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Advancing Sustainable Practices in the Chemical Industry: Strategies for Environmental Stewardship and Economic Viability

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Abstract

The chemical industry is a cornerstone of modern industrial economies but also one of the most environmentally impactful sectors. This study aims to explore and evaluate the advancement of sustainable practices within the chemical industry, with an emphasis on strategies that effectively integrate environmental stewardship and economic viability. The study employed a quantitative research design using a structured questionnaire distributed to employees working in various companies within the Greek chemical industry. A total of 87 valid responses were collected. The findings indicate that while many companies report implementing sustainability practices such as recycling, renewable energy use, and digital tools, the majority of respondents do not perceive sustainability as a key factor in the industry's future success. Corporate social responsibility emerged as the leading motivation for sustainability efforts, while financial incentives and perceived cost savings showed no significant association with the actual implementation of sustainable strategies. Demographic and professional variables had no statistically significant correlation with sustainability-related perceptions. There was, however, strong support for the introduction of mandatory sustainability certification. The study reveals a disconnect between sustainability in practice and sustainability in strategy. Although environmentally responsible actions are increasingly common, they are often driven by compliance and external pressures rather than by a strategic or innovation-oriented mindset. Future progress in the Greek chemical sector will require stronger managerial engagement, clearer policy frameworks, and a cultural shift toward viewing sustainability as a value-creating force.

Keywords

Sustainability, Chemical Industry, Sustainable Practices, Corporate Social Responsibility, Industrial Sustainability

Προώθηση Βιώσιμων Πρακτικών στη Χημική Βιομηχανία: Στρατηγικές για Περιβαλλοντική Διαχείριση και Οικονομική Βιωσιμότητα

Χρυσή Πανσεληνά

Περίληψη

Η χημική βιομηχανία αποτελεί ακρογωνιαίο λίθο των σύγχρονων βιομηχανικών οικονομιών, αλλά και έναν από τους τομείς με τις μεγαλύτερες περιβαλλοντικές επιπτώσεις. Η παρούσα μελέτη στοχεύει στη διερεύνηση και αξιολόγηση της προόδου των βιώσιμων πρακτικών εντός της χημικής βιομηχανίας, με έμφαση σε στρατηγικές που ενσωματώνουν αποτελεσματικά την περιβαλλοντική διαχείριση και την οικονομική βιωσιμότητα. Η μελέτη χρησιμοποίησε ένα ποσοτικό ερευνητικό σχέδιο χρησιμοποιώντας ένα δομημένο ερωτηματολόγιο που διανεμήθηκε σε υπαλλήλους που εργάζονται σε διάφορες εταιρείες της ελληνικής χημικής βιομηχανίας. Συνολικά συλλέχθηκαν 87 έγκυρες απαντήσεις. Τα ευρήματα δείχνουν ότι ενώ πολλές εταιρείες αναφέρουν ότι εφαρμόζουν πρακτικές βιωσιμότητας όπως η ανακύκλωση, η χρήση ανανεώσιμων πηγών ενέργειας και τα ψηφιακά εργαλεία, η πλειοψηφία των ερωτηθέντων δεν αντιλαμβάνεται τη βιωσιμότητα ως βασικό παράγοντα για τη μελλοντική επιτυχία του κλάδου. Η εταιρική κοινωνική ευθύνη αναδείχθηκε ως το κύριο κίνητρο για τις προσπάθειες βιωσιμότητας, ενώ τα οικονομικά κίνητρα και η αντιληπτή εξοικονόμηση κόστους δεν έδειξαν σημαντική συσχέτιση με την πραγματική εφαρμογή βιώσιμων στρατηγικών. Οι δημογραφικές και επαγγελματικές μεταβλητές δεν είχαν στατιστικά σημαντική συσχέτιση με τις αντιλήψεις που σχετίζονται με τη βιωσιμότητα. Υπήρξε, ωστόσο, ισχυρή υποστήριξη για την εισαγωγή της υποχρεωτικής πιστοποίησης βιωσιμότητας. Η μελέτη αποκαλύπτει μια αποσύνδεση μεταξύ της βιωσιμότητας στην πράξη και της βιωσιμότητας στη στρατηγική. Αν και οι περιβαλλοντικά υπεύθυνες δράσεις είναι ολοένα και πιο συνηθισμένες, συχνά καθοδηγούνται από τη συμμόρφωση και τις εξωτερικές πιέσεις παρά από μια στρατηγική ή

καινοτόμο νοοτροπία. Η μελλοντική πρόοδος στον ελληνικό χημικό τομέα θα απαιτήσει ισχυρότερη διοικητική εμπλοκή, σαφέστερα πλαίσια πολιτικής και μια πολιτισμική μετατόπιση προς την αντιμετώπιση της βιωσιμότητας ως δύναμης δημιουργίας αξίας.

Λέξεις – Κλειδιά

Βιωσιμότητα, Χημική Βιομηχανία, Βιώσιμες Πρακτικές, Εταιρική Κοινωνική Ευθύνη, Βιομηχανική Βιωσιμότητα

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1. Introduction

1.1 Background of the Study

The chemical industry plays a pivotal role in shaping the modern world by providing essential raw materials and intermediate products for a wide range of sectors, including pharmaceuticals, agriculture, consumer goods, construction, and energy. As a cornerstone of industrial development, the global chemical industry was valued at over USD 4 trillion in 2022, demonstrating its significant economic contribution (Statista, 2024). However, this influence comes at an environmental cost. The industry is recognized as one of the largest industrial energy consumers and a major emitter of greenhouse gases, contributing significantly to climate change, biodiversity loss, and pollution of air, water, and soil (IEA, 2021).

Over the past two decades, growing concerns about environmental degradation, resource scarcity, and social inequities have propelled the concept of sustainability to the forefront of global discourse. Sustainability, as defined by the Brundtland Commission (1987: 43), entails meeting "the needs of the present without compromising the ability of future generations to meet their own needs." This principle has evolved into a framework commonly referred to as the "triple bottom line," which integrates environmental protection, social well-being, and economic prosperity (Elkington, 1997). Within this framework, the chemical industry is being urged to innovate and operate in ways that reduce its ecological footprint while maintaining or enhancing economic viability.

One of the most influential approaches to embedding sustainability in the chemical sector is green chemistry, which promotes the design of products and processes that minimize the generation and use of hazardous substances (Anastas & Warner, 2000). This includes strategies such as the use of renewable feedstocks, energy-efficient synthesis methods, and non-toxic solvents. Alongside green chemistry, the adoption of circular economy principles is gaining traction. These principles advocate for designing out waste, keeping materials in use, and regenerating natural systems — a shift that contrasts with the traditional linear model of "take-make-dispose" (Geissdoerfer et al., 2017).

Global and regional policy frameworks have been instrumental in driving the sustainability agenda. Regulatory mechanisms such as the European Union's REACH (Registration, Evaluation, Authorisation and Restriction of Chemicals), the U.S. Toxic Substances Control

Act, and international accords like the Paris Climate Agreement and the United Nations Sustainable Development Goals (SDGs) all underscore the need for environmentally responsible practices in the chemical sector (UNEP, 2019; European Union, 2020a). These frameworks impose compliance requirements and offer incentives that motivate firms to innovate sustainably.

From an economic standpoint, the transition to sustainable practices is increasingly being viewed not only as a regulatory obligation but also as a strategic opportunity. Firms that adopt sustainable innovations can benefit from reduced operational costs, improved risk management, enhanced brand reputation, and access to emerging markets focused on environmentally friendly products (Porter & Kramer, 2011). Moreover, sustainability-linked financial instruments such as green bonds, ESG (Environmental, Social, and Governance) investments, and government subsidies offer new channels for funding sustainable transformations (Kotsantonis & Serafeim, 2019).

Nevertheless, significant challenges persist. The implementation of sustainable practices in the chemical industry often requires substantial capital investment, technological innovation, and organizational change. Many companies face barriers including outdated infrastructure, resistance from stakeholders, market volatility, and the complexity of integrating sustainability metrics into existing performance systems (Bocken et al., 2014). These challenges are further compounded in emerging economies where regulatory oversight and technological infrastructure may be less robust.

Despite these hurdles, the momentum toward sustainability in the chemical industry continues to grow. Emerging technologies such as carbon capture and utilization (CCU), green hydrogen, bio-based feedstocks, and digitalization tools like AI and blockchain for supply chain transparency are creating new opportunities for reducing environmental impacts while maintaining profitability (IEA, 2021; McKinsey & Company, 2023).

1.2 Problem Statement

The chemical industry occupies a vital position in the global economy, serving as a fundamental enabler of various other sectors including agriculture, pharmaceuticals, automotive, construction, and consumer goods. However, this influence is accompanied by a heavy environmental burden. The industry is one of the largest industrial contributors to global greenhouse gas emissions, accounting for approximately 6% of global emissions, and is a leading consumer of energy and non-renewable resources (IEA, 2021). In addition to atmospheric emissions, the sector is associated with hazardous waste production, water contamination, and long-term damage to ecosystems through toxic substance discharge and soil pollution. These impacts conflict sharply with the increasing societal and regulatory demands for environmental responsibility and sustainable development (Dehkordi et al., 2024).

Over the past two decades, sustainability has emerged as a strategic imperative across industries, driven by climate change, resource scarcity, social pressure, and policy developments such as the United Nations Sustainable Development Goals (SDGs) and the European Green Deal (European Union, 2020b). Yet, the chemical industry has been relatively slow in fully embracing and operationalizing sustainable practices. Although numerous frameworks have been introduced—such as green chemistry, circular economy principles, and life cycle analysis—most chemical firms, especially small and medium enterprises (SMEs), struggle to move beyond compliance-driven environmental initiatives toward more holistic and proactive sustainability strategies (Ncube et al., 2023; ERM Sustainability Institute, 2023).

A central problem lies in the perceived dichotomy between sustainability and profitability. For many companies, implementing environmentally friendly processes is viewed as a cost center rather than a competitive advantage. High upfront capital investments, uncertain return on investment (ROI), long payback periods, and concerns over technological scalability contribute to hesitation and inertia (Bocken et al., 2014). Furthermore, sustainability often requires a rethinking of core business operations—from product design and sourcing to manufacturing and logistics—which introduces complexity and potential disruption. These challenges are compounded by a lack of internal expertise, data infrastructure, and integration of sustainability metrics into corporate decision-making frameworks (KPMG, 2020).

At a broader level, the policy and regulatory environment, though improving, remains fragmented and inconsistent across regions. While initiatives like REACH in the European Union and the Toxic Substances Control Act in the United States aim to mitigate environmental and health risks, their implementation varies significantly, leading to disparities in enforcement, innovation incentives, and compliance burdens (UNEP, 2019). Developing countries, where many chemical manufacturing plants are now located due to lower production costs, often face weaker environmental regulations, making global sustainability standards difficult to uphold uniformly.

The complexity of the chemical value chain adds another layer of difficulty. Unlike other sectors, the chemical industry includes a wide array of sub-sectors—ranging from basic chemicals and petrochemicals to fine and specialty chemicals—each with its own environmental challenges, technological capabilities, and economic dynamics. This diversity makes it challenging to devise one-size-fits-all solutions, and underscores the need for flexible, evidence-based strategies tailored to specific industrial contexts.

