborative ventures such as joint partnerships but also create an enabling environment that incentivizes foreign companies to engage and cooperate with local enterprises**.** The intermediate grinding segment, which transforms cocoa beans into semi-processed products such as cocoa liquor, butter, and powder, is dominated by three multinational corporations namely Barry Callebaut, Cargill, and Olam which collectively control about 60–65% of global grinding capacity (Terazono, 2014; Gayi & Tsowou, 2016).

In terms of upgrading, the cocoa GVC remains bipolar: while Africa dominates raw material supply, value creation and innovation occur in the Global North. Although countries such as Côte d'Ivoire and Ghana have expanded their processing sectors, their share of higher value-added exports remains small compared to producers like Indonesia and Brazil (ICCO, 2017). The branding, manufacturing, and retailing stages capture over three-quarters of total value added, leaving farmers with the smallest share (Barrientos & Asenso-Okyere, 2009). These dynamics underscore the need for coherent industrial, trade, and innovation policies that enhance upgrading and value capture within Africa's cocoa–chocolate sector.

Methodology

This study adopts a comparative case study design focusing on four major African cocoa producing countries, namely Cameroon, Ghana, Côte d'Ivoire, and Nigeria. These countries are selected due to their central role in the global cocoa economy and their distinct policy approaches toward cocoa processing and value addition. The research relies primarily on secondary data sources, including academic literature, policy documents, and official trade and production data obtained from international databases such as FAOSTAT and World bank indicators. A GVC comparative assessment of processing performance across the four countries is conducted to identify patterns, similarities, and divergences in policy outcomes. The analysis is guided by the GVC upgrading framework including 6 dimensions namely: Input–Output Structure, Geographic Scope, Governance Structure, Upgrading, Institutional Context and Industry Stakeholders to evaluate the extent of value addition and capability development achieved in the country. The main shortcoming of this research is the use of secondary data, which hinders the ability to examine company-specific dynamics through observational approaches such as questionnaires or on-site observations. Nonetheless, the comparative and policy-oriented design provide an analytical framework for understanding how national policies influence upgrading paths and inclusion in Africa's cocoa sector.

Results

Table 1: Selected Agricultural and Demographic Indicators for Major African Cocoa Producing Countries

Indicator	Unit	Cameroon	Côte d'Ivoire	Ghana	Nigeria
Agriculture, forestry, and fishing, value added (% of GDP)	%	17.29	15.20	20.94	22.72
Population density	people per sq. km	60.02	98.01	148.50	250.21
Rural population	persons	11,543,428	14,601,421	13,772,630	104,181,246
Agricultural land	sq. km	98,969	274,993	126,037	693,982
Cocoa Production 2020	Thousand Tons	300	2100	775	275

Source: FAO, 2025; World Bank, 2025

The results in table 1 show selected key economic and demographic indicators for the four major African cocoa producing countries (Cameroon, Côte d'Ivoire, Ghana, and Nigeria). The results reveal that Nigeria has the largest rural population with about 104.2 million people as well as the largest agricultural land of about 694 thousand sq. km, the highest population density (250.21 people per sq. km) and the largest percentage of GDP derived from Agriculture, forestry, and fishing (22.72%). However, the results show that Côte d'Ivoire is the obvious leader in cocoa production, reaching 2,100 000 in 2020, far exceeding Ghana (775 000 tons), Cameroon (300 000 tons), and Nigeria (275 000 tons).

Table 2: GVC Analysis of the Cocoa Sector of Major African Producing Countries

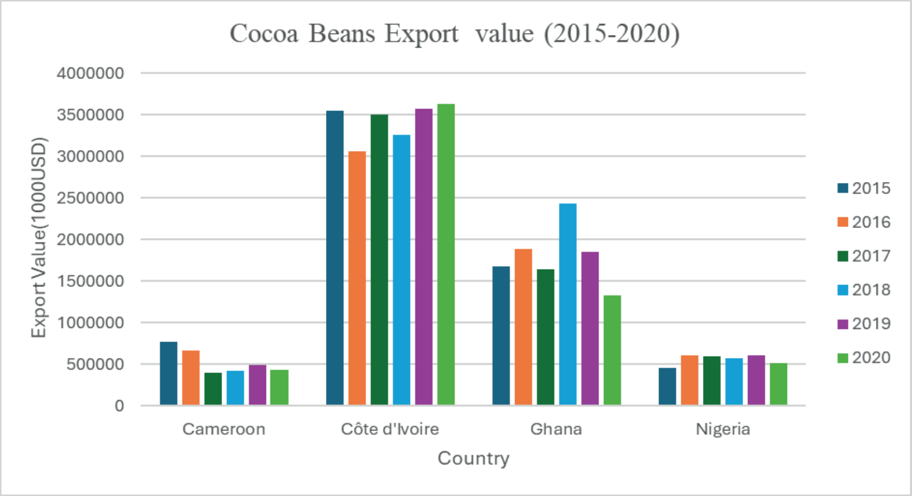
GVC Dimension	Côte d'Ivoire	Ghana	Cameroon	Nigeria
1. Input–Output Structure	World leader in cocoa production (about 40% global share). Has the largest installed grinding capacity in Africa (about 712,000 MT). Processes about 30–35% of domestic beans into liquor, butter, and powder. Most processed products are exported to Europe.	Produces about 20% of world cocoa. Local processing capacity about 440,000 MT, with utilization around 60–70%. About one-third of beans processed domestically. Focus on semi-finished products; limited chocolate manufacturing.	Produces about 220,000 MT annually. Installed grinding capacity of about 70,000 MT but low utilization (40–50%) due to energy and logistics constraints. Most beans were exported raw.	Production is about 190,000 MT. Installed processing capacity about 250,000 MT but operates below 30% efficiency. Limited domestic consumption; high dependence on imports of chocolate and confectionery.
2. Geographic Scope	Cocoa production concentrated in the southern regions (Daloa, San Pedro). Main export markets: Europe (Netherlands, France, Belgium). Major processors located near ports (San Pedro, Abidjan).	Cocoa grown in Ashanti, Volta, Brong Ahafo Western, central and Eastern regions. Processing concentrated in Tema and Takoradi. Main exports of semi-finished products go to Europe and Asia.	Cocoa production is mainly in Centre and Southwest regions; processing clustered around Douala port. Exports mainly to Europe.	Cocoa is cultivated in Ondo, Cross River, and Osun States. Processing mostly in Lagos and Ogun States near ports. Exports to EU and North America.

3. Governance Structure	Hybrid model: regulated by the CCC. Government sets farm-gate prices and promotes local processing through tax incentives and export quotas. Collaboration with global grinders (Barry Callebaut, Cargill, Olam).	Highly centralized under the Ghana Cocoa Board (COCOBOD) which Implements processing incentives Public-private coordination with multinationals (Cargill, Barry Callebaut).	Liberalized sector with weak enforcement. Coordination by National Cocoa and Coffee Board (ONCC) and Cocoa and Coffee Interprofessional Council (CICC), price setting is market driven. Foreign firms dominate processing and export.	Liberalized and fragmented governance. No dedicated cocoa board since 1986. Federal and state agencies are poorly coordinated. Policy incentives for processing (tax holidays) inconsistently applied.
4. Upgrading	Significant process and product upgrading through modern grinding and traceability systems. Limited functional upgrading beyond semi-finished exports.	Achieved process upgrading via quality control and certification; product upgrading through semi-finished exports. Limited success in chocolate manufacturing.	Early stage upgrading growing artisanal chocolate sector, but little innovation in processing technologies.	Minimal upgrading: inconsistent quality, outdated equipment, limited certification schemes. Policy instability hinders investment in higher-value segments.
5. Institutional Context	Strong institutions (‘CCC, ‘Centre National de Recherche Agronomique’ (CNRA), ‘L’Agence Nationale d’Appui au Développement Rural’ ANADER) oversee policy, extension, and research. Fiscal incentives for grinders. Access to port infrastructure supports competitiveness.	Strong institutional backing from COCOBOD and related agencies Cocoa Research Institute of Ghana (CRIG), Cocoa Health and Extension Division (CHED)). Consistent policy framework and partnerships with donors (World Bank, AfDB).	Fragmented institutions; limited R&D and extension. Weak coordination among ONCC, CICC, and ‘Société de Développement du Cacao’ (SODECAO).	Weak institutional framework. Agencies like Cocoa Research İnstitute of Nigeria (CRIN) and Federal Ministry of Agriculture and Rural Development (FMARD) operate independently. Limited public-private coordination
6. Industry Stakeholders	Active collaboration among agricultural cooperatives, government, and global processors (Barry Callebaut, Olam, Cargill). Participation in sustainability programs	Stakeholders include government, private processors, NGOs, and donor agencies. Effective coordination through Cocoa Action.	Key stakeholders include ONCC, CICC, and multinational firms. Agricultural cooperatives underrepresented weak participation in sustainability programs.	Fragmented stakeholder ecosystem. Private processors and traders operate independently; limited NGO or cooperative engagement.

Source: Author’s compilation using Naydenov et al. 2022; Hütz-Adams et al. 2016

The results of the cocoa GVC analysis in table 2 reveal that Côte d’Ivoire, Ghana, Cameroon, and Nigeria have significant differences in structure, governance, and upgrading capacity. Côte d'Ivoire, the world's largest cocoa producer, and Ghana, the second largest, both use a state-regulated hybrid systems coordinated by the CCC and COCOBOD respectively. According to the results of the analysis these institutions stabilize farm-gate prices, enforce quality standards, and facilitate limited value addition through grinding and certification. On the other hand, Cameroon and Nigeria have liberalized and fragmented markets where coordination is weaker, and multinational corporations such as Cargill, Olam, and Barry Callebaut dominate processing and export activities. Although Cameroon shows early signs of upgrading through small-scale artisanal processing and certification efforts, Nigeria's processing sector remains underutilized due to high production costs, policy inconsistency, and weak institutional coordination.

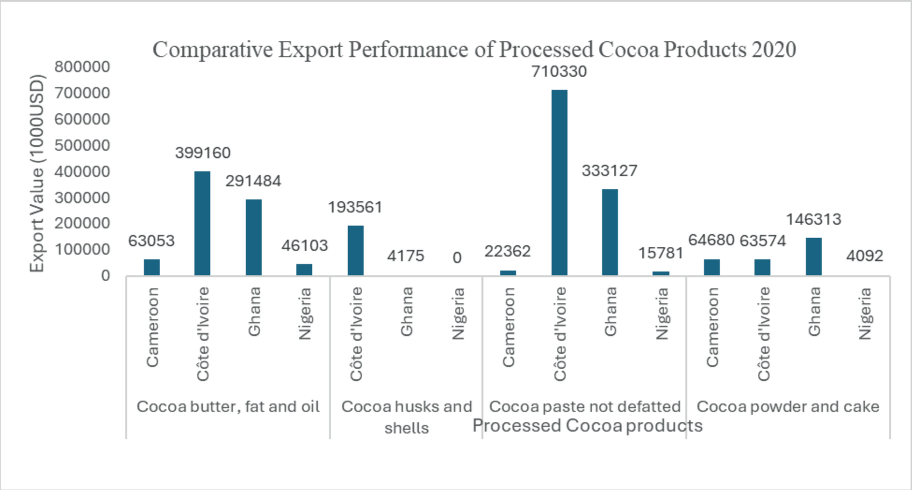
Chart 1: Cocoa Beans Export Value of Major African producing Countries (2015-2020)



Source: FAO,2025

Chart 1 illustrates the cocoa beans export value (in 1,000 USD) for Cameroon, Côte d'Ivoire, Ghana, and Nigeria between 2015 and 2020. The results reveal that Côte d'Ivoire has been consistently dominating the cocoa export market, maintaining the highest export values throughout the period, peaking at approximately 3.55 million (thousand) USD in 2020. Its lowest value was around 3.05 million thousand USD in 2016. This clearly shows its influence on global cocoa bean trade. The charts equally show that Ghana is the second largest exporter, though its values show more fluctuations. According to the chart, Ghana reached its peak in 2018 with approximately 2.45 million (thousand) USD, followed by a decline to its lowest point in 2020 at around 1.3 million (thousand) USD. Cameroon and Nigeria export significantly lower volumes compared to the two leaders. Cameroon's exports generally between 400,000 and 750,000 (thousand) USD, with a visible drop in its export value in 2017 and a slight increase in 2020. Nigeria's export values are stable, remaining consistently between 500,000 and 600,000 (thousand) USD throughout the six years, showing insignificant yearly variation.

Chart 2: Comparative Export Performance of Processed Cocoa products of Major African Producing Countries



Source: FAO,2025

Chart 2 shows the comparison of export values for processed cocoa products, namely cocoa butter and fat, cocoa husks and shells, cocoa paste (not defatted), and cocoa powder and cake of four major African producing countries. Côte d'Ivoire is the leading African cocoa processor, dominating in all categories, particularly with significant exports of cocoa paste (USD 710,330 thousand) and cocoa butter (USD 399,160 thousand), a performance that reflects its strong industrial policies and advanced grinding capacity aimed at local value addition. Ghana ranks second, demonstrating a moderately developed sector with significant exports of cocoa paste (USD 333,127 thousand) and cocoa butter (USD 291,484 thousand), often supported by public-private initiatives and its cocoa board, COCOBOD. According to the figures displayed in the chart, Cameroon has a modest profile, with its small-scale processing base notable for cocoa powder exports (USD 64,680 thousand). On the other hand, Nigeria registers very low export values across all processed products, which suggests limited industrial upgrading and a significant underutilization of its processing capacity despite its status as a major cocoa producer.

Discussion.

The GVC analysis provides a framework to discuss the presented results by focusing on how the major cocoa producing African countries are positioned within the cocoa value chain as major cocoa producers.

According to the GVC analysis the bulk of the economic value and profits in the cocoa industry are captured in the downstream segments of the chain which consist of processing (grinding, making butter/powder) and final manufacturing (chocolate) not in the upstream segment of raw bean production dominated by African countries. According to the results, the production and cocoa bean export value data confirm the primary role of Côte d'Ivoire and Ghana as upstream suppliers. However, despite their dominance in raw material supply, the huge export values for raw beans 3,628,552,000USD and 1,326,635,000USD for Cote D'Ivoire and Ghana, respectively, represent only a fraction of the final retail value of manufactured chocolate products. The global chocolate market, valued at 133.38 billion USD in 2022, is projected to expand to 181.78 billion USD by 2031 (Straits Research, 2025). This massive disparity highlights the limited value capture by major African cocoa producing countries within the cocoa GVC, as most of the profits accumulate in downstream segments, particularly in processing, branding, and retailing, dominated by multinational firms based in Europe and North America. Furthermore, the ability of the four major African cocoa producing countries to expand cocoa processing and enter chocolate manufacturing is constrained by high operating costs, limited technological know-how, and structural barriers that undermine the competitiveness of domestic firms in secondary processing segments (Naydenov et al., 2022).

In recent years, these four major African cocoa-producing countries have shown some progress in value addition. Côte d'Ivoire and Ghana, the two largest cocoa producers, globally have made notable progress, reflecting growing policy attention to domestic processing and industrial upgrading. While Côte d'Ivoire is the leading exporter of cocoa beans, it also dominates the export of processed products among the four major cocoa producing African countries (cocoa paste at 710 million USD and cocoa butter at 399 million USD). According to Yao et al., (2025), Côte d'Ivoire has emerged as the world's leading cocoa grinder, with an installed capacity exceeding 620,000 metric tons, and a government-backed target to process 50% of national output (around 1.1 million MT) locally. Furthermore, strategic investments by major multinationals such as Cargill (USD 100 million Yopougon expansion) and Guan Chong Berhad (60,000 MT plant) have reinforced this shift, supported by strong state industrial policy and incentives marking a significant move up the value chain (Yao et al. 2025).

Ghana, while still heavily reliant on raw bean exports, has also shown moderate upgrading success, with the share of locally processed cocoa rising from 30% to 34%, and the government plans to reach 50% processing capacity (GCB Strategy & Research Dept., 2022). The country's grinding sector is led by a few dominant multinational firms Barry Callebaut (67,000 MT), Cargill (65,000 MT), and Olam Processing Ghana Ltd (43,000 MT) alongside the state-linked Cocoa Processing Company (CPC). While these developments reflect progress toward midstream value addition, Ghana's processing segment remains highly concentrated, with multinational dominance limiting local ownership and innovation. Nonetheless, the steady expansion of grinding capacity demonstrates a policy supported effort by COCOBOD and the government to move beyond cocoa bean exports and strengthen domestic value retention within the cocoa GVC (GCB Strategy & Research Dept., 2022).

While Côte d'Ivoire and Ghana have demonstrated measurable progress in value addition through local grinding and industrial upgrading, Cameroon and Nigeria continue to play minor roles in global cocoa processing and processed exports, reflecting persistent structural and institutional weaknesses in their cocoa value chains. However, according to Linge (2025), in the 2024–2025 season, Cameroon processed 109,431 tons of cocoa, representing 35% of its traceable supply, a 27.7% increase from the previous year. This progress stems from recent capacity expansions by key processors, such as Atlantic Cocoa (Kribi), SIC Cacaos, Neo Industry, and Africa Processing, raising national installed capacity from just 20,000 tons in 2010 to over 150,000 tons by 2025. Policy incentives, including EU deforestation-free supply-chain regulations and price premiums for sustainable cocoa have encouraged local processing investments. However, challenges such as limited port infrastructure, restricted access to international hedging markets, and high compliance costs with traceability requirements, continue to limit Cameroon's competitiveness and the profitability of its processors.

In contrast, Nigeria, despite being one of Africa's largest cocoa producers with the highest agricultural contribution to GDP (22.7%), remains largely dependent on raw bean exports, processing only about 70,000 tons annually (Linge, 2025). The country's processing sector is characterized by underutilized capacity, weak institutional coordination, and policy inconsistency, which have constrained industrial upgrading and prevented domestic firms from integrating effectively into higher-value segments of the global cocoa–chocolate chain. For instance, according to Ejike & Chidiebere-Mark (2019), in 1990, the Nigerian government sought to ban the export of unprocessed cocoa beans as part of a broader strategy to stimulate local industrialization, increase foreign exchange earnings, and encourage technology transfer. However, this initiative was short-lived, collapsing under the weight of policy failure and resistance from key stakeholders, particularly the Cocoa

Association of Nigeria (CAN), which argued that the country's industrial processing capacity was insufficient to handle the national cocoa output (Olomola et al., 2012; Ejike & Chidiebere-Mark, 2019).

Comparatively, Ghana and Côte d'Ivoire have achieved moderate to strong upgrading through coordinated policy frameworks, industrial incentives, and public-private partnerships, whereas Nigeria and Cameroon lag due to fragmented governance and inadequate investment in processing infrastructure. These findings underscore the uneven pace of industrial transformation across Africa's cocoa-producing economies: while Ghana and Côte d'Ivoire are advancing toward midstream value addition, Nigeria and Cameroon remain locked in low-value primary production, reflecting a failure to translate agricultural strength into industrial capability and sustainable inclusion within the cocoa GVC.