Moreover, there is a significant research gap in understanding how sustainability can be systematically integrated into chemical production while maintaining competitiveness. Existing studies often focus on isolated case studies or theoretical models without offering scalable frameworks or policy recommendations. This lack of practical guidance limits the ability of firms—especially in the mid-tier and SME segments—to effectively engage in long-term sustainability planning and transformation (Porter & Kramer, 2011; Palma & Hodgett, 2025).

1.3 Research Objectives

The primary aim of this thesis is to explore and evaluate the advancement of sustainable practices within the chemical industry, with an emphasis on strategies that effectively integrate environmental stewardship and economic viability.

Specifically, the research seeks to achieve the following objectives:

1. To assess the level of awareness and organizational commitment to sustainability within chemical industry firms, particularly across different roles such as executives, sustainability officers, production managers, and R&D professionals.
2. To identify which sustainability goals and practices are most commonly prioritized and implemented by companies, including but not limited to greenhouse gas

reduction, waste minimization, renewable energy use, and the application of green chemistry principles.

3. To analyze the integration of digital technologies (e.g., AI, IoT, blockchain, big data) in sustainability management, and evaluate the extent to which digital innovation supports sustainable transformation.
4. To evaluate the perceived financial impacts and economic viability of sustainability initiatives, including cost savings, return on investment, and the availability of financial incentives such as grants and tax benefits.
5. To investigate the main challenges and barriers faced by chemical companies in adopting sustainable practices, including high implementation costs, lack of expertise, organizational resistance, regulatory complexity, and uncertainty regarding long-term benefits.
6. To explore future industry perspectives on sustainability, including anticipated regulatory developments, drivers of sustainability adoption, and support for policy mechanisms such as mandatory certification schemes.
7. To provide actionable recommendations for both industry practitioners and policymakers on how to foster more effective, economically viable, and scalable sustainability strategies in the chemical sector.

1.4 Research Questions

The integration of sustainable practices within the chemical industry is a complex and multifaceted endeavor that involves environmental, technological, financial, and organizational considerations. In order to effectively explore this complexity, the present research is guided by a set of core and supporting research questions derived from the overarching aim of aligning environmental stewardship with economic viability.

The central research question that drives this thesis is: How can the chemical industry advance sustainable practices that are both environmentally responsible and economically viable?

To comprehensively address this core inquiry, several sub-questions have been formulated, reflecting the key thematic areas identified through the literature review and the primary data collection instrument (questionnaire):

1. What is the current level of awareness and organizational commitment to sustainability among professionals in the chemical industry?
2. Which specific sustainability goals (e.g., emission reduction, energy efficiency, circular economy) are most commonly prioritized by chemical companies?
3. To what extent are digital tools such as Artificial Intelligence (AI), Internet of Things (IoT), and Big Data Analytics used to support sustainability initiatives in the chemical sector?
4. How do companies perceive the financial impact of adopting sustainable practices (e.g., cost savings, increased operational costs, long-term ROI)?
5. What are the key barriers to implementing sustainability in the chemical industry (e.g., high implementation costs, resistance to change, regulatory complexity)?
6. What do industry professionals perceive as the main drivers for adopting sustainable practices (e.g., regulatory compliance, customer demand, cost efficiency)?

1.5 Structure of the Thesis

This thesis is organized into six main chapters, each of which contributes to a comprehensive understanding of sustainable practices within the chemical industry from both theoretical and empirical perspectives. The structure reflects a logical progression—from conceptual foundations to real-world application—ensuring clarity and coherence throughout the study.

The first chapter establishes the context of the research. It presents the background of the study, outlines the environmental and economic challenges faced by the chemical industry, and formulates the central problem that the research addresses. It also defines the research objectives, poses the key research questions, and provides an overview of the thesis structure.

The second chapter provides the theoretical and conceptual underpinnings of the study. It begins by defining sustainability and its core principles, with a focus on the three pillars: environmental, social, and economic. It then explores relevant regulatory frameworks—

both international and regional—as well as industry-specific sustainability standards. Finally, the chapter examines the economic dimensions of sustainable practices, including cost-benefit considerations, investment strategies, and long-term profitability.

The third chapter narrows the focus to the chemical industry, examining its environmental impact and identifying current sustainable strategies such as green chemistry, circular economy models, and energy efficiency measures. It also discusses key challenges to implementation, such as technological barriers, financial constraints, and market pressures. Additionally, it reviews previous academic and industry research to establish a foundation for the empirical analysis.

The fourth chapter outlines the research design and methodological approach used to collect and analyze data. It describes the development of the structured questionnaire, sampling methods, data collection procedures, and ethical considerations. It also details the statistical techniques used for data analysis, ensuring the reliability and validity of the findings.

The fifth chapter presents the findings of the study, divided into descriptive and inferential statistical analyses. It provides insights into current sustainability practices in the chemical industry based on the responses of industry professionals. The discussion section interprets the results in light of existing literature and theoretical frameworks, highlights key patterns and trends, and critically examines the implications of the findings. Limitations of the study are also addressed.

The final chapter summarizes the main findings of the research and reflects on their contributions to academic knowledge and industry practice. It offers recommendations for companies, policymakers, and researchers on how to better integrate sustainable practices in the chemical industry. The chapter concludes with suggestions for future research and final thoughts on the evolving relationship between sustainability and economic performance in this critical sector.

2. Foundations of Sustainability

2.1 Theoretical Foundations of Sustainability

2.1.1 Definition and Core Principles of Sustainability

Sustainability is a foundational concept that has evolved significantly since its formal introduction into global discourse. The most widely accepted definition originates from the World Commission on Environment and Development (WCED), commonly known as the Brundtland Commission, which defined sustainability as "*development that meets the needs of the present without compromising the ability of future generations to meet their own needs*" (Brundtland Commission, 1987: 43). This definition emphasizes intergenerational equity and underscores the necessity of maintaining a balance between environmental protection, economic development, and social progress. It has since become the cornerstone of international sustainability frameworks and industrial strategies.

At the heart of sustainability lies the integration of three core dimensions: environmental, economic, and social. These dimensions are often referred to as the "triple bottom line"—a term coined by Elkington (1997)—which advocates for measuring success not solely by financial returns but also by environmental stewardship and social contribution. This framework encourages organizations to consider the broader consequences of their actions, ensuring that development does not occur at the expense of ecological integrity or societal well-being. In the context of the chemical industry, this approach requires a comprehensive re-evaluation of traditional processes that often prioritize efficiency and profit over long-term environmental and social outcomes.

Environmental sustainability, as one of the pillars, focuses on the protection and responsible use of natural resources and ecosystems. For industries like chemical manufacturing, this entails reducing emissions, managing waste responsibly, conserving water and energy, and adopting technologies that mitigate ecological harm. The application of green chemistry principles—such as the use of less hazardous substances and energy-efficient synthesis—plays a crucial role in achieving environmental goals (Anastas & Warner, 2000). These principles are especially relevant to a sector known for its environmental footprint, making sustainability not just a regulatory requirement but a strategic imperative.

Economic sustainability refers to the ability of a system or enterprise to remain financially viable while pursuing environmental and social goals. In industrial settings, this means achieving profitability through innovation, efficiency, and risk management, rather than through practices that cause long-term damage to the environment or society. Porter and Kramer (2011) argue that integrating sustainability into the core strategy of a business creates shared value, whereby both economic performance and societal outcomes are improved.

Social sustainability addresses the human and community aspects of development. It includes issues such as labor rights, health and safety, diversity and inclusion, and community engagement. Within the chemical industry, this dimension is critically important due to the potential risks associated with hazardous substances and complex supply chains. Ensuring safe working conditions, transparent communication, and equitable benefit sharing are key components of this pillar (Elkington, 1997). Social sustainability also demands ongoing stakeholder engagement and the incorporation of local and global community needs into corporate decision-making.

In addition to these three main dimensions, several guiding principles reinforce the operationalization of sustainability across sectors. One such principle is the precautionary principle, which calls for preventative action in the face of environmental uncertainty. Another is the polluter pays principle, which holds that those responsible for pollution should bear the costs of its mitigation. A third is the principle of integration, which stresses that sustainability should be embedded into all levels of organizational planning and execution, rather than treated as a peripheral or compliance-driven concern (UNEP, 2019). These principles are particularly salient in the chemical industry, where environmental risks and regulatory scrutiny are high, and the potential for innovation through sustainable transformation is substantial.

Understanding and applying the core principles of sustainability is therefore essential for fostering meaningful change within the chemical industry. These principles not only provide a moral and practical framework for action but also align closely with emerging global trends, stakeholder expectations, and the long-term viability of the sector. As such, they serve as both a compass and a foundation for the development and implementation of sustainable practices throughout the value chain.

2.1.2 The Three Pillars of Sustainability: Environmental, Social, and Economic Aspects

The concept of sustainability is universally recognized as being built upon three interrelated and mutually reinforcing dimensions: environmental, social, and economic. These pillars—often described as the triple bottom line—provide a comprehensive framework for evaluating and guiding development, business strategies, and policy interventions. Together, they ensure that sustainability efforts address not only ecological preservation but also economic resilience and social equity (Elkington, 1997).

The environmental pillar of sustainability is perhaps the most visible and urgent in today's global context, given the accelerating impacts of climate change, biodiversity loss, pollution, and natural resource depletion. This pillar emphasizes the need to protect ecosystems, reduce environmental degradation, and use natural resources in a way that ensures their availability for future generations. For the chemical industry, environmental sustainability entails significant challenges and responsibilities due to its historically high levels of emissions, energy consumption, and hazardous waste production (UNEP, 2019). The adoption of green chemistry, pollution control technologies, circular economy models, and renewable energy sources are key strategies that industries can implement to reduce their ecological footprint (Anastas & Warner, 2000). Moreover, compliance with increasingly stringent international environmental standards and frameworks—such as the Paris Agreement and the EU Green Deal—demands that chemical companies align their operations with global climate goals (European Union, 2020b).

The social pillar of sustainability focuses on the human dimensions of sustainable development. It promotes equity, justice, labor rights, public health, and community well-being. In the context of the chemical industry, this involves ensuring safe working environments, fostering inclusivity, protecting human rights across supply chains, and engaging transparently with stakeholders. Exposure to hazardous substances and industrial accidents are among the most pressing social concerns in this sector, making the health and safety of workers a critical aspect of sustainability (ILO, 1993). Furthermore, the social pillar encourages corporate social responsibility (CSR) initiatives, whereby companies invest in the communities where they operate, support education and training programs, and maintain ethical labor practices. This aspect of sustainability also requires companies to consider the implications of their products and processes for broader society, especially in terms of health and environmental justice.

The economic pillar of sustainability ensures that development and industrial activity are financially viable over the long term. It seeks to foster productivity and growth while ensuring that economic activities do not undermine environmental or social foundations. Within the chemical industry, this means achieving profitability through resource efficiency, technological innovation, and long-term investment rather than short-term gains derived from environmentally damaging practices. Porter and Kramer (2011) introduced the concept of creating shared value, arguing that businesses can enhance their competitiveness while simultaneously advancing economic and social conditions in the communities where they operate. Sustainable economic performance involves minimizing costs through energy efficiency, reducing waste, mitigating regulatory risks, and gaining access to emerging markets that demand greener and more ethical products (Kotsantonis & Serafeim, 2019). Moreover, investors increasingly consider environmental, social, and governance (ESG) performance when allocating capital, further reinforcing the integration of economic and sustainability objectives.