Conclusion

This study demonstrates that while Africa dominates global cocoa production, value capture within the cocoa–chocolate GVC remains highly uneven. The comparative analysis of Côte d'Ivoire, Ghana, Cameroon, and Nigeria shows that the ability to achieve meaningful upgrading depends primarily on coherent industrial and institutional frameworks. Côte d'Ivoire and Ghana's coordinated governance systems anchored by the CCC and COCOBOD have supported modest industrial upgrading through price stabilization, processing incentives, and public-private partnerships that link producers with multinational grinders. In contrast, Nigeria and Cameroon continue to struggle with fragmented governance, limited investment, and policy inconsistency, which hinder domestic processing and innovation. Although Cameroon's recent processing expansion and Nigeria's historical policy initiatives signal intent to diversify, both countries remain largely confined to low-value primary exports.

The findings emphasize that being a leading cocoa producer does not equate to being a dominant value capturer in the cocoa value chain. For major African cocoa producers to enhance their share of global value, policies must target infrastructure development, access to finance, and regional coordination to support efficient, competitive, and sustainable cocoa processing. Strengthening innovative systems and fostering inclusive stakeholder collaboration can further enable a transition from commodity dependence to industrial value creation, advancing Africa's broader goals of economic diversification and structural transformation.

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Chapter 3

CHEMICAL CONVERSION POTENTIAL OF WOOD AND NON-WOOD COMPONENTS

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1. INTRODUCTION

In the 21st century, the world's energy demand continues to grow steadily in light of developing technology, driven by rapidly increasing population, urbanization, and industrialization processes. The negative effects of the fossil-based chemical and energy production industry on greenhouse gas emissions, global warming, climate change, biodiversity, and environmental pollution have disrupted the ecosystem's balance, hindering sustainable development goals. Furthermore, the finite nature of fossil fuels among energy sources has necessitated the exploration and discovery of alternative energy sources. Both national and international policies focus on the development of renewable energy sources, emphasizing the efficient use of resources and the evaluation of renewable raw materials. Researches on renewable energy sources and assessments of their feasibility have led to efforts to develop significant alternative energy sources (Noone, 2013; Rockström et al., 2009). Examples of energy sources with renewal potential include biomass, geothermal, solar, hydraulic, and wind (Demirbaş, 2001; Şen, 2017).

Energy obtained from biomass can be produced at a higher rate compared to other renewable energy sources. This situation also significantly affects global energy consumption on a commercial scale. Research into obtaining energy from biomass was particularly prompted by the exorbitant increase in oil prices following the 1973 oil crisis. As a result, much research has been conducted on biomass energy. However, the subsequent decline in oil prices led to a decrease in research on energy production from biomass. Today, however, rising oil prices and the critical depletion of fossil fuel reserves have brought energy production from biomass back to the forefront (Karayılmazlar et al., 2011; McKendry, 2002a). Solar energy, one of the most important natural energy sources, is a highly effective energy source due to its ability to store very high amounts of energy within biomass. There are different technological methods applied in the conversion of biomass into energy. These are physical, chemical, thermochemical, and biochemical conversion methods. The methods applied in physical conversion technology are drying, dewatering, separation, and densification. Thermochemical conversion technology involves pyrolysis, direct combustion, carbonization, gasification, and liquefaction processes, while biochemical conversion technology results in the production of biogas, hydrogen, and ethanol products (Durkaya & Durkaya, 2016; Üçgül & Akgül, 2010).

The potential for woody biomass, classified as waste remaining in the field as a result of forestry operations, to be utilized as an energy source is quite high. Furthermore, due to the current efforts to reduce greenhouse gas emissions and mitigate the negative effects of environmental pollution, obtaining energy from woody biomass has become popular. This study provides information on how wood components are utilized as chemical substances.

2. THE CHEMICAL CONVERSION POTENTIAL OF WOOD BIOMASS

In previous centuries, wood and charcoal were used in various ways in the large industrial establishments of those times. For example, potassium carbonate found in wood ash was used in glass and soap manufacturing, coal was used in ironworking, and tar products and resin were among the basic raw materials frequently used in shipbuilding. The fact that wood and non-wood forest products had such a wide range of uses led to a risk of depletion of forest resources. In addition to the use of raw wood in glass, soap, ironworking, and shipbuilding, the advanced cellulose industry has made it possible to obtain cellulose, the most valuable part and main component of wood, thus enabling more efficient and economical use of wood raw materials (Cherubini, 2010; Rockström et al., 2009). Therefore, it can be stated that wood is currently an important raw material source frequently preferred in the chemical industry.

Beyond traditional applications, the forest products industry is of significant economic importance in terms of biomass diversity and renewable raw material potential. The main chemical components that make up forest biomass are cellulose, hemicellulose, lignin, and extractives, which have complex structures (Chen et al., 2024; Uraki & Koda, 2015). These components constitute a significant source for the production of chemicals that can be used in highly important areas such as pharmaceutical raw materials, bioplastics, biofuels, and energy storage materials (Yang et al., 2019).

The examination of the chemical components of this lignocellulosic material, which is considered an important resource, better reveals its potential in areas of application. The amount of cellulose, hemicellulose, and lignin within the lignocellulosic structure may vary depending on the tree species. However, in general terms, the components that make up biomass are approximately 50-60% carbohydrates and 30% lignin (Table 2.1.). In addition to differences in the proportions of the main components between species, there are also variations in the proportions of the components themselves. For example, the amount of pentose sugars found in the lignocellulosic structure varies between coniferous and broadleaf tree wood (Galbe & Zacchi, 2012; Kamdem Tamo et al., 2025).

Table 2.1. Cellulose, hemicellulose, and lignin contents of some lignocellulosic materials (Conde-Mejía et al., 2012; Menon & Rao, 2012).

Raw Material	Cellulose (%)	Hemicellulose (%)	Lignin (%)
Hardwoods			
Betula pendula	41	36,2	18,9
Populus alba	50,8-53,3	26,2-28,7	15,5-16,3
Acer rubrum	44,1	29,2	24
Populus euramericana	41,7	20,2	29,3
Eucalyptus viminalis	41,7	14,1	31
Softwoods			
Pinus banksiana	41,6	25,6	28,6
Pinus pinaster	42,9	17,6	30,2
Abies normanniana	43,9	26,5	28,4
Agricultural waste			
Corn cob	33,7-41,2	31,9-36	6,1-15,9
Sugar cane pulp	40-41,3	27-37,5	10-20
Wheat straw	32,9-50	24-35,5	8,9-17,3
Rice straw	36,2-47	19-24,5	9,9-24
Corn stalk	35-39,6	16,8-35	7-18,4
Barley straw	33,8-37,5	21,9-24,7	13,8-15,5
Soybean stalk	34,5	24,8	19,8
Cotton stalk	38,4-42,6	20,9-34,4	21,45
Hazelnut shell	25-30	22-28	30-40
Oat straw	31-35	20-26	10-15
Other			
Bamboo	40-50	18-20	23
Eucalyptus	45-51	11-18	29
Grass	25-40	25-50	10-30
Newspaper	40-55	24-39	18-30
Oleae europaea	25,2	15,8	19,1
Sorghum	35-40	25-30	15-20

In line with technological advances, methods for utilizing biomass have undergone significant changes over time, and more complex conversion processes have been developed. Different technological methods have been developed to obtain energy from biomass that can be used as solid, liquid, and gaseous fuels. As a result of the development of these technological methods, biomass can be utilized not only as biogas, bioethanol, and biodiesel fuels, but also as methane, hydrogen, fertilizer, and wood briquette products (Mckendry, 2002a; Seo et al., 2022). Physical, chemical, thermochemical, and biochemical separation methods, whose efficiency has been improved over time, are used to obtain these fuels. Physical methods include water removal and drying, size reduction, density increase, and separation processes. Among chemical methods, transesterification (internal ester exchange reaction) stands out, which is widely used in converting oil-based biomass into biodiesel. Within the scope of biochemical methods, products such as biogas and bioethanol are obtained from organic materials through anaerobic digestion and fermentation processes. Thermochemical methods include various techniques such as direct combustion, carbonization and pyrolysis, liquefaction, and gasification, enabling the production of energy products from biomass in different forms (Chaudhary et al., 2025; Joshua Abioye et al., 2025; Mckendry, 2002b).

The production of energy products from biomass in various forms depends on a detailed understanding of the chemical properties of wood and non-wood forest product components, which are natural biological materials. As briefly summarized above, the chemical composition of cellulose, hemicellulose, and lignin in wood and non-wood forest products consists largely of natural polymers formed by the combination of simple monomeric sugars in a specific order. These polymers contain simple building blocks that are linked together through different chemical bonds. Controlled breakdown of these bonds using enzymatic or chemical methods enables the polymers to be converted back into monomeric sugars (Sánchez & Cardona, 2008; Y. Sun & Cheng, 2002; Taherzadeh & Karimi, 2007a). These sugars can then be processed through fermentation by suitable microorganisms and converted into alcohols such as methanol (CH3OH) or ethanol (C2H5OH). This chemical process is defined in the literature as saccharification/fermentation. Based on this, the present study provides information on the saccharification of biomass and the conversion of cellulose, hemicellulose, lignin, and extractive substances into chemical products (Rowell et al., 2005; Zabed et al., 2017a).

2.1. Saccharification of Lignocellulosic Biomass

The fundamental principle behind the saccharification method is the breakdown of cellulose and hemicellulose polysaccharides present in biomass into sugars. Glucose obtained from cellulose and mannose is the main product of the saccharification process (Taherzadeh & Karimi, 2007; Zabed et al., 2017).

Hydrochloric acid and sulfuric acid concentrations are important chemicals used in the saccharification process. While concentrated acid must be at room temperature during saccharification, diluted acid must be used at specific temperatures. The fact that concentrated acid can be used at room temperature facilitates the reaction process. However, the high cost of ensuring the conditions necessary to prevent corrosion during the reaction is a negative factor (Mosier et al., 2005; Sun & Cheng, 2002).

In some saccharification processes, the pre-hydrolysis method is used to first remove hemicellulose and then hydrolyze cellulose. This pre-hydrolysis method is preferred in saccharification processes carried out with annual plants that have a high xylan content. Examples of products that can be obtained as by-products as a result of the pre-hydrolysis process include methanol, acetic acid, furfural, sorbitol, and xylitol (Upare et al., 2023; Zabed et al., 2017).

2.2. The Conversion of Cellulose into Chemical Products

Acid catalysts, enzymatic or microbial hydrolysis methods can be preferred in obtaining glucose, the building block of cellulose. With the help of enzymatic and acid hydrolysis methods, the glycosidic bonds in amorphous cellulose can be broken down simply, i.e., hydrolyzed. However, there are important factors that can cause problems in the hydrolysis of cellulose. Lignin, which is present in lignocellulosic material, reduces enzymatic activity during the enzymatic hydrolysis of cellulose, making the hydrolysis process difficult. In addition, one of the important properties of cellulose is its crystalline structure, which makes it resistant to different chemicals that can be used for hydrolysis (Himmel et al., 2007; Li et al., 2022; Zhu & Pan, 2010). Although enzymatic hydrolysis is considered one of the most suitable methods for converting cellulose into glucose through hydrolysis, the yield is not very high, ranging only between 20% and 40%. In addition to these circumstances, other factors that have a negative impact include the high cost of enzymes, the length of the reaction times, and enzyme inactivation and inhibition (Haghighi Mood et al., 2013; Kumar et al., 2008; Zhang & Lynd, 2004).

In addition to the pre-hydrolysis methods mentioned in the saccharification of wood for cellulose hydrolysis, subjecting the material to pre-treatment using different chemicals is considered a factor that could be beneficial in the hydrolysis process. These methods, which are thought to be beneficial, ensure the swelling process occurs as a result of using alkaline and ammonium solutions. According to some studies, the application of this method has demonstrated the usability of fibrous materials obtained from the hydrolysis of hardwoods and agricultural-based cellulosic materials as animal feed (Alvira et al., 2010; P. Kumar et al., 2009; Mosier et al., 2005). Additionally, important mechanical processes such as shredding, grinding, electron beam radiation, and defibration can assist in breaking down the polymer and crystal structure of cellulose. These mechanical processes are thought to contribute positively to increasing the yield of cellulose hydrolysis.

However, the high energy requirements for performing these mechanical processes are not advantageous for factories where large-scale production will take place. Fermentation has the most successful effect on glucose utilization. Depending on the type of yeast used and the health ratio of the sugar substrate, fermentation can be used to produce animal feed, alcohol, and organic acids (Lin & Tanaka, 2006; Taherzadeh & Karimi, 2008; Zheng et al., 2009).

Bioethanol can be produced from biomass materials such as corn, potatoes, vegetable waste (including household waste), etc. Mixing bioethanol with gasoline increases the octane rating, resulting in combustion with reduced emissions of toxic gases such as hydrocarbons. Ethanol, known as a colorless liquid, is clean and has the potential to be biodegradable, meaning it does not pose a risk to the environment. The mixture of ethanol with gasoline results in a lower emission rate, allowing for complete combustion. Furthermore, the mixture obtained with a general ratio of 10% ethanol and 90% petroleum ensures that it can be used as a high-octane fuel due to ethanol's high-octane rating (Broda et al., 2022; Igwebuike et al., 2024; Shrivastava & Sharma, 2023). Beyond its use as a liquid fuel, ethanol is also preferred as an important solvent in chemical processes. Using various methods, butadiene and ethylene can be obtained at high yields from ethanol, which is used as an important raw material source (J. Sun & Wang, 2014).

Another production process that holds a place as important as ethanol production in the chemical and biotechnology industries is the fermentation of sugars obtained from biomass. Glucose fermentation has the potential to be used as a sweetener in vitamins. *Torula utilis* fungus, known as Torula yeast, can be effectively used to assist in the fermentation process in the preparation of sugar solutions. Various products can be obtained as a result of glucose fermentation, examples of which include chemicals such as citric acid, lactic acid, butanol, acetic acid, isopropanol, butyric acid, and acetone (Green, 2011; Jang et al., 2012; Luo et al., 2017). On the other hand, glucose can be converted into an artificial sweetener (sorbitol) by adding catalytic alkaline hydrogen. Treating glucose with an acid catalyst under different conditions results in another saccharification product known as 5-hydroxymethylfurfural. The numerous reactions that occur during the production of 5-hydroxymethylfurfural make it possible to obtain different products such as polyamide, nylon, and epoxy furan resin (Marques et al., 2016; Nakajima et al., 2017; Rosatella et al., 2011).

2.3. Conversion of Hemicellulose (Polyose) into Chemical Products

Hemicelluloses, the second most important polysaccharide in biomass, are found in broad-leaved trees at 25-35% and in coniferous trees at 15-25% (Rowell, 2012; Sjöström, 1993). Xylans, which are the main components of hemicelluloses, are found predominantly in broad-leaved trees, while pentoses, consisting largely of mannans, are found predominantly in coniferous trees. When comparing mannans and xylans, it has been observed that xylans can be hydrolyzed more easily. This difference between xylan and mannan is particularly useful in the pre-hydrolysis treatment during saccharification, in the steam extraction process, or in the production of soluble pulp (Laine, 2005; Rowell, 2012).

The method used to convert crystalline xylose obtained from xylane into xylitol is known as catalytic hydrogenation. Xylitol has been evaluated as a more suitable sweetener for diabetics than sucrose, as it is a non-cariogenic sweetener. Considering the role of xylose in xylitol production, xylose is prominent not only in sweetener production but also in obtaining rich sugar solutions for various industrial applications (Antunes et al., 2017; Parajo et al., 1998).

Sugar solutions with a high xylose content can be obtained using the steam extraction method. In this method, annual plants or plant residues can be broken down into pieces by applying hot steam at 180-200°C using simple technology. The fibers obtained from the material that has been broken down by applying steam are then treated with an aqueous alkaline solution or water. After this treatment was applied to the fibers, it was determined that the materials obtained have significant biochemical and chemical reactivity. In addition to its potential use in enzymatic and acetic hydrolysis, this highly reactive material also has the potential to be used in fiberboard production (Bhaumik & Dhepe, 2016; Carvalheiro et al., 2008; Kamm & Kamm, 2004).

Furfural is a chemical product obtained by applying hydrogenation to xylose, a derivative of xylan. The production of furfural involves two important stages: acid-catalyzed hydrogenation and hydrolysis. While it is possible to obtain furfural from the biomass of coniferous and broad-leaved trees at a rate of between 6% and 11%, furfural can be obtained from agricultural waste at a rate of between 15% and 23% (Allen et al., 2010; Binder & Raines, 2010; Marcotullio & De Jong, 2011).

Furfural can be treated using the hydrogenation method to obtain furfural alcohol, one of the important compounds of furfural. In the production of plastics with improved resistance properties, liquid compounds of furfural with different viscosities are utilized. In addition, tetrahydrofuran (THF), which is used as an important solvent for the production of polyvinyl chloride (PVC), polyurethane, and nylon, are substances that can be obtained from furfural (Machado et al., 2016; Marcotullio & De Jong, 2011; Mukherjee et al., 2015).

2.4. Production of Chemical Products from Lignin

Lignin is one of the main components of wood, constituting 10-15% of the mass of lignocellulosic biomass. It is generally obtained as a by-product in bioethanol production processes. It has the potential to be converted biologically into high-value products such as organic acids, phenolic compounds, and vanillin. In nature, it can only be broken down by certain microorganisms (Chen et al., 2024; Galbe & Zacchi, 2012). Apart from this, it is possible to obtain different fuel additives by treating lignin with chemical methods. The potential for producing such fuel additives is important both for the development of biofuel technologies and for economic sustainability (Hamelinck et al., 2005).

Lignin, which is the primary and most important component of woody biomass, is a highly branched aromatic polymer found in the cell walls of biomass. Known as a phenylpropanoid polymer with an amorphous structure, lignin exhibits significant natural adhesive potential by binding to cellulose and hemicellulose through ester and hydrogen bonds, respectively (Balat et al., 2008; Da Costa Lopes et al., 2013). Lignin, characterized as a macromolecule with a complex structure, consists of the polymerization of three phenyl propanol units present in its structure: sinapyl alcohol (syringyl propanol), p-coumaryl alcohol (p-hydroxyphenyl propanol), and coniferyl alcohol (guaiacyl propanol). These phenylpropane units are linked to each other by C-C and ether (C-O-C) bonds to form the lignin component (Canilha et al., 2012; Pérez et al., 2002).

Hemicellulose and lignin surrounding cellulose element fibrils in the cell wall of biomass make the lignocellulosic structure more resistant to biological and chemical degradation. Lignin provides structural resistance to the cell wall and has important properties such as impermeability (Canilha et al., 2012; Da Costa Lopes et al., 2013). Lignin, with its adhesive properties that bind the components of biomass together, can also prevent biomass from dissolving in water due to this characteristic. In addition, lignin, which is closely related to cellulose microfibrils because it surrounds them, emerges as one of the most important factors that prevent the microbial and enzymatic hydrolysis of lignocellulosic biomass (Agbor et al., 2011; Pérez et al., 2002).

In addition to the resistance and functional properties that lignin contributes to biomass, it is known that the chemical composition of lignin varies depending on the type of wood. Differences have also been observed in the structures that form lignin in softwoods and hardwoods. While guaiacyl and syringyl constitute the main components of lignin in hardwoods, coniferyl alcohol has been identified as the main component in softwoods (Palmqvist & Hahn-Hagerdal, 2000; Zakzeski et al., 2010).

These differences have a decisive impact on the processes of breaking down woody biomass into its basic building blocks and converting these building blocks into various chemical products. Indeed, woody biomass is first broken down into its main components, such as cellulose, hemicellulose, and lignin; these components then enable the production of numerous industrially important products through different chemical reactions (Table 2.2).

Table 2.2. Chemical substances that can be obtained from the main components of wood (Menon & Rao, 2012; Octave & Thomas, 2009).

Lignocellulosic Biomass	**Components (Polymers)**	**Chemical Substances**
Cellulose	Levulinic acid	Succinic acid, THF, MTHF, 1,4-butanediol, NMP, Lactones
	Ethanol Lactic acid	Acrilic acid, Acetaldehyde, 2,3-pentanedione, Pyruvic acid
	3-hidroxy-propanioc acid, Itaconic acid	3-methyl THF, 3-methyl pyrolidone, 2-methyl-1,4-butanediamine Itaconic diamide
	Glutamic acid, Glucuronic acid, Succinic acid	2-pyrolidones, 1,4-butanediol, Tetrahydrofurane
Hemicellulose	Xylitol, Ethanol, Butanol, Hydrogen, 2,3-butanediol, Ferulic acid	Vanillin, Vanillic acid, Protocatechuic acid
	Lactic acid, Furfural, Chitosan, Xylo-oligosaccharides	
Lignin	Syngas, Syngas products	Methanol/Dimethy ether, Ethanol, Mixed liquid fuels
	Hydrocarbons	Cylohexanes, Higher alkylates
	Phenols	Cresols, Eugenol, Coniferols, Syringols
	Oxidized products	Vanillin, Vanillic acid, DMSO, Aldehydes, Quinones, Aromatic and aliphatic acids
	Macromolecules	Carbon fibres, Activated carbon, Polymer alloys, Polyelectrolites, Substituted lignins, Thermosets, Composites, Wood preservatives, Neutraceuticals/drugs, Adhesives and resins

2.5. Production of Chemical Products from Extractives

Extractive substances found in wood and bark, which contain a wide variety of chemical compounds, have been widely used in various fields from the past to the present in forms such as tanning agents, dyes, perfume components, and naval store products. In terms of practical use, extractive substances are generally classified as follows:

- Wood extracts obtained by solvent extraction
- Bark extracts obtained by solvent extraction
- Chemicals obtained from leaves
- Naval stores (Hill et al., 2021; Rowell, 2012).

The term “naval stores” is generally used for resins, turpentine, and tall oil, which are among the extractive groups. Historically used primarily in shipbuilding, resins continue to hold significant commercial value today in the production of varnishes, adhesives, paints, and various chemical products. Naval stores can be obtained through solvent extraction from the logs of coniferous trees, by tapping the trunks of living pine trees, or as a by-product during the production of kraft pulp from coniferous wood. These methods demonstrate the diversity of naval stores and their suitability for different industrial applications (Alpöz & Erkan, 2024; Coppen & Hone, 1995; Yıldızbaş et al., 2023).

The use of naval stores is multifunctional. Taking crude tall oil as an example, it is used in the production of surfactants, as a flotation agent, and as essential oils. The resin acid fraction of tall oil is mainly used in the sizing of paper to control water absorbency. Resin acids are used in the production of synthetic rubber, paints, chemicals, varnishes, and the synthesis of pharmaceuticals (Cannac et al., 2009; da Silva Rodrigues-Corrêa et al., 2013; Kılıç Pekgözlü & Ceylan, 2021).

Another important product evaluated under naval stores is turpentine, which is obtained from raw resin. The production volume and chemical composition of turpentine are of great importance in terms of the diversity of industrial applications. The turpentine yield of crude resin extracted by draining is generally between 18-25%. The oil consists of 60-70% α-pinene, 20-35% β-pinene, and 5-12% terpenes such as camphene or 3-carene (Coppen & Hone, 1995; Rowell et al., 2005).

The chemical composition of turpentine, particularly its solvent properties and derivatives, ensures that it has a very wide range of industrial applications. Turpentine is used as a solvent for oil and resin-based paints. Turpentine components such as α-pinene and β-pinene are actively used in the production of soaps, detergents, and perfume chemicals (Neis et al., 2019; Wiyono et al., 2006).

In addition to the wide range of uses of turpentine, other natural products that can be obtained directly from living trees also represent significant industrial and commercial potential. An example of such products is the extraction of sugar maple sap. This product, known as maple syrup, is produced in high quantities in Canada (Filteau et al., 2012; Unno, 2015).

Similar to sugar maple trees, secretions and natural juices obtained from different tree species are also used in various industrial processes. Natural latex produced commercially from the bark of the gum tree can be used as an important raw material source in rubber production. The natural latex product is converted into rubber through vulcanization, a technical-chemical process. Rubber is primarily used after the addition of fillers and plasticizers, dyes, and other additives (Langenheim, 2003; Roland, 2013).

In addition to natural sap obtained from living trees, phenolic compounds that can be extracted from wood and bark are also highly valued in the industry. Quercetin, one of the most important flavonoids among phenolic compounds, has a wide range of applications due to its antioxidant and antimicrobial activities. Quercetin extracted from wood and bark has potential applications as antioxidants, fungicides, and pharmaceuticals (Boots et al., 2008; Manach et al., 2004; Panche et al., 2016).

In addition to flavonoid compounds, other extractive substances obtained from wood and bark are also of significant industrial importance. One such product, waxes, can be extracted from the bark of coniferous and deciduous trees. Waxes are used in soaps, leather waxes, and polishes (Dalby, 2001; Rowell, 2012).

3. RESULT and DISCUSSION

When evaluated in terms of both diversity and quantity, wood and its constituent components occupy a significant position among biomass resources. The complex structure of wood, which contains cellulose, hemicellulose, lignin, and extractives, is not only used for energy production. There is also potential to produce various high-value-added chemical products from these complex structures. As mentioned in the headings above, the saccharification of cellulose enables the production of bioplastic raw materials and bioethanol, while the hydrolysis of hemicellulose enables the production of compounds such as furfural and xylitol, which are of great industrial importance. Similarly, treatments performed on lignin can yield phenolic derivatives and adhesive raw materials, while extractives can yield products such as flavonoids, resin, tall oil, turpentine, and waxes, which can make important contributions to industry. This information demonstrates that wood can be considered a multifaceted resource in terms of utilization, recycling, sustainable biochemistry, and economics, extending beyond its traditional use from the past to the present.

The environmental awareness that began to emerge in society as a result of the negative situations encountered, coupled with the limited availability of fossil fuels and the desire to avoid them due to the damage they cause to the environment, has led to a shift towards renewable clean energy sources, further highlighting the potential of wood and wood-derived by-products. The biodegradability of chemical products derived from wood is a very important feature in terms of their environmental friendliness. However, issues such as low productivity in the production processes of wood-derived products, difficulties in purification stages, and economic imbalance due to the lack of resource continuity can limit development in this area.

To overcome these negative situations, more research and applications in this field are needed. For example, developing hybrid biotechnological methods such as microbial fermentation and enzymatic hydrolysis could be effective in increasing the diversity of products obtained from wood components. Research on improving reaction techniques and purification stages during production to increase the yield of compounds such as bioethanol, xylitol, and furfural, which are obtained from cellulose and hemicellulose —important components of wood —could enhance the industrial potential for their use. Considering the developing technology and diversity of products in demand, the production and diversification of important products such as biopolymers, bioplastics, and pharmaceutical substances, in addition to classic products such as naval stores that can be obtained from wood, can make a significant contribution.

Ensuring the sustainability of forest resources and increasing their diversity is crucial for maintaining and expanding the production of value-added products derived from wood and non-wood forest products. In this context, establishing agroforestry systems capable of providing energy suitable for this sector should be considered. The dissemination and application of planned biochemical substances should be supported by state resources and international agreements. Furthermore, the preference for environmentally friendly approaches that do not harm the ecosystem in all planned industrial processes is an important issue that should accompany all topics.

As a result, it has been demonstrated that value-added biochemical products derived from wood and non-wood forest products also hold a significant place in the industrial sector. The chemical conversion and production process used in this industrial establishment has the potential to be a pioneer not only in the forest industry but also in creating sustainable production models for the future. Multidisciplinary studies and innovative technological approaches on this subject can contribute to the national and international economy.

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Chapter 4

ENDEMIC FISH SPECIES OF THE ASI, CEYHAN, AND SEYHAN RIVERS

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Introduction

The Asi (Orontes), Ceyhan, and Seyhan Rivers are known as the largest rivers in the Mediterranean. The Seyhan and Ceyhan Rivers form the Çukurova River, Türkiye's largest delta plain. These river basins are home to many endemic species and are of great importance for biodiversity. To date, many studies have been reported on the distribution and taxonomy of freshwater fish species inhabiting the Seyhan, Ceyhan, and Asi Rivers (Bayçelebi, 2020). We can list these studies as follows: Bostancı (2006) conducted the first ichthyofaunistic study in the region and revised the fish populations of these three rivers; Dağlı (2008) examined only the two northeastern tributaries of the Asi River (Kınacık and Afrin streams); Kara et al. (2010) investigated the freshwater fish populations of the upper and middle basins of the Ceyhan River; Erk'akan and Özdemir (2011) studied the fish populations of the Seyhan and Ceyhan Rivers; Alagöz Ergüden and Göksu (2012) identified fish populations in the Seyhan Dam Lake. Özcan (2013) conducted a study on the ichthyofauna of the Asi River. A recent study by İnnal (2020) reported on fish diversity and abundance at the mouth of the Seyhan River. Also, Bayçelebi (2020) studied the distribution and fish diversity in the three river systems (Seyhan, Ceyhan, and Asi).

According to a previous study, Kuru et al. (2014) reported that 368 freshwater fish species, belonging to 34 families, are distributed in Türkiye's inland waters. However, Çiçek et al. (2020) reported in their latest revision study examining a total of 384 fish species living in Turkish inland waters that 4 endemic species are extinct in Türkiye, 20 species are non-native, and 208 species are endemic to Türkiye.

In this compilation, the endemic species in the Asi, Ceyhan and Seyhan river systems are as follows: the species found in the Asi River are; *Acanthobrama orontis* Berg, 1948; *Alburnus kotschyi* Steindachner, 1863, *Pseudophoxinus turani* Küçük & Güçlü, 2014, *Squalius kottelati* Turan, Yılmaz & Kaya, 2009, *Paraphanius orontis* (Akşiray,1948)), the species found in the Ceyhan River; *Paracapoeta erhani* (Turan, Kottelat & Ekmekçi, 2008), *Acanthobrama thisbeae* Freyhof & Özulug, 2014, *Pseudophoxinus zeikayi* Bogutskaya, Küçük & Atalay, 2006 *Alburnus adanensis* Battalgazi, 1944, *Schistura ceyhanensis* Erk'Akan, Nalbant & Özeren, 2007, *Schistura evreni* Erk'Akan, Nalbant & Özeren,2007, The species found in the Seyhan River; *Squalius adanaensis* Turan, Kottelat & Doğan, 2013, *Squalius seyhanensis* Turan, Kottelat & Doğan, 2013, *Salmo labecula* Turan, Kottelat & Engin, 2012, *Salmo platycephalus* Behnke,1968, *Oxynoemacheilus samanticus* (Banarescu & Nalbant,1978), *Oxynoemacheilus seyhanensis* (Banerescu, 1968), *Schistura seyhanicola* Erk'Akan, Nalbant & Özeren, 2007).

In this study, the distribution of a total of 18 species was reported 5 species in the Asi River, 6 species in the Ceyhan River, and 7 species in the Seyhan River. Additionally, the morphological features, habitat, ecology, distribution areas, and diagnostic features of the species are provided in detail. Besides, this study presents the current status of endemic fish species in the Asi (Orontes), Ceyhan, and Seyhan river systems.

Results

Asi (Orontes) River

Systematic Features

Family: Leuciscidae

Species: *Acanthobrama orontis* Berg, 1948 (Figure 1)

Name: -

Location: Asi (Orontes) River

Distribution Area: Asi River Basin, Berdan

General Distribution: Endemic (E)

IUCN Red List Status: [NE] (IUCN, 2025)

Diagnosis: Line lateral: 48-61; Line transv:12-14/6-8; DFR: 8; AFR: 14-15; Pharyngeal teeth:5-5

Morphological Features

• The body is laterally compressed and high,

• Ventral fins are pointed and do not reach the vent.

• The ventral fins are slightly in front of the dorsal fin, and their outer edge is straight.

• Its mouth is subterminal. Its lips thin.

• Body color is grey or light brown, ventrally cream coloured. The dorsal fin is colourless.

Habitat and Ecology

Lakes and ponds with low current.

Figure 1. *Achanthobrama orontis Berg, 1948 (Photo: Sibel Alagöz Ergüden)*

Systematic Features

Family: Leuciscidae

Species: *Alburnus kotschyi* Steindachner, 1863 (Figure 2)

Name: Iskenderun Bleak

Location: Hatay

Distribution Area: Asi, Arsuz stream

General Distribution: Endemic (E)

IUCN Red List Status: [LC] (IUCN, 2025)

Diagnosis: Line lateral: 46-50; Line transv: 9/4; DFR: III 8-9; AFR: III 12-14; Pharyngeal teeth: 2.5-5.2

Morphological Features

- The body is slightly compressed from the sides and relatively high.
- The head size is very small compared to body height.
- The caudal fin is deeply forked, and the tips of its lobes are pointed.
- The body color is gray-green on the back and creamy yellow or silver on the ventral side.

Habitat and Ecology

Lakes and fast-flowing rivers.

Figure 2. *Alburnus kotschyi Steindachner,1863 (Photo: Sibel Alagöz Ergüden)*

Systematic Features

Family: Leuciscidae

Species: *Pseudophoxinus turani* Küçük & Güçlü, 2014 (Figure 3)

Name: Turan's Minnow

Location: Hatay

Distribution Area: İncesu Spring, Asi (Orontes) River

General Distribution: Endemic (E)

IUCN Red List Status: [NE] (IUCN, 2025)

Diagnosis: Line lateral:12-25; DFR: III 7; AFR: III 6; Pharyngeal teeth: 5-4

Morphological Features

• Body colour is yellowish on the lower side of the flank and belly. There is a dark grey stripe on the middle of the flank from the posterior margin of the operculum to the caudal peduncle. The black spots are present on all fins and on the dorsal-fin base.

• Mouth terminal, with slightly marked chin, its corner not reaching vertical through the anterior margin of the eye (Güçlü and Küçük 2014).

• The head is short.

• The eye is small.

Habitat and Ecology

Spring and fast-flowing rivers.

Figure 3. *Pseudophoxinus turani Küçük & Güçlü, 2014 (Photo: Sibel Alagöz Ergüden)*

Systematic Features

Family: Leuciscidae

Species: *Squalius kottelati* Turan, Yılmaz & Kaya, 2009 (Figure 4)

Name: Cilician Pike Chub

Location: Hatay, Adana

Distribution Area: Asi (Orontes), Seyhan, and Ceyhan River

General Distribution: Endemic (E)

IUCN Red List Status: [NT] (IUCN, 2025)

Diagnosis: Line lateral: 45-47; DFR: III 8; AFR: III 8-9; Pharyngeal teeth: 5.2-2.5

Morphological Features

• Body is dorsally dark grey, grayish on the flank, and whitish on the belly. The caudal fin is dark grey. Other fins (Dorsal, pectoral, pelvic, and anal) are yellowish.

• Mouth is slightly superior, long, and narrow. The angle of gape reaches vertical through the anterior margin of the eye.

• Head is long and slender.

• Eyes are large.

Habitat and Ecology

Fast-flowing rivers.

Figure 4. *Squalius kottelati Turan, Yılmaz & Kaya, 2009 (Photo: Sibel Alagöz Ergüden)*

Systematic Features

Family: Aphaniidae

Species: *Paraphanius orontis* (Akşiray, 1948) (Figure 5)

Name: Orontes Killfish

Location: Hatay

Distribution Area: Orontes River

General Distribution: Endemic (E)

IUCN Red List Status: [NE] (Froese and Pauly, 2025)

Diagnosis: Line lateral: 25-27; DFR: II 9-11; AFR: I 10-12; VFR: I 4-5

Morphological Features

• The body is thick and short. The body color is pale brown in females and dark brown in males. The dorsal, pectoral, pelvic, and anal fins are blackish.

• Mouth is slightly superior.

• Head length is equal to body height.

• Eyes are large.

Habitat and Ecology

It inhabits areas with streams and rivers, slow-flowing water.

Figure 5. *Paraphanius orontis (Akşiray, 1948) (Photo: Sibel Alagöz Ergüden)*

Ceyhan River

Systematic Features

Family: Cyprinidae

Species: *Paracapoeta erhani* (Turan, Kottelat & Ekmekçi, 2008) (Figure 6)

Name: Ceyhan Scraper

Location: Adana

Distribution Area: Ceyhan River

General Distribution: Endemic (E)

IUCN Red List Status: [LC] (Froese and Pauly, 2025)

Diagnosis: Line lateral: 64-70; DFR: III 8-9; AFR: III 5

Morphological Features

· The head and lateral body are silvery.

· The small black spots are prominent in adult individuals.

· The last simple dorsal fin ray is strong, spiny, distinctly serrated, and shorter than the head.

Habitat and Ecology

It inhabits area with rivers and drainage.

Figure 6. *Paracapoeta erhani (Turan, Kottelat & Ekmekçi) (Photo: Cüneyt Kaya; Fishbase)*

Systematic Features

Family: Leuciscidae

Species: *Acanthobrama thisbeae* Freyhof & Özulug, 2014 (Figure 7)

Name:-

Location: Adana

Distribution Area: Ceyhan River

General Distribution: Endemic (E)

IUCN Red List Status: [NE] (Froese and Pauly, 2025)

Diagnosis: Line lateral: 76-89; DFR: 11; AFR: 17-19

Morphological Features

· The body is silvery-brown on the dorsal part, and the abdomen is dirty.

· The mouth is terminally located and small.