It is crucial to understand that these three pillars are not isolated or competing objectives but are deeply interdependent. For instance, environmental degradation can lead to negative health outcomes, which in turn can affect labor productivity and social stability, ultimately harming economic performance. Likewise, strong economic growth can provide the resources necessary for environmental innovation and social development. A sustainable system, therefore, must maintain a dynamic balance among these pillars, ensuring that progress in one dimension does not come at the cost of another (Geissdoerfer et al., 2017). In the context of the chemical industry, this holistic integration is essential for ensuring that sustainability is not a peripheral concern but a core element of strategic planning and daily operations.

2.2 Regulatory Frameworks and Policies

2.2.1 International Regulations on Sustainability

In response to escalating global environmental and social challenges, a robust body of international regulations and frameworks has emerged to guide sustainable development across industries, including the chemical sector. These international instruments serve to establish common goals, set regulatory baselines, and encourage coordinated action among nations and industries. While their legal enforceability may vary depending on jurisdiction and adoption, their normative influence is substantial, shaping national laws, industry standards, and corporate strategies worldwide.

A foundational international milestone in sustainability governance is the United Nations Agenda 2030 for Sustainable Development, which was adopted in 2015 and includes 17 Sustainable Development Goals (SDGs). These goals provide a comprehensive blueprint for addressing critical global challenges such as climate change, resource depletion, environmental degradation, and inequality (United Nations, 2015). Several SDGs are directly relevant to the chemical industry, including Goal 6 (Clean Water and Sanitation), Goal 9 (Industry, Innovation and Infrastructure), Goal 12 (Responsible Consumption and Production), and Goal 13 (Climate Action) (United Nations, 2015). By aligning their strategies with the SDGs, chemical companies are increasingly expected to move beyond compliance and demonstrate a commitment to broader social and environmental objectives.

Another major international agreement is the Paris Agreement under the United Nations Framework Convention on Climate Change (UNFCCC), adopted in 2015. It aims to limit global warming to well below 2°C above pre-industrial levels and to pursue efforts to restrict the increase to 1.5°C (UNFCCC, 2016). While not industry-specific, the Paris Agreement has major implications for the chemical sector, which is both energy-intensive and a significant emitter of greenhouse gases. Countries that are parties to the agreement have committed to reducing emissions through Nationally Determined Contributions (NDCs), which increasingly incorporate sector-specific goals for industrial decarbonization. This exerts regulatory and reputational pressure on chemical manufacturers to invest in energy efficiency, adopt low-carbon technologies, and improve their emissions tracking and reporting systems.

The Basel, Rotterdam, and Stockholm Conventions also form an important regulatory triad that addresses the global trade and management of hazardous chemicals and wastes. The Basel Convention (1989) controls the transboundary movement of hazardous wastes and their disposal, seeking to protect human health and the environment from their adverse effects. The Rotterdam Convention in 1998 promotes shared responsibilities in the import and export of certain hazardous chemicals (Secretariat of the Rotterdam Convention, n.d.) while the Stockholm Convention in 2001 aims to eliminate or restrict the production and use of persistent organic pollutants (POPs), many of which are relevant to chemical production and use (Secretariat of the Stockholm Convention, n.d.). These conventions directly impact the chemical industry by regulating the handling, labeling, disposal, and cross-border movement of hazardous substances.

Moreover, the Strategic Approach to International Chemicals Management (SAICM)—a global policy framework adopted in 2006 under the auspices of the United Nations Environment Programme (UNEP) and the World Health Organization (WHO)—seeks to ensure that, by 2020 and beyond, chemicals are produced and used in ways that minimize significant adverse effects on human health and the environment (UNEP, 2019). Although SAICM is voluntary, it provides guidelines and support for capacity-building, particularly in developing countries, and fosters multi-stakeholder collaboration among governments, industry, and civil society.

Furthermore, the Global Reporting Initiative (GRI) and the Task Force on Climate-related Financial Disclosures (TCFD) are non-binding yet influential international standards that promote transparency in corporate sustainability reporting. While not regulatory in the traditional sense, they set expectations for disclosure that affect investor confidence and access to capital (GRI, 2021; TCFD, 2017). Chemical firms that fail to align with these frameworks risk being perceived as non-transparent or environmentally irresponsible, affecting both their reputation and competitiveness in global markets.

Taken together, these international regulations and frameworks underscore the growing expectation for chemical companies to align their operations with globally accepted sustainability norms. They also reveal an evolving landscape where voluntary compliance is giving way to formal accountability, and where sustainability performance is increasingly tied to financial and operational success.

2.2.2 National and Regional Environmental Policies

Greece has developed a comprehensive framework of national and regional environmental policies, aligning with European Union directives and international commitments to promote sustainable development. These policies encompass climate change mitigation, waste management, chemical safety, and the transition to a circular economy, all of which are pertinent to the chemical industry.

One of the cornerstone policies is the National Energy and Climate Plan (NECP), initially submitted in 2019 and subsequently updated to reflect more ambitious targets. The NECP outlines Greece's strategy to reduce greenhouse gas emissions by 55% by 2030 compared to 1990 levels and achieve climate neutrality by 2050. It emphasizes increasing the share of renewable energy in electricity generation to 82% by 2030 and enhancing energy efficiency across sectors. The plan also identifies specific measures for the industrial sector, including the chemical industry, to adopt cleaner technologies and improve energy performance (Ministry of Environment and Energy, 2019).

Complementing the NECP is the National Climate Law (Law 4936/2022), enacted to provide a legal framework for Greece's climate objectives. This law mandates the development of carbon budgets, sector-specific emission reduction targets, and the establishment of monitoring mechanisms to ensure compliance. It also stipulates the gradual phase-out of lignite-based power generation and promotes investments in renewable energy and low-carbon technologies, directly impacting energy-intensive industries such as chemicals (Mitsios, 2022).

In the realm of waste management, Greece has implemented the National Waste Management Plan (NWMP) and the National Waste Prevention Programme (NWPP) for the period 2020–2030. These plans aim to reduce waste generation, enhance recycling rates, and promote the circular economy. For the chemical industry, this translates to stricter regulations on hazardous waste handling, requirements for extended producer responsibility, and incentives for adopting sustainable production processes (European Environment Agency, 2023).

Chemical safety is governed by the General Chemical State Laboratory (GCSL), which operates under the Ministry of Finance. The GCSL is responsible for implementing EU regulations such as REACH (Registration, Evaluation, Authorisation, and Restriction of

Chemicals) and CLP (Classification, Labelling, and Packaging). It conducts inspections, provides guidance to industry stakeholders, and ensures compliance with chemical safety standards. The GCSL also collaborates with the Hellenic Association of Chemical Industries (HACI) to facilitate industry adherence to best practices and regulatory requirements (United Nations, 2010).

At the regional level, Greece has developed Regional Waste Management Plans (RWMPs) and Regional Climate Adaptation Plans, tailored to the specific environmental challenges and industrial activities of each region. These plans involve local authorities, industry representatives, and civil society in decision-making processes, ensuring that policies are context-specific and effectively implemented. For instance, regions with a high concentration of chemical industries may have stricter controls on emissions and waste disposal, as well as targeted support for cleaner technologies (Ministry of Environment and Energy, 2019).

In summary, Greece's national and regional environmental policies constitute a robust framework aimed at fostering sustainability across sectors. For the chemical industry, these policies necessitate a transition towards greener practices, compliance with stringent regulations, and active participation in achieving the country's environmental objectives.

2.2.3 Industry-Specific Sustainability Standards

In addition to international agreements and national legislation, the chemical industry is increasingly shaped by sector-specific sustainability standards and voluntary initiatives aimed at improving environmental, social, and economic performance. These standards provide structured frameworks for evaluating and implementing best practices across the chemical value chain, from raw material sourcing and production processes to waste management and product stewardship. As regulatory scrutiny and stakeholder expectations rise, adherence to these standards has become a strategic necessity for chemical companies seeking to maintain market access, reduce risks, and enhance their sustainability profile.

One of the most influential sector-specific initiatives is the Responsible Care® program, developed by the International Council of Chemical Associations (ICCA). Since its inception in 1985, Responsible Care has become a global initiative adopted by chemical associations and companies in over 60 countries. It is designed to improve health, safety, and environmental (HSE) performance while promoting open communication with stakeholders. Participating companies commit to continuously improving their operations through performance tracking, risk management, and transparent reporting (ICCA, 2020). The initiative also includes a sustainability charter, which integrates issues such as energy efficiency, product safety, circular economy principles, and greenhouse gas reduction into chemical manufacturing practices.

In Europe, the CEFIC Responsible Care® Program—administered by the European Chemical Industry Council—builds on the global framework and aligns with EU environmental goals. It encourages member companies to adopt performance metrics, such as those set out in the Sustainable Development Indicators (SDIs), which track progress on emissions, energy consumption, water usage, and occupational safety (CEFIC, 2022). These metrics provide chemical firms with tools to benchmark performance, communicate results to stakeholders, and meet growing environmental, social, and governance (ESG) disclosure requirements.

Chemical companies are also increasingly aligning with international environmental management standards such as ISO 14001, which specifies criteria for an effective Environmental Management System (EMS). ISO 14001 helps organizations identify environmental risks, ensure regulatory compliance, and implement continuous improvement processes (ISO, 2015). Many large and mid-sized chemical firms seek ISO 14001 certification as a demonstration of their commitment to sustainability and responsible operations. In some jurisdictions and procurement processes, ISO certification is even required to qualify for public contracts or to access environmentally conscious supply chains.

Another critical standard is the Global Product Strategy (GPS), an initiative of the ICCA that promotes the safe management of chemical products throughout their life cycles. The GPS encourages companies to conduct risk assessments, develop safety summaries, and enhance supply chain transparency. It is closely aligned with the goals of the United Nations Strategic Approach to International Chemicals Management (SAICM), ensuring that product stewardship is not limited to the production phase but extends to downstream users and final consumers (UNEP, 2019).

Voluntary corporate reporting frameworks also play a crucial role in shaping sustainability in the chemical industry. Leading firms often report their environmental and social performance in line with standards such as the Global Reporting Initiative (GRI) or the Sustainability Accounting Standards Board (SASB) guidelines for the chemicals sector. These frameworks help stakeholders evaluate companies' sustainability performance on issues including emissions, water usage, hazardous waste, workforce safety, and community impact (GRI, 2021; SASB, 2018). Transparency in sustainability reporting is increasingly demanded by investors, regulators, and consumers, and chemical firms that do not align with recognized reporting standards may face reputational and financial disadvantages.

In sum, industry-specific sustainability standards have become central to operational excellence, regulatory compliance, and competitive positioning in the chemical industry. These standards not only help firms mitigate environmental and social risks but also enable innovation, access to finance, and alignment with global sustainability goals.

2.3 Economic Viability of Sustainable Practices

2.3.1 Cost-Benefit Analysis of Sustainability Initiatives

The integration of sustainability into industrial practices—particularly in resource-intensive sectors like the chemical industry—often hinges on a detailed cost-benefit analysis (CBA). This analytical approach allows organizations to systematically assess the financial implications of sustainability-related decisions by comparing the anticipated costs of implementation with the expected economic, environmental, and social returns. In the context of corporate decision-making, cost-benefit analysis is not merely a budgeting tool but a strategic instrument that enables firms to align environmental responsibility with long-term profitability.

At first glance, the adoption of sustainable technologies and practices may appear to impose significant financial burdens. These include capital expenditures for installing clean technologies, process redesigns to reduce emissions, investments in renewable energy infrastructure, costs associated with employee training, and compliance with stricter environmental regulations (Bocken et al., 2014). Particularly in the chemical industry, where legacy infrastructure may be outdated and processes are capital-intensive, the initial costs can act as a deterrent to sustainable transformation.

However, when analyzed over the medium to long term, sustainability initiatives frequently yield substantial economic benefits. These include operational cost savings from increased energy efficiency, reduced waste disposal costs, improved resource productivity, and lower regulatory penalties (Porter & Van der Linde, 1995). For example, investments in closed-loop systems and material recycling can significantly lower the costs of raw material procurement. Similarly, firms that adopt renewable energy solutions often benefit from long-term price stability compared to volatile fossil fuel markets (IEA, 2021). These financial returns, while sometimes delayed, often exceed initial investment costs, particularly when externalities such as reputational benefits and risk mitigation are considered.

Beyond direct financial returns, sustainability initiatives also generate intangible and strategic benefits that are crucial in highly competitive industries. Enhanced brand reputation, increased customer loyalty, improved employee morale, and easier access to ESG-focused investors are often cited as key outcomes of sustainability leadership (Kotsantonis & Serafeim, 2019). Moreover, companies that proactively embrace sustainability are better positioned to anticipate and adapt to regulatory changes, thus reducing compliance risks and avoiding disruption.

The cost-benefit analysis of sustainability must also account for societal and environmental externalities, which are often overlooked in traditional financial accounting. Reduced pollution levels contribute to public health improvements and ecosystem protection, while sustainable resource use helps mitigate the depletion of non-renewable inputs (UNEP, 2019). Although these benefits may not be immediately captured in corporate balance sheets, they are increasingly recognized in integrated reporting frameworks and sustainable investment evaluations.

Importantly, the effectiveness of cost-benefit analysis depends on the inclusion of comprehensive and realistic metrics. This includes evaluating life-cycle costs, internalizing externalities, and quantifying reputational value. Traditional accounting systems may fall short in capturing these dimensions, hence the growing interest in tools such as life-cycle assessment (LCA), total cost of ownership (TCO), and ESG scoring mechanisms to supplement financial evaluation (Epstein & Buhovac, 2014).

In conclusion, while sustainability initiatives often require upfront investments, a thorough cost-benefit analysis reveals that the long-term advantages—both tangible and intangible—frequently outweigh the initial costs. For the chemical industry, which faces both environmental scrutiny and technological opportunity, such analyses are essential for making informed, future-proof decisions that support both profitability and environmental stewardship.

2.3.2 Financial Incentives and Green Investments

The transition to sustainable development requires significant financial support, particularly when organizations must adopt new technologies, restructure operations, or meet evolving regulatory standards. In recognition of this need, a variety of financial incentives and green investment mechanisms have emerged to encourage and support environmentally responsible business practices across sectors. These mechanisms, provided by governments, international bodies, and financial institutions, aim to reduce the perceived financial risks of sustainability initiatives and improve the return on investment for green projects.

Government subsidies and tax incentives are among the most common tools used to promote sustainability. These incentives can take many forms, including grants for renewable energy installations, tax credits for energy-efficient buildings or machinery, and accelerated depreciation schemes for green technologies. For instance, the United States has long offered tax credits for solar and wind energy investments through programs such as the Investment Tax Credit (ITC) and the Production Tax Credit (PTC), which have significantly boosted the growth of the clean energy sector (U.S. Department of Energy, 2021). Similarly, many EU countries offer rebates and co-financing for sustainable infrastructure upgrades, energy audits, and low-carbon transportation systems (European Commission, 2020).

In parallel, green public procurement (GPP) policies are being adopted by governments to stimulate demand for sustainable goods and services. By integrating environmental criteria into procurement processes, public agencies can incentivize businesses to develop more sustainable products. The European Union's GPP guidelines encourage member states to prioritize eco-friendly products in areas such as construction, food services, and transport, creating a predictable market for sustainability-focused firms (OECD, 2024). These policies have a multiplier effect, pushing private suppliers to align with sustainability benchmarks to remain competitive in public tenders.

On a global scale, the rise of green finance has provided businesses with access to capital specifically earmarked for sustainable projects. Green bonds, for example, are debt instruments issued to finance projects with positive environmental impacts, such as renewable energy infrastructure, energy efficiency upgrades, and climate adaptation initiatives. The green bond market has grown exponentially over the past decade, reaching over $500 billion in annual issuance in 2021 alone (Climate Bonds Initiative, 2022). Institutional investors are increasingly allocating funds to green assets as part of their Environmental, Social, and Governance (ESG) strategies, driven by both ethical considerations and risk management goals.

In addition to bonds, green investment funds and venture capital support the development of clean technologies and sustainable startups. Many investment firms now operate ESG-focused portfolios, evaluating companies not only on their financial performance but also on their environmental and social practices. According to Morningstar (2022), global assets under management in ESG funds surpassed $2.7 trillion in 2021. These funds offer capital to companies that align with sustainability objectives, fostering innovation and scaling of environmentally beneficial technologies across sectors.

Multilateral development banks (MDBs) also play a crucial role by financing sustainability initiatives in developing and emerging economies, where access to capital may be limited. Institutions like the World Bank, the European Investment Bank (EIB), and the Asian Development Bank (ADB) provide concessional loans, risk guarantees, and technical assistance to help countries achieve their climate and development goals. These institutions often fund large-scale infrastructure projects that incorporate climate resilience, renewable energy, and pollution control (World Bank, 2020).

While financial incentives and green investments offer significant potential, challenges remain in terms of accessibility, accountability, and impact measurement. Smaller enterprises often lack the capacity to apply for or administer grants and green loans. Additionally, concerns about "greenwashing"—the misrepresentation of environmental benefits—have led to calls for stricter verification standards and third-party certification of green financial instruments (Sullivan & Mackenzie, 2020). In response, initiatives such as the EU Green Bond Standard and the Climate Bonds Standard have emerged to improve transparency and credibility in green finance.

Overall, financial incentives and green investments are key enablers of sustainable transformation across all sectors. They not only lower the financial barriers to entry for sustainability initiatives but also reshape market dynamics by rewarding environmentally responsible behavior and innovation.

2.3.3 Long-Term Profitability of Sustainable Models

The debate over the economic merits of sustainability has evolved considerably in recent decades. While early perceptions often framed sustainability as a cost center or regulatory burden, increasing evidence suggests that sustainable business models can drive long-term profitability, resilience, and competitive advantage across sectors. Rather than viewing sustainability as a constraint, many forward-thinking organizations now treat it as a catalyst for innovation, value creation, and long-term financial performance.

Sustainable business models are characterized by the integration of environmental and social goals into the core strategy of a firm. These models emphasize resource efficiency, stakeholder engagement, transparency, and adaptability to environmental and market changes. One of the key financial benefits of sustainability is cost reduction through efficiency gains. Companies that reduce energy consumption, minimize waste, and optimize resource use often achieve lower operating costs and improved margins over time (Eccles & Serafeim, 2013). For example, global firms implementing circular economy principles have reported not only reduced environmental impact but also lower input costs and increased material recovery rates (Ellen MacArthur Foundation, 2015).

Another driver of long-term profitability is risk mitigation. Companies that embed sustainability into their operations are better positioned to anticipate and respond to regulatory changes, supply chain disruptions, and reputational risks. Climate-related risks—such as extreme weather, resource scarcity, and carbon pricing—can significantly affect operational continuity and asset valuation. Firms that proactively manage these risks through sustainable practices are more likely to maintain stability and investor confidence in the face of such disruptions (TCFD, 2017). Moreover, integrating Environmental, Social, and Governance (ESG) considerations into business strategy has been associated with lower capital costs and greater access to sustainable finance (Friede et al., 2015).

In addition to cost savings and risk reduction, sustainable models can generate revenue growth and market differentiation. As consumer preferences shift toward eco-friendly and ethically sourced products, companies that respond with transparent and verifiable sustainability efforts gain a competitive edge. This is evident in the rise of "green" markets, where sustainable attributes enhance brand loyalty, customer retention, and pricing power. In the fashion, food, and electronics industries, for instance, sustainability has become a key determinant of purchasing behavior among younger demographics, who are willing to pay a premium for environmentally and socially responsible products (Park et al., 2022; Muchenje et al., 2023).

Furthermore, sustainability is increasingly recognized as a driver of innovation. Companies that embrace sustainable principles often invest in research and development to create new products, services, or business models. These innovations can open new market segments, improve operational agility, and generate intellectual property assets that strengthen long-term value. For instance, the development of biodegradable packaging, low-carbon construction materials, and smart energy systems has been both environmentally impactful and commercially successful (Hart & Milstein, 2003).

From an investment perspective, there is growing consensus that firms with strong sustainability performance tend to outperform peers over the long term. A meta-analysis by Friede et al. (2015), which reviewed over 2,000 empirical studies, found a positive relationship between ESG performance and corporate financial performance in the majority of cases. Similarly, BlackRock (2020) reported that during periods of market volatility, ESG-focused funds were more resilient than conventional investments, highlighting the financial stability offered by sustainability-oriented firms.

However, the long-term profitability of sustainable models also depends on the firm's ability to embed sustainability strategically rather than treating it as a standalone or marketing function. Superficial or inconsistent efforts—often referred to as "greenwashing"—can lead to consumer backlash, regulatory penalties, and erosion of trust. Therefore, successful implementation requires measurable targets, stakeholder engagement, transparent reporting, and alignment with broader corporate objectives (UN Global Compact, 2021).

In conclusion, sustainable business models are increasingly seen not only as a moral or regulatory obligation but as a strategic pathway to long-term profitability. By reducing costs, managing risks, driving innovation, and responding to stakeholder expectations, organizations across industries can achieve sustained value creation while contributing positively to society and the environment.

3. Sustainability in the Chemical Industry

3.1 Environmental Impact of the Chemical Industry

3.1.1 Greenhouse Gas Emissions and Climate Change

The chemical industry is both a foundational sector of modern economies and a significant contributor to global greenhouse gas (GHG) emissions. As a resource-intensive and energy-dependent sector, it plays a critical role in the climate change equation—not only as a source of emissions but also as a potential driver of low-carbon innovation (European Environment Agency, 2024). Addressing the sector's GHG footprint is therefore central to any meaningful climate mitigation strategy.

Globally, the chemical industry accounts for approximately 6–8% of total anthropogenic GHG emissions, primarily due to energy consumption in high-temperature processes and feedstock use of fossil fuels (IEA, 2023). The production of basic chemicals such as ammonia, methanol, ethylene, and propylene is especially carbon-intensive, relying heavily on natural gas, coal, and oil-based raw materials. For example, ammonia production for fertilizers—through the Haber-Bosch process—is responsible for nearly 2% of global CO_2 emissions alone. In addition to carbon dioxide (CO_2), chemical manufacturing releases other potent GHGs such as nitrous oxide (N_2O) and methane (CH_4), which have significantly higher global warming potential over shorter timescales (Ritchie, Rosado & Roser, 2023).