· The head size is smaller than the body height.

· The caudal fin has deep lobes, and the caudal tip of the lobes is sharply.

Habitat and Ecology

It inhabits areas with rivers and drainage.

Figure 7. Acanthobrama thisbeae *Freyhof & Özulug,* 2014 *(Photo: Cemil Kara)*

Systematic Features

Family: Leuciscidae

Species: *Pseudophoxinus zekayi* Bogutskaya, Küçük & Atalay, 2006 (Figure 8)

Name: Ceyhan Spring Minnow

Location: Adana

Distribution Area: Ceyhan River

General Distribution: Endemic (E)

IUCN Red List Status: [VU] (Froese and Pauly, 2025)

Diagnosis: Line lateral: 37-42; DFR: 7; AFR: 6; Pharyngeal teeth: 5-5

Morphological Features

· The back side and flanks are slightly pigmented on the body, and the belly is white. Fins pale.

· Mouth is terminal.

· The head is short.

Habitat and Ecology

It inhabits areas with rivers and streams.

Figure 8. *Pseudophoxinus zekayi Bogutskaya, Küçük & Atalay, 2006 (**P**hoto: Fatih Küçük)*

Systematic Features

Family: Leuciscidae

Species: *Alburnus adanensis* Battalgazi, 1944 (Figure 9)

Name: Adana Bleak

Location: Adana

Distribution Area: Ceyhan River

General Distribution: Endemic (E)

IUCN Red List Status: [NE] (Froese and Pauly, 2025)

Diagnosis: Line lateral: 44-59; DFR: II-III; 7-9; AFR: III 8-11

Morphological Features

- Dorsal is blackish.
- The mouth is small and directed slightly upwards.
- The head is small.

Habitat and Ecology

It inhabits area with rivers and stream.

Figure 9. *Alburnus adanensis Battalgazi, 1944 (**P**hoto: Erdogan Cicek & Sevil Sungur)*

Systematic Features

Family: Balitoridae

Species: *Schistura ceyhanensis* Erk'Akan, Nalbant & Özeren, 2007 (Figure 10)

Name: Elbistan Loach

Location: Adana

Distribution Area: Ceyhan River

General Distribution: Endemic (E)

IUCN Red List Status: [DD] (IUCN, 2025)

Diagnosis: DFR: III 8; AFR: III 5; PFR: I 10-12

Morphological Features

· The head is covered with black spots.

· There are three pairs of thin whiskers at the corners of the mouth.

· The body is slightly flattened laterally and has numerous small brown spots intermingled with each other.

Habitat and Ecology

It inhabits area fast flowing streams with gravel or rocky beds.

Figure 10. *Oxynoemacheilus ceyhanensis (Erk'akan, Nalbant & Özeren, 2007) (Photo: Sevil Sungur, 2009)*

Species: *Schistura evreni* (Erk'Akan, Nalbant & Özeren, 2007) (Figure 11)

Name: Ceyhan Sportive Loach

Location: Ceyhan Basin

Distribution Area: Tekir stream, Ceyhan River, Göksu River

General Distribution: Locally Endemic

IUCN Red List Status: [LC] (IUCN, 2025)

Diagnosis: D: III 8; A: III 5; Pec: I-11; Pelv: II-7

Morphological Feature

· The body is medium-sized.

· The nose is round.

· The body is usually dark brown, spotted, and pale yellow.

Habitat and Ecology

Streams and rivers with gravel substrate and moderately fast to very fast-flowing water (IUCN, 2025).

Figure 11. *Oxynoemacheilus evreni (Erk'Akan, Nalbant & Özeren, 2007) (Photo: Freyhof et al. 2022)*

Seyhan River

Systematic Features

Family: Leuciscidae

Species: *Squalius adanaensis* Turan, Kottelat & Doğan, 2013 (Figure 12)

Name: Adana Chub

Location: Adana

Distribution Area: Seyhan River

General Distribution: Endemic (E)

IUCN Red List Status: [NT] (IUCN, 2025)

Diagnosis: Line lateral: 38-42; DFR: 11; AFR: 11

Morphological features:

· The body is silver in color.

· The mouth is large and the lips are thick.

· The head is short.

Habitat and Ecology

It inhabits areas with rivers and stream.

Figure 12. *Squalius adanaensis Turan, Kottelat & Doğan,* 2013 *(Photo: Esra Bayçelebi)*

Systematic Features

Family: Leuciscidae

Species: *Squalius seyhanensis* Turan, Kottelat & Doğan, 2013 (Figure 13)

Name: Seyhan Chub

Location: Adana

Distribution Area: Seyhan River

General Distribution: Endemic (E)

IUCN Red List Status: [DD] (Froese and Pauly, 2025)

Diagnosis: Line lateral: 42-44; DFR: 12; AFR: 11

Morphological Features

- The body is silver in color.
- The mouth is large.
- The head is short.

Habitat and Ecology

It inhabits areas with rivers and streams, drainage systems.

Figure 13. Squalius seyhanensis Turan, Kottelat & Doğan, 2013 (Photo: Esra Bayçelebi)

Systematic Features

Family: Salmonidae

Species: *Salmo labecula* Turan, Kottelat & Engin, 2012 (Figure 14)

Name: Seyhan Trout

Location: Adana

Distribution Area: Seyhan River

General Distribution: Endemic (E)

IUCN Red List Status: [EN] (Froese and Pauly, 2025)

Diagnosis: Line lateral: 109-113

Morphological Features

- The black spots are found on the body.
- The mouth is large.
- The head is long.

Habitat and Ecology

It inhabits areas with rivers and streams.

Figure 14. *Salmo labecula Turan, Kottelat & Engin, 2012 (Photo: Burak Seçer et. al, 2020)*

Systematic Features

Family: Salmonidae

Species: *Salmo platycephalus* Behnke, 1968 (Figure 15)

Name: Flathead trout

Location: Adana

Distribution Area: Seyhan River

General Distribution: Endemic (E)

IUCN Red List Status: [EN] (Froese and Pauly, 2025)

Diagnosis: DFR: 9-10; AFR: 8-9; PFR: 12

Morphological Features

- The body is brownish with black spots on it.
- The mouth is large.
- The head is long and wide.

Habitat and Ecology

It inhabits areas with rivers and streams.

Figure 15. *Salmo platycephalus Behnke,1968 (Photo: Cüneyt Kaya, Fishbase 2025)*

Systematic Features

Family: Nemacheilidae Regan, 1911

Genus: *Oxynoemacheilus* Bănăraescu & Nalbant, 1966

Species: *Oxynoemacheilus samanticus* (Bănărescu & Nalbant, 1978) (Figure 16)

Name: Samanti sportive loach

Location: Seyhan

Distribution Area: Seyhan River Basin, Kızılırmak River drainage

General Distribution: Endemic (E)

IUCN Red List Status: [LC] (IUCN, 2025)

Diagnosis: DFR: III 8; AFR: III 5

Morphological Features

- The body is cylindrical.
- The eye is small.
- The nose is long and cylindrical.
- Pectoral fins are short
- Body color is yellowish or brown.

Habitat and Ecology

Fast-flowing waters of streams and rivers with gravel substrate (IUCN, 2025).

Figure 16. *Oxynoemacheilus samanticus (Bănărescu & Nalbant, 1978) (Photo: Turan et al., 2023)*

Species: *Schistura seyhanicola* (Erk'akan, Nalbant & Özeren, 2007) (Figure 17)

Name: Adana loach

Location: Seyhan, Ceyhan

Distribution Area: Mediterranean tributary, Seyhan River Basin, and Ceyhan River

General Distribution: Endemic (E)

IUCN Red List Status: [EN] (IUCN, 2025)

Diagnosis: DFR: III 8; AFR: III-5; PFR I-8; VFR: II-6

Morphological Features

- The head is pointed.
- The eye is large.
- The body has yellow and brown spots in places.

Habitat and Ecology

The species occurs in moderately fast-flowing waters of rivers with gravel substrate (IUCN, 2025).

Figure 17. *Schistura seyhanicola* (*Erk'akan, Nalbant & Özeren, 2007) (Photo: Eğlence Stream, Bayçelebi, 2020)*

Species: *Oxynoemacheilus seyhanensis* (Bănărescu, 1968) (Figure 18)

Name: Samanti Loach

Location: Seyhan

Distribution Area: Seyhan basins.

General Distribution: Endemic (E)

IUCN Red List Status: [CR] (IUCN, 2025)

Diagnosis: DFR: II-8; AFR: II-5; PFR: I-10; VFR: I-6

Morphological Features

- Their bodies are oval.
- The tail stalk is high.
- It is covered with very small scales.

Habitat and Ecology

The Samanti loach species occurs in moderately fast-flowing waters of streams with a gravel or muddy substrate (IUCN, 2025).

Figure 18. *Oxynoemacheilus seyhanensis (Bănărescu, 1968) (Photo: Freyhof et al. 2011)*

Discussion and Conclusion

This study assessed the current endemic fish fauna of the Asi, Seyhan, and Ceyhan Rivers. Up to now, there are 18 endemic species in the Asi, Ceyhan, and Seyhan Rivers. These species have been named according to recent revisions as follows: *Acanthobrama orontis, Alburnus kotschyi, Pseudophoxinus turani, Squalius kottelati, Paraphanius orontis, Paracapoeta erhani, Acanthobrama thisbeae, Pseudophoxinus zeikayi, Alburnus adanensis, Schistura ceyhanensis, Schistura evreni, Squalius adanaensis, Squalius seyhanensis, Salmo labecula, Salmo platycephalus, Oxynoemacheilus samanticus, Oxynoemacheilus seyhanensis, Schistura seyhanicola*. Two endemic *Alburnus* species are known from these three river systems. Bostancı (2006) and Erk'akan and Özdemir (2011) reported a belonging to the *Alburnus* genus species in the Seyhan River as *A. adanensis*. Later, Birecikligil et al. (2016) declared *A. adanensis* as a synonym of *A. sellal*. However, Freyhof et al. (2018) accepted a valid species of *A. adanensis*. Bektaş et al. (2020) investigated the molecular characters of the genus *Alburnus* and considered it a synonym of the genus *A. kotschyi*.

Half of the endemic fish species have been described in the last thirty years (Coad and Sarıeyüpoğlu 1988). Furthermore, it is expected that more species will be characterized through further studies, particularly with the use of new data, such as molecular data. However, these fish species have been described primarily based on morphological characteristics. Further studies are needed for the newly described species. For example, *C. turani* and *C. erhani*, described from the Seyhan and Ceyhan Rivers, respectively, were claimed as junior synonyms of *C. barroisi* by Erk'akan and Özdemir (2011) without any explanation (Çiçek et al. 2018).

To date, twelve endemic salmon species have been described, 10 of which have been identified in the last decade (Turan et al. 2010, 2011, 2012, 2014). Trout have been identified based on phenotypic traits that vary depending on their ecology. This is well-documented in trout from Lake Mistassini, Québec, Canada (Marin 2015). Furthermore, the recently described species *S. plathycephalus and S. labecula* from the Seyhan Basin are sympatric and likely synonymous due to their low genetic distance (Bardakcı et al. 2006; Çiçek et al. 2018).

According to the IUCN 2025 assessments, *A. orontis*, *P. turani*, and *P. orontis*, found in the Asi River system, have not yet been evaluated in the IUCN criteria. *S. kottelati* is near threatened (NT), while *A. kotschyi* is least concerned (LC). In the Ceyhan River system, according to IUCN (2025) assessments, *A. thisbeae* and *A. adanensis* are still not in the evaluated (NE), *P. zekayi* is in the vulnerable (VU) and *Schistura ceyhanensis* is in the data deficiency (DD), and *P.erhani* and *S. evreni* are in the least concern (LC) status. In the Seyhan River system, according to the latest IUCN 2025 assessments, *O. seyhanensis* is in critical (CR), *S. adanaensis* is in near threatened (NT), *S. labecula*, *S. platycephalus*, *S. seyhanicola* are in endangered (EN), *Squalius seyhanensis* is data deficient (DD), and *O. samanticus* are in least concern (LC) status.

The survival of endemic species factors affecting include habitat destruction and restrictions imposed by limited habitats; dams, hydroelectric power plants, and the invasion of alien species; water withdrawal due to agricultural irrigation; and drought due to climate change. These factors are increasingly posing a threat to the three river systems. Therefore, it is crucial that relevant ministries, especially the Ministry of Environment, Urbanization, and Climate Change, swiftly implement the necessary protection measures and establish protected areas for endemic species.

In conclusion, the present study was designed to assess the current status of endemic freshwater fish species in the Asi, Ceyhan, and Seyhan basins. It also highlights the need to establish a protected area for endangered and endemic fish species.

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Chapter 5

LIGNIN-BASED FLAME RETARDANTS FOR SUSTAINABLE TEXTILE APPLICATIONS: MECHANISMS, METHODS, AND FUTURE PERSPECTIVES

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1. INTRODUCTION

Many natural and synthetic fibers used in the textile industry are materials that can easily ignite and spread flames rapidly because they contain high amounts of organic compounds. This situation poses serious fire safety risks in areas such as clothing, home textiles, transportation, and technical textiles. Therefore, improving flame-retardant (FR) properties of textile products is crucial for user safety and regulatory compliance (Dagher et al., 2025).

A large portion of traditional FRs containing halogen and phosphorus can release toxic gases (e.g., HCl, HBr, dioxin, and furan derivatives) at high temperatures (Ling et al., 2023). The bioaccumulation potential, environmental persistence, and endocrine-disrupting effects of these chemicals pose significant risks to human health and the ecosystem. For these reasons, biobased and environmentally friendly FRs that have low environmental impact, do not emit toxic gases, and can be produced from renewable resources have been intensively researched in recent years (Xu et al., 2025).

In this context, natural polymers such as casein, chitin, starch, pectin, and lignin stand out among sustainable FR agents. These biopolymers, due to their tendency to char during combustion, can reduce heat transfer by creating a protective barrier on the surface and preventing oxygen from reaching the lower layers (Turku et al., 2024). Lignin, in particular, is one of the most attractive candidates in this group due to its structural properties, abundance, and low cost (Goliszek et al., 2024).

Lignin, found in plant cell walls along with cellulose and hemicellulose, is a three-dimensional aromatic biopolymer composed of phenylpropanoid units (Vásquez-Garay et al., 2021). It provides plants with mechanical strength, hydrophobicity, and resistance to biodegradation (Ma et al., 2024). The structure of lignin varies depending on the biomass source and extraction method. While the lignin content in woody plants is generally between 18–35%, it is found in nonwoody plants at 15–25%, in agricultural wastes (e.g., wheat straw and corn stalks) at 10–20%, in softwoods at 25–35%, and in hardwoods at 18–25% (Mateo et al., 2025). This widespread distribution demonstrates that lignin is abundant in both woody and agricultural biomass and can be obtained as a high-volume, low-cost industrial byproduct.

Lignin, a significant byproduct of the pulp and paper industry, is primarily derived from the black liquor produced during the kraft pulping process. On average, approximately 1.7–1.8 tons of black liquor are produced for one ton of cellulose pulp on a dry basis. This means that the approximately 170 million tons of black liquor produced annually worldwide contains approximately 70 million tons of lignin (Mateo et al., 2025). At an industrial scale, lignin is divided into three main categories: lignosulfonates (≈88%), kraft lignin (≈9%), and organosolv lignin (≈2%) (Bajwa et al., 2019). However, despite its large production volumes, lignin has historically been used primarily as a fuel for heat and power generation. Only a small portion of the lignin produced (less than 2%) is used commercially, primarily in the production of dispersants, adhesives, surfactants, and specialty chemicals. The remaining part is burned for energy recovery or used as filler in animal feed (Balk et al., 2023).

Lignin represents a major byproduct of the pulp and paper industry. For instance, the kraft pulping process generates approximately 1.7–1.8 tonnes of black liquor for every tonne of cellulose pulp produced on a dry basis. Consequently, about 170 million tonnes of black liquor, containing large amounts of lignin and other organic polymers, are generated annually worldwide, corresponding to an estimated 70 million tonnes of recoverable lignin from pulping operations (Mateo et al., 2025).

The primary industrial forms of lignin include lignosulfonates (≈88%), kraft lignin (≈9%), and organosolv lignin (≈2%) (Bajwa et al., 2019). Historically, the majority of lignin has been combusted as a fuel source for heat and power generation, with less than 2% being commercialized. The portion utilized commercially has mainly been applied in the formulation of dispersants, adhesives, and surfactants. Currently, it is estimated that only about 2% of the lignin produced is utilized for specialty chemical applications, while the remaining portion is either burned for energy recovery or incorporated into animal feed as a bulking agent (Bulk et al., 2023).

Due to its aromatic structure and high carbon content, lignin has significant potential as a natural FR. During thermal decomposition, it forms a carbonized char layer instead of volatile combustible compounds, slowing the combustion process and limiting heat transfer (Dai et al., 2020). It has been reported that lignin undergoes thermal degradation at temperatures above 150 °C, forming a thermally stable carbon residue (char) when temperatures reach 700 °C (Brodin et al., 2010; Brebu et al., 2013). The high thermal resistance of lignin is largely due to its structural and chemical properties. The aromatic rings within the polymer chain, thanks to their high bond energies, are heat-resistant and do not degrade easily. The C–C and C–O–C (ether) bonds that connect lignin units, combined with a dense cross-link network, maintain the integrity of the molecule and retard thermal degradation. Furthermore, the phenolic and oxygenated functional groups within lignin promote the formation of carbon residue (char) at high temperatures, which increases the material's thermal resistance and provides it with a natural FR function. These properties make lignin not only a heat-resistant polymer but also an FR biomaterial (Brebu and Vasile, 2010). On the other hand, lignin's FR mechanism of action occurs in two stages. First, it prevents oxygen from reaching the surface by releasing water, carbon dioxide, and phenolic derivatives during the heating process. Second, it forms a protective carbon layer on the surface via aromatic carbon structures. This layer reduces heat conduction and flammable gas evolution, prolongs combustion duration, reduces flame propagation speed, and delays ignition (Mandlekar et al., 2018).

Lignin can be used as a natural additive in textile materials, particularly those derived from cellulosic fibers prone to burning, such as cotton, viscose, and linen. It can be mixed directly into the fiber matrix, applied as a coating, or used in conjunction with polymer-based binders. When modified with compounds containing phosphorus and nitrogen, lignin exhibits synergistic FR effects (Zhang et al., 2012; Won et al., 2024; Zhao et al., 2025). It enhances charring ability and prevents flame propagation through free radical scavenging reactions in the gas-phase (Gu et al., 2025).