A major challenge in the chemical sector is the dual role of fossil fuels as both energy sources and feedstocks, making decarbonization more complex than in sectors where fossil fuels are used solely for combustion. Traditional energy efficiency measures, while helpful, are insufficient on their own to bring emissions in line with the goals of the Paris Agreement, which seeks to limit global warming to well below 2°C above pre-industrial levels (UNFCCC, 2016). This means that the chemical industry must explore and invest in deeper transformations, including alternative feedstocks (e.g., biomass or CO_2), electrification of heat processes, and carbon capture, utilization, and storage (CCUS) technologies (IEA, 2021).

In recent years, industry leaders have begun to take more concrete actions toward climate goals. Some large multinational chemical companies have adopted net-zero targets for 2050 and intermediate science-based targets (SBTs) for 2030. These strategies typically involve transitioning to renewable energy sources, improving process efficiency, integrating circular economy principles, and developing low-carbon product lines. However, progress is uneven, and smaller firms often lack the capital or expertise to make significant emissions reductions without supportive policy frameworks or financial incentives (Malehmirchegini & Chapman, 2025).

Moreover, the growing emphasis on Scope 3 emissions—indirect emissions associated with a company's value chain—adds another layer of complexity. For the chemical sector, Scope 3 emissions may include upstream impacts from raw material extraction and downstream emissions from product use and disposal. These indirect emissions can be several times higher than direct operational emissions, particularly for petrochemical-based products such as plastics and synthetic fertilizers. As such, comprehensive climate strategies must address the entire product life cycle, from design and production to post-consumer waste management (Carruthers, 2024).

Climate-related risks also extend beyond regulatory compliance and reputation. Physical risks—such as extreme weather, water scarcity, and supply chain disruptions—pose significant threats to the continuity of chemical operations. These risks are expected to intensify with ongoing climate change, further motivating companies to integrate resilience into their infrastructure and planning (TFCFD, 2017).

In conclusion, while the chemical industry has made initial strides toward climate mitigation, the sector remains one of the most challenging to decarbonize due to its energy and feedstock dependencies. Achieving substantial reductions in GHG emissions will require coordinated efforts across technology innovation, policy support, financial investment, and systemic shifts in industrial design and consumption patterns.

3.1.2 Waste Management and Pollution Control

The chemical industry generates a wide range of waste streams and pollutants, many of which pose significant risks to human health and the environment. These include hazardous solid and liquid wastes, airborne emissions, and wastewater contaminated with toxic or persistent substances. As global environmental regulations tighten and public awareness increases, waste management and pollution control have become critical components of sustainable operations in the chemical sector (European Environment Agency, 2024).

Chemical manufacturing processes often involve complex reactions using hazardous inputs such as solvents, heavy metals, and persistent organic pollutants. The resulting waste can be highly toxic, flammable, or corrosive, requiring specialized handling, storage, and disposal methods. Improper management of such materials can lead to soil and groundwater contamination, ecosystem disruption, and long-term public health impacts (UNEP, 2019).

Effective waste management in the chemical industry begins with waste minimization at the source, a principle grounded in cleaner production and green chemistry. By optimizing reaction pathways, reducing excess reagents, and designing processes with fewer byproducts, companies can significantly lower the volume and toxicity of waste produced (Anastas & Warner, 2000). Process intensification and real-time monitoring technologies also contribute to improved efficiency and reduced emissions, minimizing environmental footprints while enhancing economic performance.

In cases where waste generation is unavoidable, segregation, treatment, and safe disposal become essential. Technologies such as incineration with energy recovery, advanced oxidation, and chemical neutralization are commonly used to treat hazardous wastes before final disposal. For wastewater, treatment processes often include physical, chemical, and biological methods to remove or degrade harmful substances. In recent years, the use of membrane filtration, photocatalysis, and bio-remediation has expanded the toolkit for effective pollution control (Awaleh & Soubaneh, 2014).

The chemical industry also contributes significantly to air pollution, particularly through the release of volatile organic compounds (VOCs), sulfur oxides (SO_x), nitrogen oxides (NO_x), and particulate matter. These pollutants contribute to smog formation, acid rain, and respiratory illnesses. Regulatory frameworks such as the European Union's Industrial Emissions Directive and the U.S. Clean Air Act set strict emission limits and require continuous monitoring and reporting of airborne pollutants (European Commission, 2020; U.S. EPA, 2024).

Waste management also plays a crucial role in circular economy strategies, where waste is treated as a resource rather than a liability. In the chemical sector, this may involve recovering solvents for reuse, recycling process water, or converting byproducts into marketable co-products. Some companies have developed closed-loop systems that allow for near-zero waste operations, improving both environmental and financial outcomes (Ellen MacArthur Foundation, 2015). However, achieving full circularity remains challenging due to the complex composition of chemical wastes and potential contamination risks.

Despite progress, significant challenges remain, especially in developing countries where waste management infrastructure is weak and regulatory enforcement is limited. Illegal dumping, inadequate treatment facilities, and lack of public awareness continue to pose threats to communities located near chemical plants. International cooperation, capacity building, and investment in waste management technologies are therefore essential to advancing global standards and closing performance gaps (UNEP, 2019).

In summary, the chemical industry must adopt a multifaceted approach to waste and pollution control—combining prevention, treatment, compliance, and circular economy principles. These efforts are critical not only for regulatory compliance and corporate responsibility but also for building resilient, sustainable operations in an increasingly resource-constrained world.

3.1.3 Resource Depletion and Raw Material Usage

The chemical industry is fundamentally reliant on the continuous input of natural resources, particularly fossil fuels, minerals, water, and biomass. These raw materials serve both as energy sources and as feedstocks for the synthesis of a wide array of chemical products, including plastics, fertilizers, pharmaceuticals, and industrial solvents. As global demand for chemical products grows, concerns about resource depletion, supply chain security, and environmental degradation have become increasingly urgent (Malehmirchegini & Chapman, 2025).

Traditionally, the chemical industry has been heavily dependent on non-renewable resources, especially crude oil and natural gas. These fossil fuels are used not only for process energy but also as raw materials in the production of petrochemicals, which account for a significant portion of global chemical output. According to the International Energy Agency (2021), petrochemical production is expected to become the largest driver of oil demand growth by 2030, surpassing the transportation sector. This trend underscores the unsustainable nature of current resource usage patterns and highlights the urgency of transitioning to more sustainable feedstocks.

In addition to hydrocarbons, the chemical industry consumes substantial quantities of minerals and rare earth elements, which are essential in the production of catalysts, electronic chemicals, and specialized compounds. The extraction and processing of these materials often involve environmentally intensive practices, contributing to land degradation, water pollution, and loss of biodiversity (UNEP, 2011). Furthermore, the concentration of resource deposits in politically unstable or ecologically sensitive regions raises concerns about long-term availability and ethical sourcing.

Water is another critical resource for the chemical sector, used extensively for cooling, cleaning, and processing. In water-stressed regions, high industrial water consumption can exacerbate local shortages and create conflict between industrial and community needs. Efforts to reduce water use, implement closed-loop systems, and treat wastewater for reuse have been implemented in some facilities, but industry-wide progress remains uneven (WWAP, 2020). As climate change continues to affect water availability, water management will become an even more central issue for sustainable chemical production.

To address resource depletion, many companies are exploring the use of renewable and bio-based feedstocks. These alternatives include biomass-derived inputs such as lignocellulosic sugars, algae, and agricultural waste, which can be converted into platform chemicals with lower environmental impact. While bio-based chemicals offer potential for reducing carbon intensity and fossil dependency, challenges remain regarding land use, scalability, and cost competitiveness (Clark et al., 2009). Ensuring that bio-based solutions do not contribute to food insecurity or deforestation is also a critical consideration.

The concept of material circularity offers another pathway to reduce pressure on raw resources. By designing products for reuse, recycling, and recovery, the chemical industry can significantly reduce its reliance on virgin inputs. For instance, chemical recycling technologies allow for the depolymerization of plastics back into monomers, which can then be reused in manufacturing. Similarly, solvent recovery systems and catalyst regeneration techniques help extend the life cycle of key materials (Ellen MacArthur Foundation, 2021).

However, the implementation of circular economy principles at scale requires systemic change, investment in infrastructure, and collaboration across supply chains.

Finally, increasing regulatory and market pressure is pushing companies to adopt more responsible sourcing strategies. Frameworks such as the EU's Critical Raw Materials Act and global ESG reporting standards encourage firms to assess the origin, sustainability, and lifecycle impact of their raw materials. Integrating life cycle assessment (LCA) into sourcing decisions helps identify environmental hotspots and supports more sustainable procurement practices (European Commission, 2023).

In conclusion, the chemical industry's reliance on finite natural resources presents significant sustainability challenges. Shifting toward renewable inputs, improving material efficiency, and embracing circular economy strategies are essential to ensure the long-term viability of the sector and to minimize its ecological footprint.

3.2 Sustainable Strategies and Best Practices

3.2.1 Green Chemistry Principles

Green chemistry, also known as sustainable chemistry, is a fundamental framework guiding the transformation of the chemical industry toward more environmentally benign and economically viable practices. It is defined as "*the design of chemical products and processes that reduce or eliminate the use and generation of hazardous substances*" (Anastas & Warner, 2000: 11). This approach moves sustainability upstream—into the realm of product and process design—emphasizing prevention rather than remediation of pollution. By integrating green chemistry principles into the core of chemical manufacturing, companies can reduce their environmental impact while enhancing efficiency, safety, and market competitiveness.

The framework of green chemistry is based on 12 guiding principles developed by Paul Anastas and John Warner. These principles provide a strategic foundation for minimizing the environmental and health risks associated with chemical processes and products. Key principles include waste prevention, atom economy (maximizing the incorporation of all materials used in the process into the final product), the use of less hazardous chemical syntheses, designing safer chemicals, energy efficiency, the use of renewable feedstocks, and degradation of products after use (Anastas & Warner, 2000). These principles aim to guide chemists, engineers, and industry decision-makers toward sustainable innovation.

One of the most impactful areas of green chemistry is the design of safer chemicals and reaction pathways. This involves selecting reactants and solvents that are inherently non-toxic and designing molecules that degrade into harmless byproducts at the end of their lifecycle. For instance, replacing chlorinated solvents with water or supercritical CO_2 in synthesis and purification steps significantly reduces toxicity and environmental persistence (Clark & Macquarrie, 2002). Safer design also enhances worker safety and lowers regulatory burdens associated with hazardous substance management.

Another critical application is the reduction of energy use, especially in reactions that require high temperatures or pressures. Green chemistry encourages energy-efficient alternatives such as microwave-assisted synthesis, flow chemistry, and biocatalysis, which allow reactions to proceed under milder conditions while maintaining high yields. These innovations not only reduce greenhouse gas emissions but also lower operational costs, contributing to both environmental and economic performance (Poliakoff et al., 2002).

Renewable feedstocks play a central role in green chemistry by replacing fossil-derived inputs with bio-based alternatives such as plant biomass, algae, or agricultural waste. For example, the production of polylactic acid (PLA) from corn starch is a green alternative to petroleum-based plastics. However, the adoption of bio-based feedstocks must also consider life cycle impacts, including land use and food security, to avoid unintended consequences (Bozell & Petersen, 2010).

The chemical industry also benefits from the principle of real-time analysis for pollution prevention, which involves monitoring reactions as they occur to avoid the formation of hazardous byproducts. Advances in process analytical technologies (PAT) and in-line sensors have made it possible to optimize reaction conditions dynamically, improving yields and reducing waste. This principle is increasingly important in high-throughput industrial settings where continuous processing and automation are becoming standard (Sheldon, 2017).

Despite its benefits, the implementation of green chemistry principles remains uneven across the industry. Barriers include the high cost of transitioning from legacy systems, limited availability of green alternatives for certain chemicals, and lack of regulatory mandates. Nevertheless, growing investor interest in ESG performance, stricter environmental regulations, and increasing consumer demand for sustainable products are driving greater adoption. Academic institutions and government agencies have also supported the dissemination of green chemistry through research funding, curricula, and recognition programs such as the U.S. Presidential Green Chemistry Challenge Awards (U.S. EPA, 2024).

In conclusion, green chemistry principles offer a transformative pathway for the chemical industry to achieve sustainability at the molecular level. By designing inherently safer and more efficient processes, the industry can reduce environmental impacts, protect human health, and create long-term economic value.

3.2.2 Circular Economy and Waste Reduction

The linear model of production and consumption—based on extracting raw materials, producing goods, using them, and disposing of waste—has long defined the operations of the chemical industry. However, this approach is increasingly recognized as unsustainable due to escalating resource depletion, environmental degradation, and waste accumulation. In response, the circular economy (CE) model has gained global momentum as a strategic framework that emphasizes resource efficiency, product longevity, and closed-loop systems. For the chemical industry, adopting circular economy principles presents both a challenge and an opportunity to reduce waste, enhance sustainability, and create new value streams (Deep, 2024).

A circular economy is defined as an industrial system that is restorative or regenerative by design. It seeks to decouple economic activity from the consumption of finite resources by designing out waste and pollution, keeping materials in use, and regenerating natural systems. Within the chemical sector, this means shifting from virgin fossil-based inputs to renewable or recycled feedstocks, designing products for end-of-life recovery, and optimizing processes to minimize or eliminate waste throughout the production cycle (Ellen MacArthur Foundation, 2019).

One of the key strategies in this context is chemical recycling, which goes beyond mechanical recycling by breaking down polymers into their original monomers or other valuable feedstocks. Unlike conventional methods, chemical recycling allows for the recovery of high-purity materials even from contaminated or mixed plastic waste streams. Technologies such as pyrolysis, gasification, and depolymerization have shown promise in converting plastic waste into usable inputs for new chemical production, although technical and economic barriers remain (Ragaert et al., 2017).

In addition to recycling, industrial symbiosis offers another model for implementing circularity. In this approach, waste or byproducts from one process or facility are used as inputs for another, fostering cross-sector collaboration. For example, CO_2 captured from a chemical plant can be used in the production of carbonates or synthetic fuels, while waste heat can be redirected to adjacent manufacturing operations. Such symbiotic relationships not only reduce waste but also improve energy and material efficiency across value chains (Chertow, 2007).

Product redesign and material innovation are also central to the CE transition in the chemical industry. By reengineering molecules and materials for durability, reusability, and recyclability, companies can extend product life cycles and facilitate resource recovery. For instance, designing surfactants or solvents that degrade harmlessly after use, or engineering packaging materials that are fully biodegradable or compatible with closed-loop recycling systems, directly aligns with both CE and green chemistry principles (Clark & Deswarte, 2008).

Digital technologies such as blockchain, AI, and IoT are playing a growing role in enabling circular economy practices. These tools enhance traceability, optimize resource use, and provide real-time data on material flows. For example, blockchain can be used to verify the origin and lifecycle of chemical materials, while IoT sensors monitor equipment efficiency and process emissions, supporting preventive maintenance and waste reduction (World Economic Forum, 2023).

Despite the potential of circular economy models, implementation remains uneven across the chemical sector. Barriers include the complexity of chemical supply chains, technical limitations in recycling infrastructure, lack of harmonized standards, and economic disincentives for using secondary materials. Policy frameworks such as the European Union's Circular Economy Action Plan and the European Chemicals Strategy for

Sustainability are helping to address these challenges by introducing regulatory incentives and extended producer responsibility requirements (European Union, 2020b).

In conclusion, the circular economy represents a transformative paradigm for the chemical industry, offering a systems-level solution to reduce waste and resource dependency. While challenges persist, continued innovation, supportive regulation, and collaboration across the value chain are essential to realizing the full potential of circularity in chemical production.

3.2.3 Energy Efficiency and Renewable Energy Integration

Energy is a cornerstone of chemical manufacturing, as many processes require high temperatures, high pressure, and continuous operations, often over long durations. As a result, the chemical industry is one of the most energy-intensive sectors globally, accounting for approximately 10% of total industrial final energy consumption and a significant share of related CO_2 emissions (IEA, 2021). Reducing energy use through improved efficiency and integrating renewable energy sources are therefore critical to the industry's sustainability transition.

Energy efficiency is widely recognized as the most cost-effective and immediate means to reduce greenhouse gas emissions in the chemical sector. Improvements can be made at multiple levels—from upgrading equipment and optimizing heat integration, to enhancing process control systems and minimizing downtime. Common strategies include the use of high-efficiency heat exchangers, advanced distillation technologies, and cogeneration (combined heat and power) systems, which recover and reuse energy from one part of the process to power another (Saygin et al., 2011).

In recent years, digitalization and smart manufacturing technologies have further enhanced energy efficiency potential. The use of real-time monitoring, predictive maintenance, artificial intelligence (AI), and Internet of Things (IoT) sensors enables companies to fine-tune operations, detect inefficiencies, and reduce energy waste (World Economic Forum, 2020). These Industry 4.0 solutions are increasingly being adopted to create more agile, responsive, and low-carbon production systems within chemical plants.

Alongside efficiency measures, the integration of renewable energy is a growing priority. Chemical production has traditionally relied on fossil fuels not only for electricity and heat but also as feedstocks. While electrifying chemical processes is technically complex due to high-temperature requirements and continuous energy loads, progress is being made in using renewable electricity—primarily from wind and solar—for both indirect and direct applications. Electrification of steam generation and mechanical processes is expanding, and electrochemical synthesis is emerging as a promising area of innovation (IEA, 2021).

Green hydrogen—produced through electrolysis powered by renewable energy—is another pathway to decarbonize the chemical industry, particularly in ammonia, methanol, and synthetic fuel production. Green hydrogen offers a sustainable alternative to conventional hydrogen derived from natural gas (via steam methane reforming), which is currently responsible for substantial CO_2 emissions (IRENA, 2020). As the cost of electrolyzers and renewable power decreases, green hydrogen is expected to become a viable replacement in key chemical processes, although challenges remain in infrastructure and scale.

The use of biomass and bio-based energy is also being explored, especially in the form of bioheat or bio-based feedstocks that provide both energy and material value. However, care must be taken to ensure that biomass sourcing does not compete with food production or lead to deforestation, which would undermine environmental objectives (Clark & Deswarte, 2008).

Government policies and international frameworks are supporting these transitions. The European Union's Emissions Trading System, industrial energy efficiency directives, and green finance mechanisms (e.g., tax credits and subsidies for clean energy investments) are incentivizing companies to shift toward cleaner energy models (European Commission, 2020). Additionally, voluntary sustainability standards and science-based target initiatives encourage companies to align their decarbonization strategies with climate goals.

Despite these advancements, the pace of renewable energy integration in the chemical industry remains limited compared to other sectors, mainly due to technical complexity, high capital costs, and concerns over energy reliability. Nevertheless, the convergence of technological innovation, policy support, and stakeholder pressure is gradually lowering these barriers and driving the industry toward a more energy-resilient and sustainable future.

3.2.4 Sustainable Supply Chain Management

Sustainable supply chain management (SSCM) has emerged as a critical priority in the chemical industry, where complex, globalized value chains are increasingly scrutinized for their environmental and social impacts. From raw material extraction and production to distribution and end-of-life disposal, each stage of the supply chain presents sustainability challenges and opportunities. SSCM involves integrating environmental, social, and governance (ESG) considerations into supply chain decisions and processes, aiming to reduce risk, improve transparency, and create long-term value (Seuring & Müller, 2008).

The chemical industry's supply chains are particularly intricate due to the nature of its products and inputs. Many chemicals are hazardous, require specialized transportation and storage, and have long and opaque sourcing paths. This complexity makes traceability and sustainability assessments more difficult compared to other sectors. In response, firms are increasingly adopting tools such as life cycle assessment, supplier audits, and sustainability certification schemes to monitor upstream impacts and improve accountability (Sarkis et al., 2011). These tools help evaluate emissions, resource consumption, and social risks associated with each product stage—from extraction of feedstocks to end-user applications.

A key strategy in sustainable supply chain management is supplier collaboration and engagement. Leading chemical firms are working more closely with their suppliers to promote cleaner production practices, reduce hazardous inputs, and share sustainability data. Collaborative programs often include supplier training, shared performance metrics, and joint innovation efforts aimed at reducing environmental footprints (Pagell & Wu, 2009). For example, supplier codes of conduct are now common, outlining expectations on issues such as waste management, emissions control, labor rights, and ethical sourcing.

Digital technologies are also transforming supply chain transparency and efficiency. Blockchain, for instance, is increasingly used to provide tamper-proof records of material provenance, ensuring compliance with sustainability standards and enabling traceability across borders. Meanwhile, data analytics and cloud-based platforms are used to track emissions, energy consumption, and inventory flows in real time, allowing for more responsive and efficient supply chain decisions (Wichmann et al., 2021). These technologies enhance supply chain resilience, especially in the face of climate-related disruptions and geopolitical instability.

Logistics optimization plays another important role in SSCM for the chemical industry. Transportation is a major source of emissions and risk due to the hazardous nature of chemical cargo. Sustainable logistics strategies include route optimization, modal shifts to rail or waterways, the use of low-emission vehicles, and improved packaging to reduce waste and leakage risks (McKinnon et al., 2015). Additionally, proximity sourcing—where materials are procured closer to manufacturing facilities—can help reduce carbon emissions and enhance supply chain resilience.

The circular economy also intersects with sustainable supply chains. Closed-loop models—where products and materials are recovered, recycled, or reused at the end of their lifecycle—require supply chain systems that support reverse logistics, product take-back schemes, and partnerships with waste management firms. This shift demands not only technical solutions but also contractual and logistical frameworks that enable circular flows of materials (Genovese et al., 2017).

Regulatory developments and stakeholder expectations are further accelerating the adoption of SSCM practices. Frameworks such as the European Union’s Corporate Sustainability Due Diligence Directive and REACH regulation (Registration, Evaluation, Authorisation, and Restriction of Chemicals) require companies to take responsibility for the environmental and human rights impacts of their supply chains (European Commission, 2022). In parallel, investors and customers increasingly demand ESG transparency and responsible sourcing, making SSCM not only a compliance requirement but a competitive differentiator.

3.3 Challenges in Implementing Sustainability in the Chemical Industry

3.3.1 Technological Barriers

One of the most persistent barriers is the entrenchment of legacy infrastructure. Chemical production facilities often operate on capital-intensive systems designed for high-throughput processes powered by fossil fuels. Retrofitting or replacing this infrastructure with low-emission alternatives, such as electrified reactors or bio-based systems, requires significant investment, planning, and downtime, making firms hesitant to transition (IEA, 2021). Moreover, these systems typically have long lifespans—sometimes exceeding 30 years—leading to technological lock-in that slows innovation cycles (Levi & Cullen, 2018).