In recent years, many studies have been carried out on the use of lignin as an FR in the textile industry. Mandlekar et al. (2017) investigated the FR properties of alkali lignin and metal phosphinates in a polyamide 11 (PA11) matrix. Lignin was found to exhibit a synergistic FR effect with phosphinates, forming a dense, protective carbon layer during combustion. This combination significantly reduced the peak heat release rate (PHRR) while increasing heat resistance and carbon residue values. Shukla et al. (2019) investigated the FR effects of treating cotton fabric with 30% (w/v) sodium lignin sulfonate. The LOI value increased from 18% to 28.5% in cotton treated with 30% lignin. Thermogravimetric analyses revealed that the lignin-treated fabric retained approximately 35% of its mass at 500°C, whereas the control sample retained only approximately 8% of its mass under the same conditions. Additionally, the lignin treatment imparted a pleasant natural yellow color to the fabric, provided UV protection, and did not significantly reduce the fabric's physical strength. Łukawski et al. (2020) developed lignin/carbon nanotubes (CNTs)/potassium carbonate (K_2CO_3) composite coatings to enhance the FR properties of cotton roving fibers. The coatings were applied to cotton by dip-coating using solutions with varying lignin and CNT contents. The results indicated that the optimal composition was a composite coating containing 1% lignin, 1% CNTs, and 1% K_2CO_3. This composition increased the LOI of cotton from 17.1% for raw cotton to approximately 38.5%, while the temperature during vertical combustion decreased from 457 °C to 190 °C. Petkovska et al. (2022) applied a layer-by-layer multifunctional nanocoating using a lignin derivative (magnesium lignosulfonate), chitosan, and monoammonium phosphate to cotton fabrics. The coating provided an effective FR function, exhibiting self-extinguishing behavior even in just two layers. After lignin treatment, the sample's LOI value increased from 18.5% to 38%. Li et al. (2024) obtained an FR by combining lignin-silica-based liquid derived from rice hulls with DOPO (9,10-dihydro-9-oxa-10-phosphafenanthrene-10-oxide). This liquid, applied to cotton fabrics using a single-stage dip coating method, was found to exhibit self-extinguishing properties in vertical burning tests. Furthermore, reductions of up to 78% in peak heat release and 65% in total heat release were recorded. This treatment increased the fabric's tensile strength by 21.7%. The LOI value of the sample was increased from 17.7% to 27.5% with lignin treatment. Won et al. (2024) added a lignin-based FR to cotton fabrics at a rate of 10% by weight using the dipping method. Compared to control cotton fabrics, the burning time of the lignin-added cotton fabrics decreased by 6.8 seconds, the maximum flame height decreased by 5.4 cm, and the char residue increased by 25%. Liu et al. (2024) developed multifunctional cotton fabrics using alkali lignin and ammonium polyphosphate (APP). Lignin, thanks to its rich aromatic structure, increased carbonation capacity, resulting in flame retardancy, while APP, working synergistically with its phosphorus content, supported the formation of a dense and protective char layer. As a result of this combination, the fabric's LOI value increased from 18.6% to 48.5%, achieving a "V-0" FR rating in the UL-94 test (Underwriters Laboratories Standard 94).

In recent years, lignin nanoparticles (LNPs) have also gained attention in FR applications. Thanks to their homogeneous distribution, nanolignin integrates better into the polymer or textile matrix and forms a denser and more compact ember layer during the carbonization process, reducing both flame spread and dripping tendency (Chollet et al., 2019; Won et al., 2024; Ouadil et al., 2025; Pereira et al., 2025).

With all these properties, lignin stands out as an ecological and effective FR additive in textile materials, thanks to both its natural structure and modifiability. Whether used alone or synergistically with other elements, it increases the fire resistance of textiles and makes a significant contribution to environmentally friendly production (Kumar and Barbhai, 2023).

This review comprehensively examines the mechanisms of lignin-based FRs, application methods, performance evaluations, and future research trends regarding the use of lignin as an FR agent in the textile industry.

2. CHEMICAL STRUCTURE AND THERMAL BEHAVIOR OF LIGNIN

Lignin, along with cellulose and hemicellulose, is one of the three main biopolymers found in plant cell walls and the second most abundant natural polymer in nature (Alam et al., 2024). Structurally, it has an amorphous, three-dimensional, branched structure formed by three primary phenylpropanoid units (C9 units): p-hydroxyphenyl (H), guaiacyl (G), and syringyl (S), linked by various ether (C–O–C) and carbon-carbon (C–C) bonds. The ratio of these monomers varies depending on the plant species. G units predominate in softwoods, while the proportion of S units is higher in hardwoods; in herbaceous plants, all three units (S, G, and H) are present together (Vasile and Baican, 2023). These differences are the fundamental factors determining both the structural heterogeneity and the thermal and chemical reactivity of lignin.

Lignin contains functional groups such as methoxy ($-OCH_3$), hydroxyl ($-OH$), carbonyl ($-C=O$), and carboxyl ($-COOH$) (Shorey et al., 2024). These groups increase lignin's polarity, hydrogen bonding capacity, and susceptibility to chemical modification (Wang et al., 2019). At the same time, its high aromatic ring density and carbon content (approximately 60–65%) make lignin thermally stable and prone to char formation. This property is one of the most critical parameters for the use of lignin as an FR (Dai et al., 2020).

The thermal degradation behavior varies depending on the type of biomass from which the lignin is derived and its purity, but primarily occurs between 200–600°C (Li et al., 2023). According to thermogravimetric analysis (TGA) data, lignin exhibits mass loss between 160–400°C due to the decomposition of methoxy and hydroxyl groups. At 350–500°C, a carbon-rich char layer forms due to the condensation of aromatic ring structures (Lu and Gu, 2022). This char layer reduces the flame contact of the underlying material by inhibiting oxygen diffusion and limiting heat transfer. Thus, lignin provides a protective barrier in the condensed-phase, thus providing an FR effect (Malucelli, 2024).

The thermal degradation products of lignin also directly affect the combustion process. During decomposition, phenolic compounds, aldehydes, ketones, and gases (e.g., CO_2, CH_4, H_2O) are released (Lu and Gu, 2022). Some of these volatile products can slow flame propagation by scavenging free radicals in the gas-phase. Therefore, lignin can contribute to the dual-direction FR mechanism through both condensed-phase charring and gas-phase radical inhibition (Won et al., 2024).

Lignin types obtained through different processing methods—such as kraft, soda, organosolv, and deep eutectic solvent (DES) lignins—vary significantly in terms of chemical bond structure and impurity content. While kraft lignin, due to its high sulfur content, can release gases such as SO_2 during thermal decomposition (Borella et al., 2022), organosolv (Pongchaiphol et al., 2022) and DES (Lin et al., 2023) lignins exhibit more uniform thermal behavior due to their purer, lower ash content, and controlled molecular weight. Therefore, organosolvs and DES lignins are more suitable for textile applications, thanks to both environmentally friendly production processes and controlled chemical structures.

Lignin's chemical structure, high aromatic character, charring tendency, and adaptability of its functional groups to modification make it an environmentally friendly and effective biobased FR candidate. Lignin's thermal stability and char-forming ability, both alone and in combination with phosphorus, nitrogen, or metal additives, significantly enhance the fire resistance of textiles (Mandlekar et al., 2018).

3. MECHANISMS OF LIGNIN-BASED FLAME RETARDANTS

The FR effect of lignin is based on two primary mechanisms: condensed-phase char formation and gas-phase radical inhibition. Furthermore, the combination of lignin with phosphorus and nitrogen can significantly increase the efficiency of these mechanisms by creating synergistic effects (Zhao et al., 2025). The aromatic rings, oxygen-containing functional groups, and high carbon content in the chemical structure of lignin play a decisive role in each of these processes (Dai et al., 2020).

3.1. Condensed-Phase Mechanism

The most dominant FR effect of lignin occurs in the condensed-phase. During heat treatment or flame contact, lignin forms a carbon-rich char layer by condensing aromatic structures and removing volatile products such as water, carbon monoxide (CO), and carbon dioxide (CO_2). This char layer serves as a protective barrier. It prevents oxygen from reaching the underlying fiber layers, restricting heat transfer and limiting the release of flammable volatile gases. This double-sided effect reduces the combustion rate and prevents the spread of fire (Liu et al., 2026). The higher the char rate, the greater the thermal stability and flame resistance of the material.

The aromatic structure of lignin has a significantly more complex carbon skeleton than other biopolymers, such as cellulose and hemicellulose (Cao et al., 2014). Therefore, the post-combustion char residue content of lignin is approximately 40% (Sharma et al., 2004). This high residue content allows lignin to act as a natural carbon source in condensed-phase FRs.

3.2. Gas-Phase Mechanism

Another aspect of lignin's FR effect is its radical inhibitory effect, which occurs in the gas-phase. During thermal degradation, lignin produces volatile compounds including phenolic compounds, methoxy radicals, aldehydes, and ketones. Some of these components can slow down chain combustion reactions by scavenging free radicals such as H· and OH· formed in the flame zone. This effect operates similarly to the radical scavenging mechanism in halogenated FRs. However, it occurs without the release of toxic gases. Furthermore, the water vapor and carbon dioxide formed by lignin degradation provide a cooling and diluting effect by increasing the dilution of combustible gases. Therefore, lignin can exhibit dual-phase FR behavior, especially when combined with phosphorus or nitrogen-added applications (Liu et al., 2026).

3.3. Synergistic Effects and Hybrid Applications

While lignin's FR effectiveness alone provides a certain level of protection, it is significantly increased when used in combination with inorganic or phosphorus-containing components. Phosphorus-containing compounds, particularly ammonium polyphosphate and phosphoric acid derivatives, interact with lignin to form phosphate bridges. This promotes charring reactions and densifies the char structure (Zhang et al., 2018). Similarly, when used with lignin, nitrogen-containing compounds such as melamine, urea, and chitosan form an intumescent barrier layer during thermal degradation. This layer forms a foam-like carbon barrier on the surface, further limiting oxygen permeation. Furthermore, complexation of lignin with metal ions (e.g., Fe^{3+}, Al^{3+}, Mg^{2+}) can increase thermal stability by reducing heat transfer during combustion (Zhang et al., 2012; Liu et al., 2025; Agustiany et al., 2025).

Such hybrid lignin applications both enhance condensed-phase charring and increase radical scavenging capacity in the gas-phase. Lignin–phosphorus–nitrogen ternary methods yield high Limit Oxygen Index (LOI) values and low heat release rates (HRR) in textile coatings (Piao et al., 2022).

3.4. Interaction with Textile Fibers

The FR mechanism of lignin may have different effects depending on the fiber type. In cellulosic fibers such as cotton and viscose, lignin forms chemical bonds or hydrogen bridges on the surface, providing a strong char layer. In synthetic fibers like polyester and polyamide, the FR effect of lignin is generally achieved through surface coatings or composite formulations. In this case, the char layer formed by lignin acts as a protective shield on the polymer surface, retarding thermal degradation (Łukawski et al., 2020; Magovac et al., 2022).

Lignin functions as an effective dual-phase FR through both condensed-phase charring and gas-phase radical inhibition (Liu et al., 2026). Lignin enhanced with phosphorus, nitrogen, or metal additives offers an environmentally friendly and non-toxic alternative to traditional halogenated FRs, making it a strong candidate for sustainable FR solutions in the textile industry (Mandlekar et al., 2020).

4. INTERACTION BETWEEN LIGNIN AND TEXTILE FIBERS

The chemical (e.g., hydrogen bonds, covalent bonds, ionic interactions) and physical (e.g., van der Waals forces, surface adsorption, and film formation) interactions between lignin and the fiber surface determine lignin's ability to impart FR properties to textiles. The binding method of lignin to the fiber surface directly affects the durability, thermal stability, and FR performance of the resulting coating (Liu et al., 2024).

4.1. Interaction with Natural Fibers

Natural fibers such as cotton, linen, and viscose can interact strongly with lignin through hydrogen bonding because they contain hydroxyl (–OH) groups on their surfaces. The phenolic and aliphatic hydroxyl groups in lignin's structure form a dense hydrogen bond network with the hydroxyl groups in the cellulose chain (Gaynor et al., 2022). This bonding allows lignin to adsorb homogeneously onto the fiber surface. It also enables the formation of a compact interfacial structure that supports char formation during thermal degradation (Łukawski et al., 2020).

Lignin can also form covalent bonds on the surface of cellulosic fibers through partial esterification or etherification reactions. This chemical bonding becomes particularly pronounced when modified lignin types (e.g., sulfonated, phosphorylated, or aminated lignin) are used (Łukawski et al., 2020). Thus, lignin is chemically anchored to the fiber surface, providing permanent FR properties resistant to washing cycles (Liu et al., 2024).

4.2. Interaction with Synthetic Fibers

In synthetic fibers (e.g., polyester, polyamide, acrylic), the more hydrophobic and less reactive surfaces make direct lignin bonding difficult. In this case, lignin is usually applied through binders or surface modification processes. For example, the amide groups of polyamide fibers can form hydrogen bonds with the phenolic hydroxyl groups of lignin (Kandola et al., 2025). In contrast, the carboxyl groups formed on the surface of polyester fibers by surface plasma treatment or alkaline hydrolysis facilitate lignin adsorption (Ruwoldt et al., 2023).

The interaction between lignin and polyester or polyamide is often physical adsorption or film coating. Such physical coatings reduce heat and oxygen transfer by creating a carbonaceous barrier on the fiber surface during exposure to flame. However, due to the weak chemical bonding, the wash resistance of such coatings can be limited. This problem can be largely overcome by applying lignin to the surface in conjunction with silane-based agents (Ghosh et al., 2025).

4.3. Interaction in Hybrid Applications

In recent years, lignin has been used in conjunction with FRs containing phosphorus, nitrogen, or metal ions, achieving synergistic effects. In these hybrid applications, lignin serves both as a carbon source to promote charring and as a reactive matrix for inorganic FR agents (Weng et al., 2023). For example, in lignin-phosphorus composites, the hydroxyl groups on the lignin surface form ester bonds with phosphorous compounds, which release phosphoric acid derivatives during thermal degradation, contributing to the densification of the char layer (Mendis et al., 2016). Similarly, in lignin–metal ion complexes (e.g., lignin–Mg^{2+}, lignin–Al^{3+}), both thermal stability and heat-absorbing effects are enhanced during flame propagation (Yan et al., 2020). Such synergistic methods significantly enhance the FR performance of lignin, particularly in polyester or polyamide fibers.

5. LIGNIN-BASED FLAME RETARDANT APPLICATION METHODS

The methods used to apply lignin to textile materials to impart FR properties vary depending on parameters such as lignin solubility, molecular weight, surface reactivity, and fiber type. The application approach determines not only the way lignin adheres to the fiber surface but also final performance characteristics such as charring behavior, thermal stability, and wash resistance (Won et al., 2024).

5.1. Dipping

One of the most common approaches involves impregnating or dipping a lignin solution or suspension into the textile material. In this method, lignin is dissolved in solvents such as water or ethanol or prepared as a colloidal suspension. The fabric is then immersed, excess solution is removed with squeeze rollers, and the fabric is dried (Li et al., 2024).

Because cellulosic fibers (e.g., cotton, viscose) are compatible with the hydrophilic nature of lignin, lignin molecules can adsorb to the fiber surface through hydrogen bonds (Gaynor et al., 2022). However, in synthetic fibers (e.g., polyester, polyamide), lignin adhesion is weak due to the surface's hydrophobic nature. In this case, the bonding capacity is increased by treating the surface with plasma oxidation, alkaline hydrolysis, or surface activators before impregnation (Ruwoldt et al., 2023; Lee et al., 2025).

While impregnation is a simple, low-cost, and scalable technique, the washing resistance of the coating can be limited. Therefore, it is generally recommended to use lignin in conjunction with crosslinking agents (e.g., glutaraldehyde, silanes, or chitosan) (Galan et al., 2021).

5.2. Coating

Lignin can form a film-forming layer on textile surfaces. This layer acts as a protective barrier, reducing heat transfer and limiting oxygen transmission. Blade coating, dip-coating, spray coating, and layer-by-layer (LbL) techniques are prominent coating methods (Ghosh et al., 2025).

LbL nanocoatings, particularly those formed with lignin-chitosan or lignin-pectin combinations, yield promising results thanks to their high charring rate and low flame propagation speed (Villamil Watson and Schiraldi, 2020). The advantage of coating processes is the ability to impart additional functions such as color, UV resistance, and antimicrobial properties. This increases the importance of lignin as an environmentally friendly additive in multifunctional "smart textile" designs (Ghosh et al., 2025).

5.3. Chemical Modification

Lignin may need to be chemically modified to bond directly to the textile surface. Phosphorylated, nitrogenated, or metallized lignin derivatives have been developed for this purpose (Mendis et al., 2016; Yan et al., 2020; Weng et al., 2023).

Phosphorylated lignin catalyzes charring reactions by forming phosphoric acid derivatives during thermal decomposition, enhancing FR. Nitrogen modification introduces components into the lignin structure that act as radical scavengers in the gas-phase during thermal degradation (Weng et al., 2023). Metal ion modifications (e.g., lignin–Al^{3+} and lignin–Fe^{3+} complexes), on the other hand, absorb heat, accelerating carbonization and limiting heat transfer (Yan et al., 2020).

As a result of these modifications, lignin surface reactivity increases and it can integrate more permanently into textile fibers through covalent bonds. Modified lignins also become more resistant to water and more thermally stable.

5.4. Composite and Blend Methods

Another strategy is to blend lignin with polymer matrices to form composite coatings or fibers. Lignin can be processed with poly(vinyl alcohol) (PVA), polylactic acid (PLA), polyurethane (PU), or epoxy resins to produce biocomposite FR coatings (Dai et al., 2020; Yang et al., 2021; Liu et al., 2025). In these methods, lignin serves as the carbon source, while the polymer matrix provides mechanical strength and surface integrity. PVA/lignin and PU/lignin blends, in particular, are attracting attention with their FR and UV-protective properties. Furthermore, lignin-containing nanofibers produced via electrospinning represent a new research area for developing lightweight and thermally resistant textile coatings (Liu et al., 2025).

5.5. Green and Environmentally Friendly Application Approaches

Recently, environmentally friendly solvents, particularly DESs and ionic liquids, have attracted considerable attention in the preparation of lignin-based FRs. These solvents increase lignin solubility and provide a more homogeneous distribution without damaging the fiber surface (Kim et al., 2025). Furthermore, it has been reported that in applications performed in DES media, lignin molecules are partially immobilized on the surface through ionic interactions, thus increasing the durability of the coating. This approach is both compatible with green chemistry principles and offers a sustainable option for utilizing industrial waste lignin.

The choice of application method depends on the target textile type, the desired FR performance level, and processing conditions. Simple impregnation methods are cost-effective and scalable, while chemical modification and composite systems provide greater strength and effectiveness. However, the fundamental goal of all approaches is to integrate lignin into the fiber surface in a permanent, homogeneous, and thermally stable manner.