Another barrier is the lack of mature and scalable sustainable technologies for many core chemical processes. While advancements have been made in areas such as green hydrogen and chemical recycling, many of these technologies remain at the pilot or demonstration stage and are not yet economically viable for large-scale deployment. For example, electrochemical and photocatalytic routes for chemical synthesis show potential for reducing carbon emissions but face technical challenges such as low selectivity, high energy consumption, and limited durability of catalysts (Schoedel et al., 2020).

Data availability and digital integration also present challenges. Although digital technologies like AI, IoT, and predictive analytics have the potential to optimize energy use, monitor emissions, and reduce waste, their effectiveness depends on real-time data, advanced modeling capabilities, and skilled personnel. Many companies, particularly small and medium-sized enterprises (SMEs), lack the digital infrastructure or expertise needed to implement such solutions effectively (World Economic Forum, 2020). The interoperability of digital systems and concerns over cybersecurity further complicate digital transformation in chemical operations.

Process complexity and product specificity add another layer of difficulty. Unlike standard manufacturing sectors, the chemical industry produces a vast array of products with varying chemical compositions, safety requirements, and regulatory constraints. As a result, sustainable technologies must be highly customized, limiting the potential for universal solutions. For instance, technologies suitable for producing bio-based plastics may not be transferable to agrochemicals or pharmaceutical intermediates, reducing economies of scale and increasing costs (Abou-Elela et al., 2007).

Regulatory uncertainty and lack of harmonized standards can also delay the development and deployment of new technologies. Without clear, long-term regulatory signals—such as carbon pricing, technology-neutral funding, or mandates—companies may be reluctant to invest in sustainable innovation. Inconsistent standards across countries or regions further complicate technology deployment in multinational operations, creating uncertainty around compliance and market viability (OECD, 2018).

Finally, knowledge diffusion and collaboration bottlenecks hinder progress. While academic research in green chemistry and low-carbon technologies is advancing, there is often a disconnect between research institutions and industrial practitioners. Technology transfer remains limited due to intellectual property concerns, lack of public-private partnerships, and insufficient funding for applied research and demonstration projects (Bozeman et al., 2015).

3.3.2 Financial and Economic Constraints

One of the foremost challenges is the high upfront capital investment required for sustainable infrastructure and technologies. Retrofitting existing facilities, installing emissions control equipment, switching to renewable energy sources, or adopting circular production systems often involves substantial costs. These investments may not yield immediate financial returns, making them less attractive to firms focused on short-term profitability or under pressure from shareholders to deliver quarterly gains (Bocken et al., 2014).

Additionally, uncertainty regarding the return on investment (ROI) poses a major obstacle. While sustainable practices can offer long-term savings and competitive advantages, quantifying these benefits is not always straightforward. Variables such as volatile energy prices, fluctuating raw material costs, evolving environmental regulations, and unpredictable consumer demand can complicate the financial forecasting of green investments (Kiron et al., 2017). This uncertainty discourages smaller firms and even risk-averse multinationals from committing to large-scale transformation initiatives.

The issue of access to finance is particularly acute for small and medium-sized enterprises (SMEs) in the chemical sector. SMEs often lack the financial resources, credit access, and administrative capacity to apply for green loans, grants, or sustainability-linked bonds. Moreover, traditional financing institutions may be reluctant to support unproven or capital-intensive sustainability projects, especially in regions with underdeveloped green finance markets (UNEP FI, 2020).

Economic constraints are further compounded by market competitiveness and cost pressures. In global markets where chemical products are commoditized and price-sensitive, companies may be hesitant to increase production costs through sustainability investments, especially if customers are not willing to pay a premium for greener products. Without market-based incentives or consumer demand for sustainable alternatives, the business case for costly environmental upgrades may appear weak, particularly in highly competitive export-oriented industries (Porter & Kramer, 2011).

Government subsidies and regulatory incentives can help alleviate financial burdens, but in many regions these are either insufficient, inconsistently applied, or geared toward specific technologies rather than systemic change. Furthermore, carbon pricing mechanisms, while effective in theory, often remain too low or fragmented globally to meaningfully shift investment decisions in the chemical industry (OECD, 2022). Without a predictable and robust policy environment, companies are less likely to invest in long-term sustainable solutions.

Lastly, many firms suffer from internal budgeting and accounting limitations that prevent them from accurately evaluating the full value of sustainability. Traditional financial metrics such as payback period or net present value often fail to capture the strategic, reputational, and risk-mitigation benefits of sustainable investments (Epstein & Buhovac, 2014). As a result, sustainability projects are often deprioritized in favor of initiatives with more tangible or short-term financial returns.

3.3.3 Resistance to Change and Organizational Barriers

One of the most pervasive organizational barriers is institutional inertia, or the tendency of organizations to maintain existing routines and resist deviation from established practices. The chemical industry is characterized by long-standing operational processes, hierarchical management structures, and a deep reliance on efficiency-driven production systems. These characteristics often discourage experimentation and innovation, especially when the perceived risks of change—financial, operational, or reputational—are high (Lozano, 2013).

Cultural resistance also plays a critical role in shaping the organizational response to sustainability. In many firms, especially those focused on traditional manufacturing, there is a lack of awareness or belief in the strategic value of sustainability. If sustainability is framed merely as a compliance obligation or public relations effort rather than a value-generating activity, employees may be less likely to engage or support it (Sroufe, 2017).

Another challenge is the lack of leadership commitment and vision. Organizational transformation toward sustainability requires strong leadership that can articulate a clear strategy, allocate resources, and foster a culture of innovation and accountability. In many cases, top management may endorse sustainability rhetorically but fail to back it with concrete policies, performance incentives, or organizational restructuring. This "decoupling" between policy and practice undermines credibility and weakens internal momentum (Baumgartner, 2014).

Siloed organizational structures also hinder the integration of sustainability across departments. In many chemical firms, environmental performance is confined to health, safety, and environment (HSE) departments, rather than being embedded into core functions such as R&D, procurement, marketing, or finance. This isolation prevents sustainability considerations from influencing product design, investment decisions, or supplier relationships, limiting their overall effectiveness (Engert et al., 2016).

Limited employee engagement and training further obstruct progress. Sustainability often requires new technical knowledge, data management capabilities, and process optimization skills. However, many firms fail to invest in training programs or continuous learning platforms to equip staff with the necessary competencies. As a result, even well-intentioned initiatives may falter due to implementation gaps or operational resistance from underprepared personnel (Daily et al., 2007).

Finally, the absence of robust monitoring and performance evaluation systems can stall progress. Without measurable targets, feedback loops, and reporting mechanisms, it is difficult to track sustainability performance, reward achievements, or identify areas for improvement. Many organizations lack integrated sustainability metrics or fail to link them to broader business KPIs, which reduces internal accountability and weakens the case for continuous improvement (Epstein & Buhovac, 2014).

3.3.4 Market and Consumer Demand for Sustainability

Market and consumer demand are powerful external forces shaping the pace and direction of sustainability transitions in the chemical industry. As environmental and social awareness grows among stakeholders—ranging from end-users and business customers to investors and regulators—there is mounting pressure on chemical companies to adopt more sustainable practices, offer eco-friendly products, and demonstrate transparent value chains. However, the complex nature of chemical supply chains and limited consumer visibility into chemical inputs present both opportunities and challenges in responding to this evolving demand landscape.

In recent years, B2B customers—including sectors such as automotive, construction, electronics, and packaging—have begun to integrate sustainability criteria into their procurement decisions. These downstream industries face growing pressure from regulators and end-users to reduce their environmental footprint, and as a result, they increasingly seek chemical inputs with lower carbon intensity, reduced toxicity, and improved recyclability (UNEP, 2019). This shift creates demand for green chemicals, bio-based materials, and closed-loop solutions, thereby incentivizing chemical manufacturers to innovate and differentiate through sustainability.

However, in B2C markets, where consumers directly interact with chemical-derived products such as detergents, cosmetics, or packaging, demand for sustainability is more variable. Studies show that while consumers express a strong preference for environmentally friendly products, this sentiment often fails to translate into consistent purchasing behavior—a phenomenon known as the "value-action gap" (Young et al., 2010). Price sensitivity, lack of information, and perceived product performance issues can weaken consumer commitment, especially in markets where green alternatives carry a cost premium.

Despite this inconsistency, consumer expectations are rising, particularly among younger demographics and in high-income markets. Consumers increasingly expect companies to demonstrate environmental responsibility, social fairness, and transparency across the product life cycle. This trend is further amplified by eco-labeling schemes, sustainability ratings, and third-party certifications (e.g., Ecolabel, USDA BioPreferred), which influence purchasing decisions and brand loyalty (Grankvist et al., 2004).

The role of investors and financial markets is also transforming market demand. ESG (Environmental, Social, and Governance) considerations have become central to investment strategies, with a growing number of asset managers evaluating chemical firms based on their climate policies, resource efficiency, and supply chain ethics. Companies that underperform on sustainability metrics may face reduced access to capital, shareholder activism, or divestment. Conversely, firms that align with ESG criteria can benefit from green bonds, sustainability-linked loans, and favorable risk assessments (Kotsantonis & Serafeim, 2019).

Still, market mechanisms alone are not sufficient to drive systemic transformation in the chemical sector. Many sustainable products continue to struggle with limited scalability and market uptake, particularly in cost-sensitive applications. Without regulatory mandates or pricing mechanisms that reflect environmental externalities (e.g., carbon taxes or extended producer responsibility schemes), market signals may remain too weak to shift industry behavior at scale (OECD, 2022).

To overcome these limitations, collaborative initiatives and customer education are gaining traction. Partnerships across value chains, including joint ventures between chemical firms and their clients, are being used to co-develop sustainable products that meet specific performance and environmental criteria. Meanwhile, educational campaigns, product labeling, and digital transparency tools are helping to close the information gap and empower consumers to make informed choices (Hazen et al., 2020).

3.4 Previous Research on Sustainable Practices in the Chemical Industry

The chemical industry has been a focal point for sustainability research, given its significant environmental footprint and central role in various value chains. Key areas of study include green chemistry adoption, circular economy implementation, corporate sustainability strategies, performance measurement, and barriers to sustainability adoption.

Green chemistry emphasizes designing chemical products and processes that reduce or eliminate hazardous substances. Anastas and Warner (2000) laid the foundation with the 12 principles of green chemistry. In the pharmaceutical sector, Tucker and Faul (2016) highlighted how adopting green chemistry practices led to cost savings and reduced environmental impact during drug development. Similarly, a study by Sheldon (2017) discussed the importance of metrics like the E-factor in evaluating the efficiency of chemical processes, noting that pharmaceutical industries often have higher E-factors, indicating greater waste generation per unit of product. This underscores the need for adopting greener synthesis routes to minimize waste and improve process efficiency.

The circular economy aims to minimize waste and make the most of resources. Genovese et al. (2017) evaluated the circular economy performance of global chemical companies from 2013 to 2022, focusing on production efficiency and circular material flows. The study found that while some companies have made significant strides, overall progress remains uneven, with challenges in scaling up circular practices.

Integrating sustainability into corporate strategy has shown positive outcomes. Engert and Baumgartner (2016) analyzed how firms embed sustainability into strategic planning and performance measurement. Their findings suggest that companies with well-integrated sustainability governance structures tend to perform better on both environmental and economic metrics. Moreover, a study by McKinsey & Company (2022) indicated that chemical companies with higher exposure to end markets aligned with sustainability trends achieved enterprise-value-to-revenue valuations approximately four times higher than those focused on traditional markets.