6. PERFORMANCE EVALUATION AND TEST METHODS OF LIGNIN-BASED FLAME RETARDANTS

The effectiveness of lignin-based FRs should be verified not only through their chemical and thermal mechanisms but also through performance parameters measured through standard tests. These tests provide an objective assessment of FR properties (Dai et al., 2020; Liu et al., 2026). The aromatic rings and oxygen-containing functional groups in the lignin structure activate both char formation in the condensed-phase and radical suppression mechanisms in the gas-phase during thermal degradation (Won et al., 2024). Therefore, the success of lignin addition depends not only on its chemical composition but also on the method of integration into the textile matrix and the additive systems used.

The Limiting Oxygen Index (LOI), one of the most fundamental performance indicators, determines the minimum oxygen content required for a material to sustain combustion. A material's flammability is assessed by its Limited Oxygen Index (LOI). Materials with an LOI of 21.0% or less are considered highly flammable (e.g., cotton). These materials can burn in oxygen levels equal to or less than atmospheric oxygen. LOI values of 21.0% to 25.0% indicate that the material is moderately flammable (e.g., polyamide and polyester), while LOI values of 25.0% and above indicate that the material is limitedly flammable (e.g., meta- and para-aramids). LOI measurements are performed in accordance with ASTM D2863-23 or ISO 4589-3. In LOI measurements, vertically positioned samples are ignited with a propane flame approximately 2 cm above the surface (Alongi et al., 2015; Liu et al., 2026). LOI values in lignin-added cotton or polyester systems are generally reported to increase from 18–20% to 25–35% (Shukla et al., 2019; Łukawski et al., 2020; Petkovska et al., 2022; Li et al., 2024). In hybrid applications created with phosphorus and nitrogen modifications, LOI values can reach up to 40%, and this increase is directly related to lignin's ability to form an oxygen barrier and promote charring.

The UL-94 classification is the primary method used to assess the flammability of polymer and textile surfaces, categorizing materials from Class V-0, the most non-flammable, to Class V-2, which is the most flammable. During testing, plastic samples are placed vertically or horizontally in accordance with ASTM D3801, IEC 60695, IEC 60707, and ISO 1210, and their undersides are ignited with a methane flame approximately 2.5 cm long (Alongi et al., 2015; Liu et al., 2026). When lignin used with phosphorus and nitrogen compounds, it provides FR performance on polymer and textile surfaces, reaching the UL-94 classification value of the material from V-2 to V-0 or V-1 levels. In these tests, lignin-based coatings can achieve results particularly close to V-0 due to their rapid charring and barrier effect, which prevents flame transmission to the substrate. Hybrid lignin–phosphorus/nitrogen applications, on the other hand, exhibit shorter afterflame times and a lower tendency for dripping formation, confirming the effectiveness of both condensed-phase and gas-phase mechanisms (Dai et al., 2020; Weng et al., 2023).

Thermogravimetric analysis (TGA) is widely used to determine the thermal degradation behavior of lignin-added textile applications. TGA curves show that lignin addition generally raises the onset temperature of decomposition and significantly increases the amount of char (Liu et al., 2026). For example, in cotton fabrics modified with lignin, carbon residue can reach from 35% at 500°C (Shukla et al., 2019). In applications containing phosphorus or metal additives, char formation is more intense and thermal degradation occurs more slowly, indicating improved FR performance.

Micro Combustion Calorimetry (MCC) tests, which evaluate heat production during combustion, reveal that lignin addition reduces the heat release rate (HRR) and delays the peak maximum heat release (PHRR), indicating that lignin acts as a thermal buffer that slows combustion kinetics. Cone Calorimeter (CC) tests (ASTM E1354, ISO 5660), which simulate more comprehensive and realistic conditions, measure parameters such as HRR, total heat release (THR), smoke production rate (SPR), and ignition time (TTI) (Liu et al., 2026). Lignin-based coatings reduce HRR and THR values by 25–50% in the CC test and increase char formation. Furthermore, lignin modifications reduce smoke production and limit the emissions of toxic gases during combustion.

Microstructural changes in the material are examined using Scanning Electron Microscopy (SEM). In lignin-added samples, the post-combustion char layer has a denser, more compact, and more holistic morphology. This prevents oxygen diffusion and protects the underlying fibers. Fourier Transform Infrared Spectroscopy (FTIR) analyses of the charred layer confirm that aromatic carbon-carbon bonds increase, hydroxyl groups decrease, and thermal cross-linking reactions occur during lignin degradation. Raman spectroscopy indicates that the char layer contains graphite-like (sp^2) structures, which reduce thermal conductivity and enhance FR efficiency. Recent Differential Scanning Calorimetry (DSC) studies have also examined the melting behavior and degree of crystallinity in lignin-added samples (Dai et al., 2020).

Overall, all these tests demonstrate that lignin-based applications offer a versatile FR effect. In the condensed-phase, it creates a char layer, creating a physical barrier, and in the gas-phase, it slows combustion reactions through a radical suppression mechanism. Furthermore, lignin's environmentally friendly, non-toxic, and biodegradable nature supports its evaluation as a sustainable alternative to conventional halogenated or phosphorescent FRs.

7. ADVANTAGES, LIMITATIONS, AND FUTURE PERSPECTIVES OF LIGNIN-BASED FLAME RETARDANTS

Lignin-based FRs stand out for their environmental friendliness and sustainability. Lignin, a natural component of plant cell walls, is a renewable and biobased resource and, unlike halogenated FRs, does not create environmental problems such as toxic gas emissions or bioaccumulation (Mandlekar et al., 2020). Furthermore, lignin is economically advantageous, especially when derived from industrial byproducts (kraft lignin, organosolv lignin, etc.). Lignin offers a dual-phase FR effect, both through condensed-phase charring and gas-phase radical stifling mechanisms (Liu et al., 2026). This effect is synergistically enhanced when used in conjunction with phosphorus, nitrogen, or metal additives. Furthermore, lignin-based coatings can provide additional functions such as UV resistance, antimicrobial activity, and color stability in addition to FR properties. This makes them a suitable option for multifunctional textile applications (Petkovska et al., 2022). However, lignin-based applications also have some limitations and challenges. Direct lignin binding is difficult, particularly in synthetic fibers. Coatings applied via physical adsorption may exhibit limited resistance to washing and abrasion (Ferreira et al., 2025). High lignin loadings can negatively impact the fiber's flexibility, mechanical strength, and texture. Furthermore, lignin varies in chemical structure and molecular weight depending on the source and production method. This heterogeneity can make standardizing FR performance difficult. Especially in high-performance applications, synthetic fibers and hybrid applications may require additional treatments such as chemical modification or surface activation, which can complicate the production process and increase costs.

Research is ongoing on new modification methods to enhance lignin FR performance. In addition to phosphorus-, nitrogen-, and metal-based modifications, treatments with environmentally friendly solvents like DESs and ionic liquids ensure a homogeneous and permanent attachment of lignin to the fiber surface. Nanotechnology and multilayer applications offer strong bonding to the fiber surface and high FR efficiency through lignin-based nanoparticles and layer-by-layer coatings. This approach holds great potential for future "smart textile" applications. Lignin derived from industrial byproducts can be created into low-cost and sustainable FRs with appropriate modification and application methods. This offers a value-added solution for both the textile and composite materials industries. Finally, halogen-free lignin-based FRs offer significant advantages in terms of compliance with future international fire safety standards and environmental regulations.

Lignin-based FRs offer a strong alternative to conventional FRs with their sustainability, environmentally friendly structure, and dual-phase combustion mechanism. However, limitations such as surface adhesion, mechanical properties, and lignin heterogeneity should be considered, and optimal application strategies and modification techniques should be developed. In future studies, the performance of lignin-based FRs can be enhanced through nanotechnology, hybrid applications, and green chemistry approaches. This will enable the implementation of sustainable and high-performance FR solutions in both textile and technical materials.

8. CONCLUSIONS

Lignin has great potential as an environmentally friendly and sustainable FR agent in the textile industry. Thanks to its naturally aromatic structure and high carbon content, it forms a protective char layer in the condensed-phase during thermal degradation and acts as a radical suppressor in the gas-phase, slowing flame propagation. Interaction mechanisms with cellulosic and synthetic fibers directly determine lignin's surface adhesion and FR performance, while hybrid applications using phosphorus, nitrogen, or metal additives significantly increase this effectiveness.

However, lignin applications also have some limitations. Due to its inherent heterogeneity, issues of reproductive and homogeneity can arise. Lignin samples derived from different plant sources vary in chemical composition and molecular weight. Lignin's inherent insulating nature necessitates additional modification or compositing for electrical conductivity or sensor applications. Furthermore, solubility, fiber-matrix compatibility, and mechanical strength issues can also be observed in some coating and fiber modification processes.

Application methods include impregnation, coating, and chemical modification. The advantages and limitations of each method are closely related to the fiber type, lignin source, and targeted performance criteria. Performance evaluations (LOI, UL-94, TGA, MCC, Cone Calorimeter) demonstrate that lignin-based FRs are effective in terms of both thermal and combustion behavior. However, surface adhesion problems, changes in mechanical properties, and lignin heterogeneity should be considered.

In the future, the effectiveness and durability of lignin-based FRs can be increased through nanotechnology-based applications, hybrid applications, and green chemistry approaches. The use of lignin derived from industrial byproducts enables the development of both economical and sustainable FR solutions. LNP and lignin-based nanoparticles offer a more homogeneous distribution and functionality on the fiber surface, enabling for the optimization of properties such as UV resistance, moisture management, electrical conductivity, and antimicrobial performance. Furthermore, the production of lignin and polymer composites using biodegradable, recyclable, and environmentally friendly methods is a significant research area that supports sustainable textile design.

In conclusion, lignin-based FRs offer an environmentally friendly and high-performance alternative to halogenated and toxic FR agents in the textile industry, creating significant opportunities for future research and applications. Future studies should focus on standardized lignin sources, controlled modification techniques, and the integration of nanotechnology to maximize lignin's potential and overcome current limitations.

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Chapter 6

EFFECT OF OSMO-PRIMING IN NATURALLY AGED PEPPER SEEDS

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Introduction

Pepper (*Capsicum annuum* L.) is one of the most valuable warm season vegetable crops widely grown in greenhouses, open fields, and net houses. It is used for fresh food, cooking, and processing, and is also an important source of bioactive compounds. (Arın and Arabacı, 2019; Kaya, 2022). Türkiye, with 3.5 million tonnes, is the third place in terms of pepper production in world (FAO, 2025). Pepper, generally propagated by seedling, is not only open field crop, but is also an important vegetable of greenhouse production in our country. It has relatively a hard seed coat and a protective endosperm layer surrounding the embryo and these reduces the movement of water, gas exchange and diffusion of endogenous inhibitors responsible for poor germination (Chartzoulakis and Klapaki, 2000; Basu and De, 2003; Tu et al., 2022). Therefore, pepper seeds have low viability and rapidly lose vigor, and their storage life is shorter than other vegetable seeds. Low seed viability causes reduced germination, delay, heterogeneous seedling establishment, and decreased survival during seedling transportation.

In vegetable seedling production (especially commercial production), the basic condition for obtaining a high number of homogeneous seedlings in the shortest possible time is to have high-quality seeds. Despite the ongoing breeding efforts to develop numerous new varieties with superior traits, certain pre-sowing practices aimed at further improving seed performance (especially under extreme conditions) have found practical application. One of the seed treatments before sowing is priming. Taking into account the difficulties encountered in agricultural production due to climate change and global warming, seed priming is assessed as a promising tool for enhancing sustainable crop production and food security. Priming research has shown that primed crop seeds, including pepper seeds, have several benefits, such as earlier germination, faster root and shoot development etc. (Bradford et al., 1990; Zhang et al., 2012; Biswas et al., 2023; Mavi et al., 2024). However, post-application gains may vary depending on the technique used, temperature, environment, duration, type, variety, etc. (Ozbay, 2018; Sher et al., 2019; Waqas et al., 2019; Thakur et al., 2022; Afzal, 2023). There are various priming techniques available, such as hydro-priming, osmo-priming, hormonal priming, and halo-priming etc. Hydropriming is a common priming technique that is extensively used by farmers for different crops (Das and Prabha, 2024). But, main disadvantage of hydro priming is that water entry into the seed is uncontrolled and root emergence can be seen during the treatment. In osmopriming, seeds are kept in an osmotic solution that initiates the first stage of germination but prevents radicle protrusion. By this process, a range of pre-germination metabolic activities can be triggered and enhance the activities of the antioxidant system (Lei et al., 2021). Polyethylene glycol (PEG), commonly used for osmopriming, has the advantages of slow initial rate of seed absorption, prevent cell damage due to excessive water absorption, and provide time for cell self-repair to prepare for subsequent germination and seedling growth (Lei et al., 2021; Thakur et al., 2022; Arın, 2023). In several researches, osmopriming with PEG was performed on pepper seeds, it was determined that osmopriming with PEG in pepper reduced salt stress (Rachmawati et al., 2023), that the positive effects of priming applications including PEG could be preserved for up to 6 months of storage (Tu et al., 2022), that in a study where many priming agents were used on 'California Wonder' variety pepper seeds, PEG-treated seeds showed the highest tolerance to cold and salt stress (Yadav et al., 2011), that among the PEG concentrations tested, 150 g/L PEG improved the germination rate and seedling development in dry conditions (Prellia et al., 2023), and that the germination rate increased and the germination period shortened in pepper seeds kept in PEG solution with -1 MPa osmotic potential compared to the control (Demirkaya, 2006). Although Corbineau et al. (2023) stated that priming also enhances the germination of aged seeds, and the beneficial effects of priming remain even after the seeds are re-dried and often persist during storage, scientific studies on the effect of osmopriming on aged pepper seeds are quite limited. Li et al. (2025) found that priming with 20% PEG had the best effect on improving the seed vigor of aged pepper seeds, compared with 15% or 25% PEG treatment.

This study aimed to evaluate whether the germination properties of aged pepper seeds could be improved by osmotic priming using PEG, and whether it is possible to make aged pepper seeds marketable.

Materials and Methods

As plant materials, it was used the seeds of 'Charleston Bağcı' pepper variety, which was produced in 2014, and suitable for open field production and consumed as fresh or fried. Its fruits are 15-17 cm in length and 2,5-3.0 cm in diameter and yellowish light green color. (Bursa Seed Co., Bursa-Türkiye).

Pepper seeds, except for untreated control seeds, were kept in PEG6000 solution with 4 different osmotic potentials (-0.1, -0.5, -1.0 and -1.5 MPa) for 6 different times (12, 24, 36, 48, 60 and 72 hours). The concentration of the solutions was determined according to formula by Michel and Kaufmann (1973), and the results of some studies in the literature were taken into account in the selection of concentration and time (Aloui et al., 2014; Ibrahim, 2019).

Seeds were disinfected with a 1% solution of sodium hypochlorite (NaClO) before osmopriming, washed with distilled water, and kept in transparent food containers with dimensions of 18x12x6 cm lined with blotting paper, using the solution and times mentioned above (Figure 1a). To prevent concentration changes due to evaporation, the containers were sealed with cling film and their lid. After being kept in a climate chamber under dark conditions at 20±1 °C for six different periods of time, the seeds were washed under running tap water for approximately three minutes to remove the PEG solution, and then rinsed with distilled water. The seeds were then dried under laboratory conditions until they reached their initial seed weight.

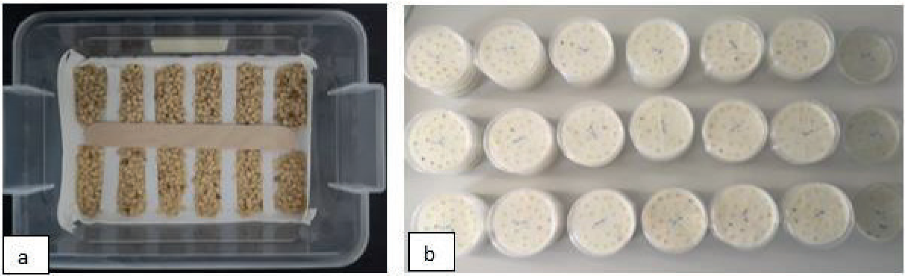

Figure 1. Treatments with PEG6000 solutions of seeds (osmopriming) (a) and germination tests (b).

For the germination tests, we used 9-cm-diameter Plexiglas Petri dishes. Each dish was lined with two layers of blotting paper and filled with 5 mL of distilled water (Figure 1b). The tests were conducted in a climate chamber set to a temperature of 20 ± 1 °C and a humidity level of 55 ± 5%. Seeds with 2 mm roots were considered germinated during daily counts, and the test continued until no further germination occurred. After 7 days of incubation, the seed germination at the first count (only the percentage of normal seedlings) was determined as one of the indicator traits of seed vigor (ISTA, 2020).

Germination percentage (GP) was calculated by proportion and arcsine square root transformation values used for statistical analyses, but actual values of germination percentage was presented in Tables.

Mean germination time (MGT) was calculated by using the following formula.

Mean germination time (MGT) $= \sum nxd / \sum n$

Where n = Number of germinated seeds on day d, and d = Number of days counted from the beginning of the germination

Uniformity index $= \frac{NSGS + NSGBS + NSGAP}{\text{Total number of germinated seeds}} \ x\ 100$ (Ebone et. al., 2020)

Where NSGS is the number of seeds, which germinate in the day with higher seed germination; NSGBS is the number of seeds, which germinate in the day before NSGS; and NSGAP is the number of seeds, which germinate in the day after NSGS.

Mean daily germination (MDG) considered as one the parameters of seed vigor were calculated according to Patil et al., (2011).

Mean daily germination (MDG) = Total germination (%) /Number of days to final germination

For the coefficient of the rate of germination (CRG) was used formula below described by Bewley and Black (1985).

Coefficient of rate of germination (CRG) = $[\sum n / \sum (t x n)]\ x\ 100$

Where t is the time in days, starting from day 0, the days of sowing, and n is the number of seeds completing germination on day t.

The experiment was set up in a randomized block design with three replicates, in which pepper seeds were kept in four different solutions of PEG_{6000} with different osmotic potentials for six different periods of time, with untreated seeds (control) included. All data were subjected to analysis of variance, and the significance of differences between mean values was compared using the LSD test.

Results

Germination percentage (%, GP)

While the application duration and solution concentration (dose) and duration interaction did not have a statistically significant effect on the germination percentage of aged pepper seeds, different solution concentrations created significant differences, and all PEG solutions gave germination values above the 66.7% germination percentage (GP) obtained from the control (untreated). Although they take part the same importance group (a), the highest GP of 81.5% was observed in seeds primed in a PEG solution having an osmotic potential of -0.5 and -1.0 MPa.

*Table 1. Effect of PEG_{6000} solutions with different osmotic potentials (MPa) and application duration on the germination percentage (GP, %) of pepper seeds and groups according to the LSD test**

*LSD (%1) for doses: 8.01035

First count germination percentage (%, FCGP)

Main effects and interactions	Doses / Duration	Control	-0.1	-0.5	-1.0	-1.5	Duration main effect
Dose X Duration interaction and Duration main effect	12 hours	23,3	31,3	46,7	32,0	31,3	**32,9 b**
	24 hours	23,3	57,3	53,3	58,7	44,0	**47,3 a**
	36 hours	23,3	65,3	50,0	62,7	64,0	**53,1 a**
	48 hours	23,3	73,3	61,3	65,3	69,3	**58,5 a**
	60 hours	23,3	58,7	69,3	74,7	73,3	**59,8 a**
	72 hours	23,3	56,0	65,3	76,0	78,6	**59,9 a**
Dose main effect		**23,3 b**	**57,0 a**	**57,7 a**	**61,6 a**	**60,1 a**	Average 51,9

*Table 2. Effect of PEG_{6000} solutions with different osmotic potentials (MPa) and application duration on the first count germination percentage (FCGP, %) of pepper seeds and groups according to the LSD test**

*LSD (%1) for doses: 12.44170; LSD (%1) for duration: 13.63190

All PEG doses increased the germination percentage in the first count (FCGP) compared to the control (Table 2). Similarly, the duration of exposure of pepper seeds to the PEG solution affected the germination percentage obtained in the first count, and a linear increase was observed between the increase in application duration and germination percentage.

Main effects and interactions	Doses / Durations	Control	-0.1	-0.5	-1.0	-1.5	Duration main effect
Dose X Duration interaction and Duration main effect	12 hours	66,7	82,7	82,7	73,3	81,3	**77,3**
	24 hours	66,7	69,3	74,7	84,0	81,3	**75,2**
	36 hours	66,7	76,0	89,3	81,3	77,3	**78,1**
	48 hours	66,7	85,3	72,0	77,3	80,0	**76,3**
	60 hours	66,7	86,7	85,3	84,0	85,3	**81,6**
	72 hours	66,7	65,3	85,3	89,3	80,0	**77,3**
Dose main effect		**66,7 b**	**77,5 a**	**81,5 a**	**81,5 a**	**80,9 a**	Average 77,6

Mean germination time (MGT)

The concentration of osmopriming solution (doses) and duration, also interaction had significant effect mean germination time (MGT) (Table 3). Seeds treated with PEG solution germinated 0.4 -3.1 days earlier than untreated seeds. In general, as the duration of exposure to the PEG solution increased, the MGT of the seeds decreased. The shortest germination time of 5.2 days was determined in seeds kept in PEG solution with an osmotic potential of -1.0 MPa for 72 hours.

Table 3. Effect of PEG_{6000} solutions with different osmotic potentials (MPa) and application duration on mean germination time (MGT, days) of pepper seeds and groups according to the LSD

test*

Main effects and interactions	Doses / Duration	Control	-0.1	-0.5	-1.0	-1.5	Duration main effect
Dose X Duration interaction and Duration main effect	12 hours	8,3 a	7,7 ab	7,6 abc	7,9 a	7,8 ab	**7,9 a**
	24 hours	8,3 a	6,2 efgh	6,7 cdef	6,8 bcde	7,5 abcd	**7,1 b**
	36 hours	8,3 a	6,1 efghı	6,1 efghı	6,6 def	6,2 efgh	**6,7 bc**
	48 hours	8,3 a	5,8 efghı	5,9 efghı	6,0 efghı	6,2 efgh	**6,5 c**
	60 hours	8,3 a	5,8 efghı	6,0 efghı	6,0 efghı	6,2 efgh	**6,4 c**
	72 hours	8,3 a	7,5 abcd	5,3 hı	5,2 ı	5,5 ghı	**6,4 c**
Dose main effect		**8,3 a**	**6,6 b**	**6,2 b**	**6,3 b**	**6,5 b**	Average 6,9

*LSD (%1) for doses: 0.405396; LSD (%1) for duration: 0.440893; LSD (%1) for interaction: 0.993013

Mean daily germination (MDG)

Although the main effect of duration on mean daily germination (MDG) and the interaction between duration and dose were not significant, the effect of solution concentrations on MDG was significant (Table 4). Treatment with polyethylene glycol (PEG) increased MDG values regardless of the osmo-priming doses and the highest value of 8.2 was obtained from seeds kept in a -1.0 MPa solution.

*Table 4. Effect of PEG_{6000} solutions with different osmotic potentials (MPa) and application duration on mean daily germination (MDG) of pepper seeds and groups according to the LSD test**

Main effects and interactions	Doses / Duration	Control	-0.1	-0.5	-1.0	-1.5	Duration main effect
Dose X Duration interaction and Duration main effect	12 hours	5,7	6,7	6,8	6,3	6,5	**6,4**
	24 hours	5,7	7,2	7,4	8,2	6,6	**7,0**
	36 hours	5,7	8,0	8,3	8,4	7,3	**7,5**
	48 hours	5,7	9,1	7,0	7,9	8,2	**7,6**
	60 hours	5,7	7,3	8,6	9,4	5,7	**7,4**
	72 hours	5,7	7,5	8,5	8,8	10,2	**8,1**
Dose main effect		**5,7 b**	**7,7 a**	**7,8 a**	**8,2 a**	**7,4 a**	Average 7,3

*LSD (%1) for doses: 1.50541

Uniformity index

None of the osmotic solution concentrations, application duration, or their interactions significantly affected uniformity (Table 5).

*Table 5. Effect of PEG_{6000} solutions with different osmotic potentials (MPa) and application duration on uniformity index of pepper seeds and groups according to the LSD test**

Main effects and interactions	Doses / Duration	Control	-0.1	-0.5	-1.0	-1.5	Duration main effect
Dose X Duration interaction and Duration main effect	12 hours	64,1	63,5	58,6	57,0	72,8	**63,2**
	24 hours	64,1	76,2	62,8	72,9	69,0	**69,0**
	36 hours	64,1	74,4	74,8	66,1	62,7	**68,4**
	48 hours	64,1	73,1	75,2	69,3	72,5	**70,9**
	60 hours	64,1	62,1	68,8	64,0	66,4	**65,1**
	72 hours	64,1	58,2	70,7	72,6	68,6	**66,8**
Dose main effect		**64,1**	**67,9**	**68,5**	**66,9**	**68,7**	Average 67,3

*All is not significant

Coefficient of rate of germination (CRG)

The values of coefficient of rate of germination (CRG) were higher than control for both the main effects and interaction (Table 6). CRG, which was 12 in the control, was 19.4 in seeds kept in a PEG solution with an osmotic potential of -1.0 MPA for 72 hours. The CRG value of seeds increased steadily as the duration of stay in the solution increased.

*Table 6. Effect of PEG_{6000} solutions with different osmotic potentials (MPa) and application duration on coefficient of rate of germination and groups according to the LSD test**

Main effects and interactions	Doses / Duration	Control	-0.1	-0.5	-1.0	-1.5	Duration main effect
Dose X Duration interaction and Duration main effect	12 hours	12,0 l	12,9 jkl	13,1 ıjkl	12,6 kl	12,7 kl	**12,7 e**
	24 hours	12,0 l	16,2 defg	15,0 fghıj	14,7 ghıjk	13,3 hıjkl	**14,2 d**
	36 hours	12,0 l	16,5 cdefg	16,3 defg	15,2 fghı	15,3 fgh	**15,0 cd**
	48 hours	12,0 l	16,8 cdefg	16,9 bcdef	16,7cdefg	16,1 efg	**15,7 bc**
	60 hours	12,0 l	15,8 efg	17,6 abcde	18,5 abc	16,6 cdefg	**16,1 ab**
	72 hours	12,0 l	15,6 efg	19,0 ab	19,4 a	18,2 abcd	**16,8 a**
Dose main effect		**12,0 c**	**15,6 ab**	**16,3 a**	**16,1 ab**	**15,4 b**	Average 15,1

*LSD (%1) for doses: 0.86703; LSD (%1) for duration: 0.94786; LSD (%1) for interaction: 2.12378

Discussion

Rapid and uniform seed germination and seedling formation are base conditions for success in vegetable production. This can primarily be achieved through the use of high-quality seeds. Also, biotic and abiotic stress pressure is increasing due to the effects of global climate change and global warming leading to a rise in demand for high-quality and improved production material (seeds) in vegetable production. Although plant breeders are developing new varieties with improved stress tolerance and qualities, some pre-planting practices such as osmopriming, which improve seed quality, are becoming widespread. Among osmoticum, Polyethylene glycol (PEG) is the most common substance used to control water potential in primed seed due to its nontoxic nature and large molecular size that impedes its penetration into the seed (Ibrahim, 2019; Lei et al., 2021; Prellia et al., 2023). Although it has been stated that priming could enhances germination traits of aged seeds, scientific studies on the effect of osmopriming on aged pepper seeds are quite limited in literature (Li et al., 2025). If osmopriming can increase the germination capacity of aged seeds, seeds that fall below germination standards can be used in production, and also extend the storage life of seeds through priming applications. According to the results of this experiment, designed to assess this, determined that osmopriming application could promote the germination all germination parameters (except uniformity index) of aged pepper seeds (Tables 1, 2, 3, 4, 5, 6). In our previous study (Arin and Deveci, 2025), while germination characteristics were improved in non-aged pepper seeds with osmopriming, no change was observed in the germination percentage. However, in this study, significant increases also in the germination percentage were achieved. The positive effects of osmopriming on aged seeds may vary depending on factors such as species, variety, and degree of aging (Fanti and Perez 2003; Reed et al., 2022; Arın, 2023). Depending on seed age and storage conditions, physiological changes such as decreases in membrane integrity and enzyme activity occur. In this sense, seed priming could be considered one of the useful pre-sowing practices among methods for improving seed germination capacity. Tu et al. (2022) stated that priming with PEG can slow the initial rate of seed absorption, prevent cell damage due to excessive water absorption, and provide time for cell self-repair to prepare for subsequent germination and seedling growth. Also, it is expressed that seed priming treatment accelerates the initial stages of seed growth by overcoming any event of defective repair, like the gradual loss of telomeric sequences, DNA strand breakage, the loss of proper DNA confirmation, and any other incidents produced by oxidative damage, which can cause cell death during germination (Tombegavani, et al., 2020; Canizares et all., 2025).

Upon evaluating all data from the experiment, which showed that treatment with PEG enhanced the germination characteristics of aged pepper seeds, it was found that keeping the seeds in solutions with an osmotic potential of -0.5 and/or -1.0 MPa for periods exceeding 12 hours is advisable.

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Chapter 7

PESTICIDE USE IN AGRICULTURE: A COMPARISON OF DEVELOPED AND DEVELOPING COUNTRIES

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Introduction

Pesticides are one of the fundamental components of modern agricultural systems that increase crop productivity and support food security to meet the food needs of the growing world population. The necessity to increase food production to feed a rapidly growing human population places pressure on the intensive use of pesticides and fertilizers (Carvalho, 2017). However, the uncontrolled and intensive use of these chemicals leads to problems such as the disruption of ecosystem balance, increased risks to human health, and the jeopardizing of sustainable agriculture goals.

Global pesticide use significantly increased by 52.15% between 2004 and 2023, rising from approximately 2.4 million tonnes to 3.7 million tonnes. In the last 10 years, global pesticide use has increased by 13.62%. In 2023, the distribution of pesticide use by continent was: America 49.25%, Asia 28.06%, Europe 11.92%, Africa 5.66%, and Oceania 5.11%. The continent of Oceania, with 5.6 kg per hectare, and the continent of America, with 5 kg per hectare, are above the world average pesticide use (2.4 kg/ha^{-1}) (FAO, 2025).

Approximately 3 billion kg of pesticides are used globally each year, with an estimated budget of 40 billion USD. This widespread use, in addition to increasing crop yields, leads to a significant reduction in harvest losses and consequently to an increase in food availability (Sharma et al., 2020). Pesticide use has rapidly increased since the mid-20th century, and global consumption now reaches 2-4 million tonnes annually (Tudi et al., 2021; Reddy et al., 2024). The Green Revolution increased reliance on synthetic pesticides, particularly herbicides, insecticides, and fungicides, to maximize productivity and reduce labor requirements (Ridgway et al., 1978; Jacquet et al., 2022). Initially, developed countries led the use, while developing countries now have an increasingly larger share and often have less stringent regulations (Poudel et al., 2020).

Pesticides are recognized for preventing significant crop losses, playing a critical role in food supply and economic development by preventing losses of up to 78% in fruits, 54% in vegetables, and 32% in cereals (Sarkar et al., 2021; Ngegba et al., 2022).

Despite their benefits, pesticides pose serious risks. Only a small portion reaches target pests; the remainder contaminates soil, water, and non-target organisms, leading to bioaccumulation and ecosystem degradation (Sharma et al., 2019; Sharma et al., 2020; Tudi et al., 2021; Rad et al., 2022; Esimbekova et al., 2022). As pollutants, when applied to soil, pesticides can degrade soil properties due to off-target contamination and devastating effects on biodiversity (Aktar et al., 2009). Human exposure through occupational contact, food residues, and environmental drift has been linked to acute poisoning, chronic diseases, and an increased risk of cancer (Sharma, 2020).

Furthermore, the use of unsafe pesticides harms the environment and endangers health throughout the food chain (Nurika, 2022; Onwudiegwu et al., 2025).

Assuming that one-third of current crop production relies on pesticide use, it appears impossible to abandon chemical pesticides in the near future. Given the environmental pressure created by chemical pesticides, there is a need to seek environmentally friendly alternative solutions to replace these products to ensure agricultural sustainability (Ayyıldız, 2022).

From this perspective, examining pesticide use at the country level is important for ensuring sustainability in agriculture. Specifically, a comparison of pesticide use in developed and developing countries can help determine the levels of agricultural chemical use in different nations, thereby facilitating the identification of potential measures to be taken. In recent years, various studies on pesticide use and its importance have been conducted in Türkiye (Arslan et.al., 2018; Arslan and Çiçekyıl, 2018; Erdal et al., 2019; Erdil and Tiryaki, 2020; Ayyıldız, 2022; Hayran et al., 2022; Özarcan and Taşçı, 2022; Sevim et al., 2023; Erdoğan, 2024; Yılmaz et al., 2024) and globally (Sharma et al., 2019; Leong et al., 2020; Hedlund et al., 2020; Tudi et al., Jacquet et al., 2022, Khan et al., 2023, Mance et al., 2025; Hamed and Hidayah, 2025). However, there is also a need for studies that compare pesticide use from the perspective of developed and developing countries, while also evaluating Türkiye's situation in this regard.

Purpose and Method

The aim of this study is to examine pesticide use in agriculture worldwide from the perspective of developed and developing countries, and to comparatively evaluate the statistical data obtained. In this context, the status of pesticide use in agriculture in Türkiye, which is among the group of developing countries, has been examined in detail. Considering the classification of the International Monetary Fund (IMF) for comparing data from developed and developing countries, 20 developed countries and 20 developing countries were selected for this study, and statistical data related to pesticide use were evaluated. Detailed information about the selected countries in the study is provided in Table 1. In light of the findings, the current state of pesticide use worldwide has been presented, and solutions have been proposed for the identified problems. The main material of the study consists of data obtained from the Turkish Statistical Institute (TURKSTAT), the United Nations Food and Agriculture Organization (FAO), and relevant sources and reports. When evaluating statistical data in the study, the 10-year period between 2014 and 2023 was taken as the basis. In the evaluation of the collected statistical data, percentage and index calculations were performed and presented in tables and graphs.

Table 1. *Countries Selected in the Research*

	Developed Countries	Developing Countries
1	United States of America	Brazil
2	Germany	Syria
3	Japan	Malaysia
4	United Kindom	Iran
5	Czech Republic	Iraq
6	Italy	Ukraine
7	Spain	Kazakhstan
8	Netherlands	Poland
9	France	India
10	Greece	Romania
11	Australia	China
12	Denmark	Egypt
13	Belgium a	Qatar
14	Austria	Bulgaria
15	Switzerland	Saudi Arabia
16	Sweden	Azerbaijan
17	Norway	Argentina
18	Portugal	Mexico
19	Canada	Lebanon
20	Korea	Türkiye

Source: IMF(*World Economic Outlook* Classification,2023)

Results

Pesticide Use in World

The world population is expected to increase by one-third, reaching approximately 9.7 billion by 2050 (UN, 2022). In parallel with this increase in the world population, the demand for agricultural and food products is also increasing. The growing world population also brings with it the problem of food security. For this reason, countries are seeking to obtain higher yields from areas used for agriculture to meet the food needs of their populations. In agricultural production, one of the most important inputs that increases yield is agricultural chemicals known as pesticides.

One of the main objectives of agricultural policies worldwide is to increase production, enhance productivity, and reduce costs. However, intensive input use in agriculture damages natural resources, negatively affects the environment, and creates serious problems for human health (Yılmaz et al., 2024). To meet the food needs of the increasing world population, one of the most common ways to achieve yield increase is pesticide use, the situation of which in the last 10 years is given in Table 2. Accordingly, pesticide use worldwide increased by 14% between 2014 and 2023. In the same period, among the pesticides used in agricultural products, the group with the highest increase in usage was herbicides, with a 27.77% increase. According to 2023 data, the distribution of global pesticide use was 54.61% for herbicides, 21.16% for fungicides, 20.64% for insecticides, 0.47% for rodenticides, and 3.12% for others (Table 2). Herbicides are the most common type of pesticide, accounting for more than 50% of pesticides used in the agricultural sector (Sharma et al., 2019). Worldwide, pesticide use per cultivated area in 2023 increased by 12.15% compared to 2014, reaching 2.4 kg ha ^{1} (FAO, 2025).

Table 2. *World Pesticide Use by Groups (kg ha^{-1})(2004-2023)*

Years	Insecticides (tons)	Herbicides (tons)	Fungicides and Bactericides (tons)	Rodenticides (tons)	Other Pesticides nes (tons)	Total Pesticides (tons)	Index (2014=100)
2014	771260	1572370	732486	13335	148858	3238309	100
2015	777822	1592649	721967	15467	168885	3276790	101
2016	800428	1648924	751338	17082	176694	3394466	105
2017	771242	1639715	715877	15422	166033	3308289	102
2018	773584	1643963	746569	15140	187806	3367062	104
2019	718963	1824016	718581	16814	163074	3441448	106
2020	681749	1883096	741693	14783	142111	3463432	107
2021	780756	1957139	848529	16536	119322	3722282	115
2022	788106	2017450	815278	16057	112343	3749234	116
2023	759403	2009099	778387	17505	114696	3679090	114

Source:www.fao.org

Pesticide Use in Developed and Developing Countries

Data on pesticide use per hectare in developed and developing countries worldwide between 2004 and 2023 are presented in Figure 1. As seen in Figure 1, pesticide use per hectare in both developed and developing countries has been above the world average over the years. According to 2023 data, while pesticide use worldwide was 2.4 kg ha^{-1}, it was 4.09 kg ha^{-1} in developed countries and 3.99 kg ha^{-1} in developing countries. Pesticide use is often preferred by producers because it provides the desired yield and reduces labor costs in weed control. For this reason, it is also used in developed and developing countries. It is stated that if pesticide use is abandoned in production, product quality and yield would decrease by up to 60%, and production value would significantly drop (Zhang, 2018). This situation can make producers dependent on pesticide use.

Generally, pesticide use is more strictly controlled in developed countries. Technological advancements and farmer education ensure the controlled use of pesticides. Residues are better monitored, and there are stricter limits for hazardous chemicals. In contrast, oversight is weak in many developing countries. Monitoring infrastructure is limited, and banned or hazardous substances are used more frequently. Access to training and protective equipment is also often inadequate (Lazarević-Pašti T, 2025).

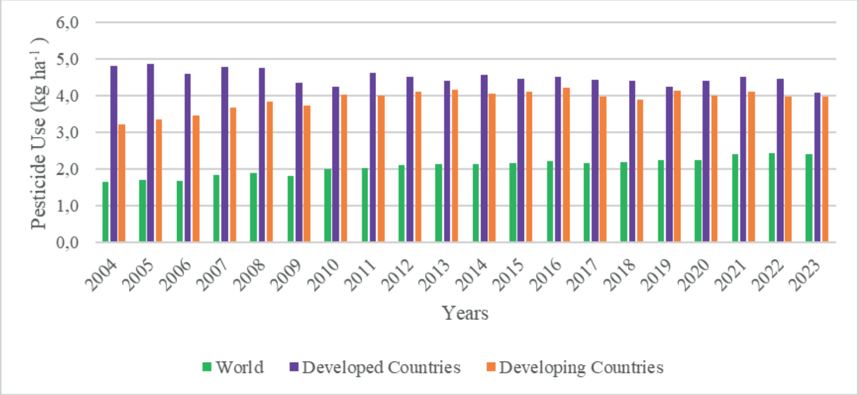

Figure 1. *Pesticide Use Per Hectare in Developed and Developing Countries (kg ha^{-1}) (2004-2023)*

Source:www.fao.org

Statistical data regarding pesticide use in developed and developing countries worldwide between 2014 and 2023 are presented in Table 3. In developed countries, pesticide use, which was 945,531 tonnes in 2014, increased by 9% to reach 1,030,225 tonnes in 2023. In developing countries, pesticide use, which was 1,365,948 tonnes in 2014, increased by 13% to reach 1,544,618 tonnes in 2023. Overall, an increase is observed in both country groups, but the increase is greater in developing countries.

Table 3. *Pesticide Use in Developed and Developing Countries (tons)(2014-2023)*

Years	Pesticide Use in Developed Countries	Index (2014=100)	Pesticide Use in Developing Countries	Index (2014=100)
2014	945531	100	1365948	100
2015	948056	100	1377363	101
2016	1000411	106	1390070	102
2017	992433	105	1350976	99
2018	1016625	107	1323966	97
2019	981308	104	1425724	104
2020	1027321	109	1461842	107
2021	1052742	111	1520876	111
2022	1035791	109	1552528	114
2023	1030225	109	1544618	113

Source:www.fao.org

Figure 2 shows the distribution of pesticide use by country in developed countries in 2023. Among developed countries, the USA is the largest pesticide user with 429,501 tonnes and a 42% share. Australia with 182,264 tonnes (18%) and Canada with 95,645 tonnes (9%) are among other major pesticide-using countries. The negative impacts that pesticides can have on the environment, health, and economy are well known in developed countries. For this reason, agricultural products to be consumed in all developed countries, especially in the EU, are continuously monitored for environmental and health aspects (Delen et al., 2005). Particularly, European Union countries are imposing new restrictions on agricultural chemicals and residues every day. Thanks to the common policies of the European Union, all member countries have adopted the same approach regarding agricultural chemicals. The application, management, and licensing of agricultural chemicals have been subjected to a series of rules (Yılmaz et al., 2024).

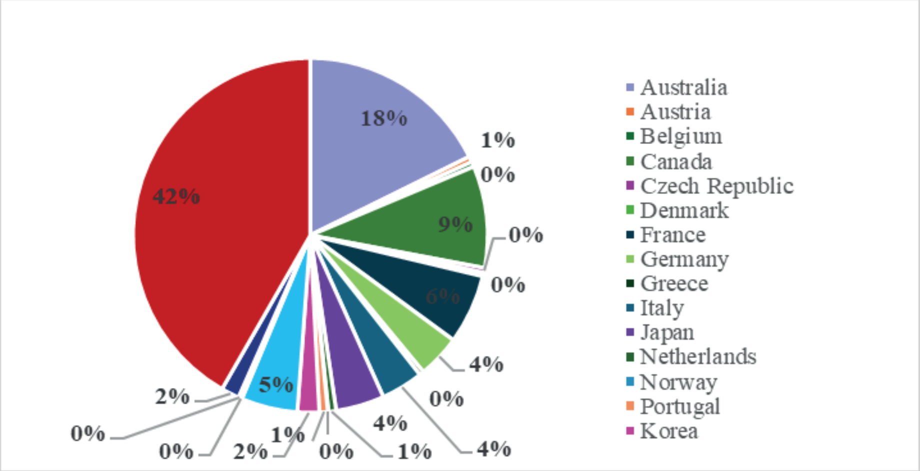

Figure 2. *Distribution of Pesticide Use by Country in Developed Countries (2023)*

Source: www.fao.org

Figure 3 shows the distribution of pesticide use in developing countries for 2023. Brazil is the largest pesticide-using country with 800,652 tonnes of pesticide use and a 52% share. Argentina with 262,507 tonnes (7%) and China with 229,026 tonnes (15%) are other major pesticide-using countries. When comparing developed and developing countries, it is observed that more pesticides are used in developing countries. Globally, while pesticide use is under strict control in developed countries, a lack of oversight and unconscious use in developing countries can lead to serious problems. Although chemical control increases yield, indiscriminate spraying poses risks to living health through environmental pollution, soil accumulation, and residual products (Yılmaz, 2015).

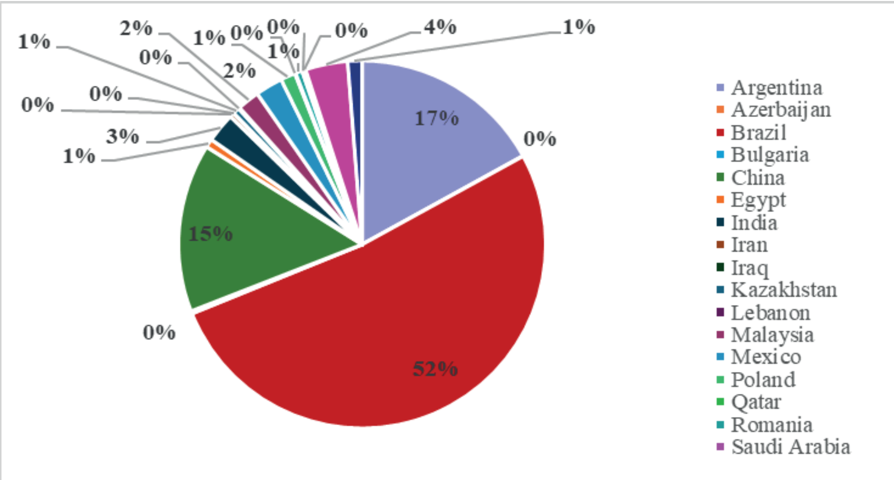

Figure 3. *Distribution of Pesticide Use by Country in Developing Countries (2023)*

Source: www.fao.org

In the distribution of 943,918 tonnes of pesticides used by developed countries in 2023, herbicides account for 75%, fungicides and bactericides for 15%, and insecticides for 10%. Between 2019 and 2023, a decrease of 2.14% in insecticide use and 1.05% in fungicide and bactericide use was observed in pesticide consumption (Figure 4). Conversely, herbicide use in developed countries increased by 12.74% in the last 5 years. Among developed countries, Australia had the largest increase in herbicide use between 2019 and 2023, with a 90% increase. Canada is the second country with a 26.48% increase in herbicide use.

Pesticide use in countries is influenced by factors such as cropping patterns, pesticide prices, climatic conditions, pest and disease intensity, resistance development, ease of access to pesticides, and input intensity of production. While high income levels of farmers and easy access to pesticides increase usage rates in the European Union, legal regulations and public interventions are more effective in developed countries, whereas financial measures such as subsidies and incentives are more effective in developing countries (Yılmaz et al., 2024).

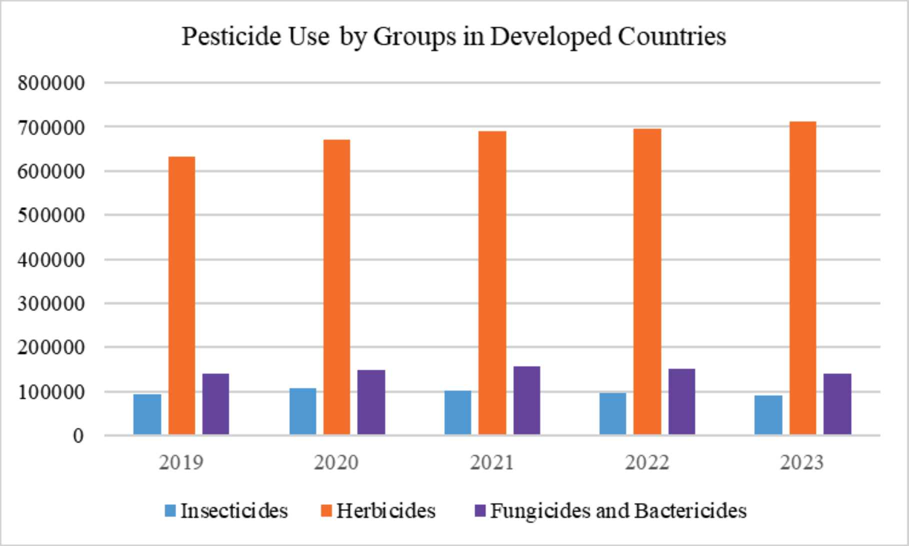

Figure 4. *Pesticide Use by Groups in Developed Countries (tons)(2019-2013)*

Source: www.fao.org

Figure 5 shows the distribution of pesticide use by groups in developing countries. As seen in the figure, a similar pattern is observed as in developed countries. In 2023, out of 1,466,780 tonnes of pesticide use in developing countries, herbicides constituted 62%, fungicides and bactericides 21%, and insecticides 17%. Between 2019 and 2023, fungicide and bactericide use increased by 17.88%, herbicide use by 15.53%, and insecticide use by 0.95% in pesticide consumption. Among developing countries, Brazil achieved the largest increase in fungicide and bactericide use between 2019 and 2023, with a 67% increase. Qatar is the second country with a 29% increase in fungicide and bactericide use. Among the 20 developing countries examined, Türkiye had the largest increase in herbicide use between 2019 and 2023, with 116%. The primary reason for this increase is the rise in the use of herbicides belonging to the glyphosate and its derivatives, and the 2,4-D group. The increase in glyphosate use stems from the preference for chemical methods over mechanical weed control (e.g., tillage) to reduce production costs, and the emergence of glyphosate-resistant weeds leading to increased herbicide application (Kaymak et al., 2015).

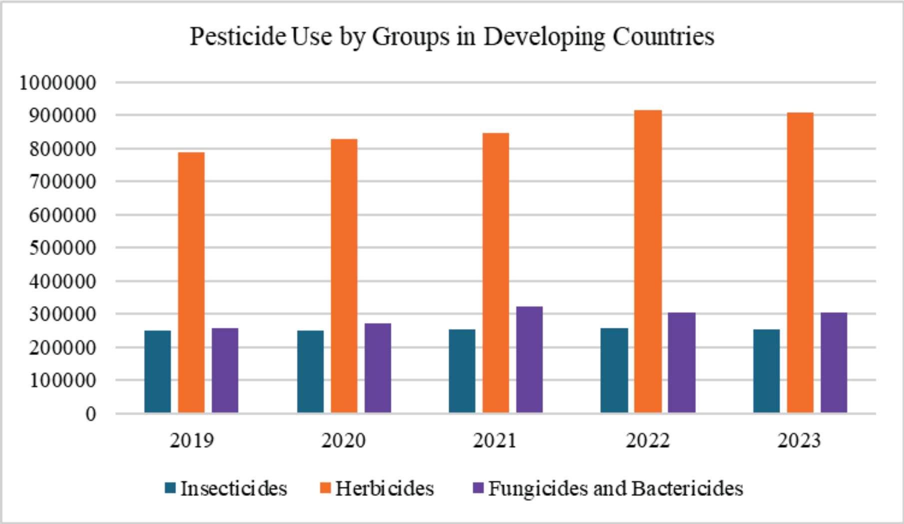

Figure 5. *Pesticide Use by Groups in Developing Countries (tons)(2019-2023)*

Source: www.fao.org

Pesticide Use in Türkiye

Table 4 presents the amounts of pesticide use by group and index calculations in Türkiye between 2015 and 2024. Accordingly, the amount of pesticide use, which was 39,026 tons in 2015, increased by 37.13% to 53,515 tons in 2024. In 2024, fungicides and bactericides constituted 33.91% of the pesticides used, herbicides 23.78%, insecticides 25.08%, acaricides 4.15%, rodenticides 0.41%, and other pesticides 12.67%.

Global pesticide use was 2.4 kg ha^{-1} in 2023. Türkiye accounts for 1.56% of global pesticide use. Pesticide use per hectare in Türkiye is 2.4 kilograms, which is below the EU average (2.7 kg ha^{-1}) and at the same level as the world average. (FAO 2025).

Table 4. *Pesticide Use by Groups in Türkiye (tons) (2015-2024)*

Years	Insecticides	Fungicides	Herbicides	Acaricide	Rodenticide+ Molluscicide	Other	Toplam	Index (2015=100)
2015	8117	15984	7825	1576	197	5327	39026	100
2016	10425	20485	10025	2025	259	6835	50054	128
2017	11436	22006	11759	2452	236	6209	54098	139
2018	13583	23047	14794	2486	309	5801	60020	154
2019	11609	19698	12644	2124	264	4958	51297	131
2020	12347	20600	13250	2200	280	4995	53672	138
2021	11071	19098	13320	2342	283	6851	52965	136
2022	12205	19446	14553	2462	298	6410	55374	142
2023	12326	19614	15509	3104	297	6916	57766	148
2024	13420	18145	12727	2223	221	6779	53515	137

Source: www.tuik.gov.tr

Regarding pesticide use by region in Türkiye, the Mediterranean Region ranks first with 15 thousand tons of pesticide use, followed by the Aegean Region with 12.8 thousand tons, and the Marmara Region with 9.5 thousand tons. The amount of pesticides used in these three regions constitutes 69.6% of the pesticides used in Türkiye. The Mediterranean Region is the most intensive pesticide-using region due to its high product diversity, extensive greenhouse presence, and intensive agricultural product trade (Özarcan and Taşçı, 2022). The distribution of the top 10 provinces in pesticide use in Türkiye is given in Figure 6. Accordingly, these 10 provinces accounted for 58% of the 53,515 tons of pesticide use in Türkiye in 2024. A common characteristic of these provinces is their leading role in the production of vegetables, fruits, and greenhouse products. Adana province with 7,122 tons, Mersin province with 4,811 tons, and Antalya province with 3,892 tons are our provinces with the highest pesticide use.

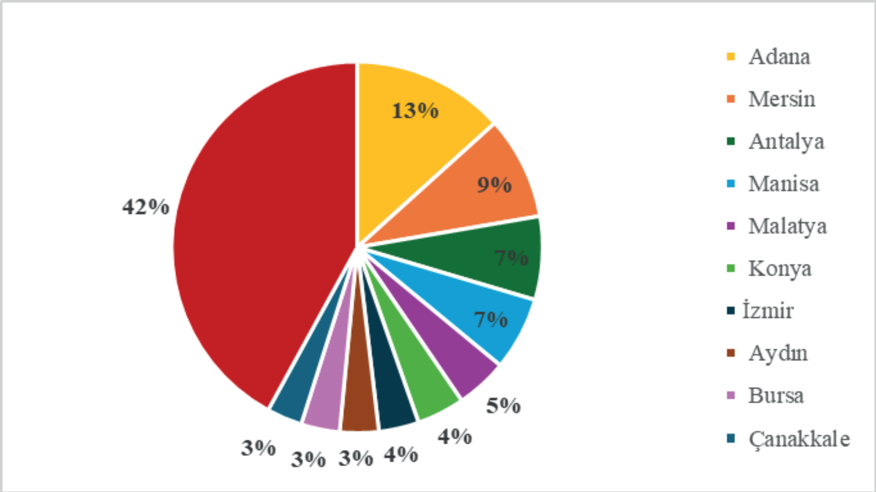

Figure 6. *Distribution of the 10 Provinces with the Highest Pesticide Use in Türkiye (%)*

Source:www.tuik.gov.tr

Conclusion and Recommendations

As in the rest of the world, pesticide use continues to be seen as the most effective method for combating diseases, pests, and weeds in agricultural control in both developed and developing countries. Because it provides high yields in meeting the food needs of the increasing world population, pesticide use in production is readily adopted by producers. However, pesticide use in agriculture has far more negative effects than we anticipate. Even those who aim to achieve only short-term profit by using agricultural chemicals cause harm in the long run to almost everything, from soil to the environment, from workers to society.

In developed countries, pesticide use exhibits a more controlled and regulated structure. In these countries, strict legal frameworks, effective inspection mechanisms, advanced monitoring systems, and sustainable agricultural policies optimize pesticide use. Furthermore, farmers have a high level of awareness, and the use of environmentally friendly methods such as biological control and integrated pest management (IPM) is more widespread. In contrast, in developing countries, pesticide use can often be excessive and uncontrolled due to insufficient oversight, low awareness, economic constraints, and inappropriate application techniques. This situation leads to serious consequences in terms of both environmental pollution and human health risks.

Intensive pesticide use causes residue problems, especially in agricultural products intended for export, and difficulties in obtaining products of the desired quality. Therefore, it is necessary to investigate the possibilities of using alternative control methods to chemical control and to prioritize producer awareness efforts on this issue. In addition to crop and pest diversity, climate change can also cause differences in the emergence process of harmful organisms and shifts in the agricultural control calendar. Repeated spraying, which may occur due to changes in temperature or precipitation, also brings with it the risk of residues in the product. All measures taken and conscious practices implemented to reduce pesticide use will be important for sustainable agriculture, both for obtaining healthier products, keeping resources clean, and reducing pesticide costs, which hold a significant place in production costs.

As a result, these imbalances in pesticide use threaten both food security and sustainable agriculture goals on a global scale. Therefore, international cooperation towards reducing and safely managing pesticide use is of great importance.

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