Effective measurement and reporting are essential for tracking sustainability progress. Epstein and Buhovac (2014) emphasized the need for robust monitoring systems that link sustainability metrics to broader business KPIs. This alignment facilitates internal accountability and continuous improvement. Additionally, the adoption of environmental management systems, such as ISO 14001, has been associated with improved environmental performance in chemical companies.

Finally, a study by the Green Chemistry & Commerce Council (2015) highlighted that the existing infrastructure of the established chemical industry is so efficient that it is hard for new entrants, green or not, to compete with the established supply chain, creating a significant barrier to the adoption of green chemistry practices.

4. Methodology

4.1 Research Design

This study employs a quantitative research design with a descriptive and correlational approach, aiming to examine the adoption and perception of sustainable practices within the chemical industry. The choice of a quantitative methodology is appropriate given the structured nature of the research objectives, which seek to measure, compare, and interpret sustainability-related behaviors and attitudes among employees in the sector.

The study is non-experimental, relying on self-reported data from participants rather than manipulated variables or interventions. The data were analyzed to identify patterns, associations, and potential predictors of sustainability engagement across various demographic and organizational variables, such as company size, job role, and years of experience.

This design ensures both internal consistency and external relevance, allowing the results to be interpreted within the context of the broader sustainability discourse in industrial sectors, while also providing practical implications for chemical companies seeking to enhance their sustainability performance.

4.2 Data Collection Method

For the purposes of this research, data were collected using a structured questionnaire, which is one of the most widely used tools in quantitative research due to its ability to gather standardized information from a large number of participants efficiently and consistently (Creswell, 2014). The use of a questionnaire was particularly appropriate for this study, as it allowed for the systematic collection of data from employees across different companies in the chemical industry, while also enabling comparisons between responses and the application of statistical analysis.

The questionnaire was self-designed by the researcher and structured according to the research objectives and questions of the study. Its content was informed by an extensive review of existing literature on sustainability in the chemical industry and related concepts, such as green chemistry (Anastas & Warner, 1998), sustainable supply chains (Genovese et al., 2017), corporate environmental performance (Epstein & Buhovac, 2014), and barriers to sustainable practice implementation (Wang & Wang, 2021). Drawing from these sources ensured that the questionnaire was both conceptually grounded and relevant to current industry trends and concerns.

The final version of the questionnaire consisted of 21 closed-ended questions, grouped into five thematic sections:

- Demographic and Professional Profile: Questions about gender, age, educational background, years of professional experience, and current job position in the company.
- Environmental Practices and Compliance: Items exploring the company's adherence to environmental regulations, waste management practices, emissions reduction strategies, and pollution control.
- Economic Aspects and Resource Efficiency: Questions assessing the perceived cost-benefit of sustainability initiatives, energy use, raw material efficiency, and long-term economic viability.
- Technological and Organizational Innovation: Questions related to the use of green technologies, process improvements, digital monitoring systems, and internal sustainability policies.
- Perceived Barriers and Opportunities: This section captured participants' views on challenges such as financial limitations, regulatory uncertainty, technological gaps, and resistance to change, as well as potential incentives for enhancing sustainable practices.

All questions were closed-ended, utilizing a mix of Likert-scale items (e.g., from 1 = Strongly Disagree to 5 = Strongly Agree), multiple choice, and single-response options, which facilitated ease of response and quantitative analysis. The questionnaire was reviewed by two academic experts for content validity and clarity before distribution.

The use of a closed-ended questionnaire provided several benefits: it allowed for clear and consistent measurement across all respondents, minimized ambiguity in interpretation, and supported the application of statistical tools to explore relationships and trends within the data (Bryman, 2016).

4.3 Sampling

The sampling strategy employed in this study was non-probability purposive sampling, which is appropriate for research that aims to gather insights from a specific target population with relevant experience or knowledge (Etikan, Musa, & Alkassim, 2016). The focus of this research was on professionals working in various companies within the chemical sector in Greece, making it essential to select participants who are directly involved in or aware of sustainability practices within their organizations.

The inclusion criteria were defined as follows: participants had to (a) be employed in a company operating in the chemical industry, (b) hold a position that allows them to observe or engage with sustainability-related decisions, and (c) be willing to voluntarily complete the questionnaire. No restrictions were placed on age, gender, or job title, provided the participant met the above conditions.

The final sample consisted of 87 respondents, representing a range of roles, organizational levels, and company types within the chemical sector, including manufacturing, processing, R&D, and quality control functions. The sample size was determined by the availability and willingness of participants during the data collection period. While not statistically representative of the entire Greek chemical industry, the sample provides sufficient diversity for exploratory analysis and allows for initial conclusions to be drawn regarding sustainability perceptions and practices in the sector.

Given the absence of a publicly accessible and comprehensive registry of all chemical sector employees in Greece, random sampling was not feasible. Therefore, purposive sampling ensured that only informed and context-relevant responses were collected. This method also allowed the researcher to concentrate on acquiring quality responses rather than a larger but potentially less relevant dataset.

4.4 Procedure and Ethical Considerations

The data collection procedure followed a clear and ethically responsible approach to ensure the reliability of the results and the protection of participants' rights. Before initiating the distribution of the questionnaire, the research design and tool were reviewed by academic supervisors to ensure methodological coherence and alignment with ethical research standards. In compliance with the General Data Protection Regulation (GDPR), no personal information was collected that could directly or indirectly identify any natural person. All responses were anonymized and stored securely to protect participant confidentiality.

The questionnaire was administered electronically, via Google Forms, primarily through email and professional networks, targeting individuals working in various Greek chemical companies. The online format was selected for its cost-effectiveness, wide reach, and convenience for participants, especially given the time constraints and dispersed geographical locations of potential respondents.

Participants were first provided with an informed consent statement at the beginning of the questionnaire. This statement clearly explained the purpose of the study, the voluntary nature of participation, the estimated time required to complete the questionnaire (approximately 10–12 minutes), and the anonymous treatment of all responses. Participants were explicitly informed that they could exit the questionnaire at any point without any negative consequences, and no personally identifiable information was collected.

To ensure ethical compliance, the following principles were strictly observed:

- Voluntary participation: Respondents were not coerced in any way. Only those who willingly chose to participate completed the questionnaire.
- Anonymity and confidentiality: All responses were anonymized and treated with strict confidentiality. No identifying data were collected, stored, or analyzed.
- Non-maleficence: The questions were designed to avoid discomfort or harm. None of the items touched on sensitive personal or financial data.
- Data security: The electronic data collected were stored securely on a password-protected device accessible only to the researcher and academic supervisors.

No incentives were provided for participation to avoid influencing responses. Upon completion of the questionnaire period, the responses were compiled and transferred to a statistical analysis software tool for processing. Only aggregated data were used in the analysis to maintain participant anonymity.

4.5 Statistical Analysis

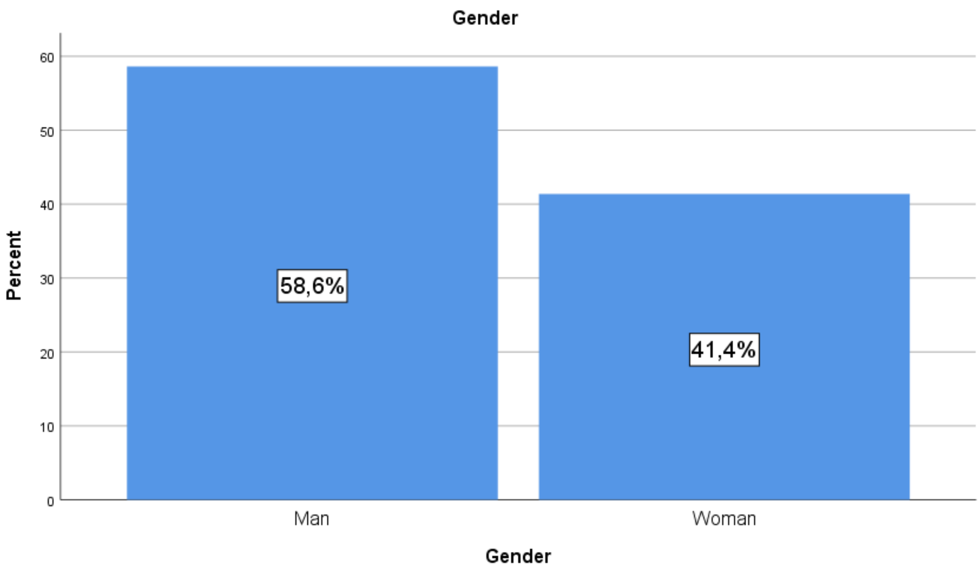
The data collected through the questionnaire were subjected to quantitative statistical analysis using the software package IBM SPSS Statistics (version 25). The choice of statistical methods was guided by the study's objectives, which included identifying general trends in sustainable practices, assessing relationships between variables, and drawing comparisons between participant groups. Initially, descriptive statistics were applied to summarize the basic characteristics of the sample and to provide an overview of participant responses. This stage of analysis enabled a clear depiction of the current state of sustainability awareness and implementation within chemical companies in Greece, as perceived by employees. Following the descriptive analysis, inferential statistical methods were used to test relationships and differences between variables. More precisely, chi-square tests were used. A significance level of $p < 0.05$ was adopted for all hypothesis testing.

5. Results and Discussion

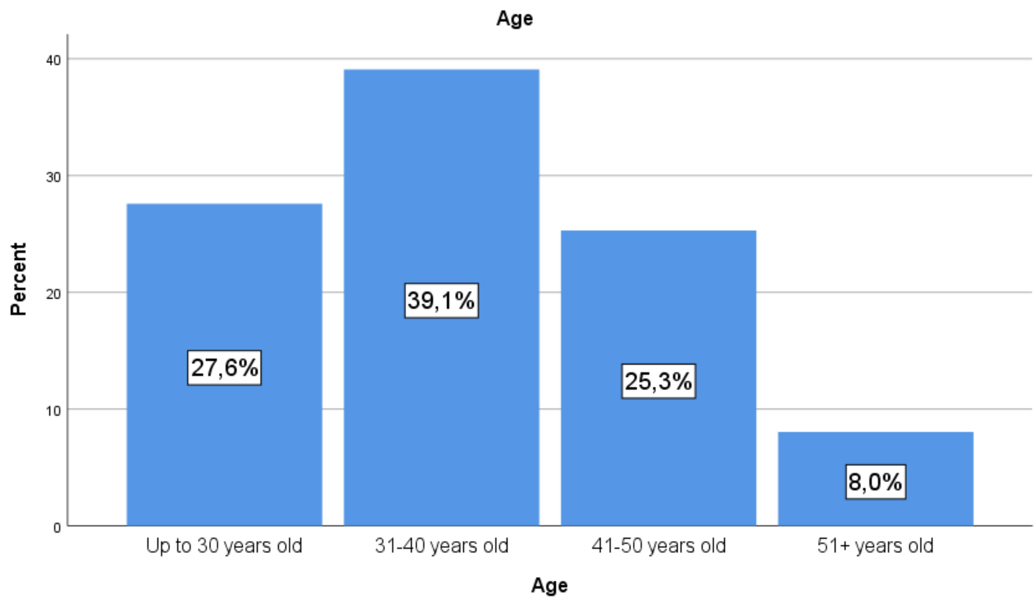
5.1 Results

5.1.1 Descriptive Statistics

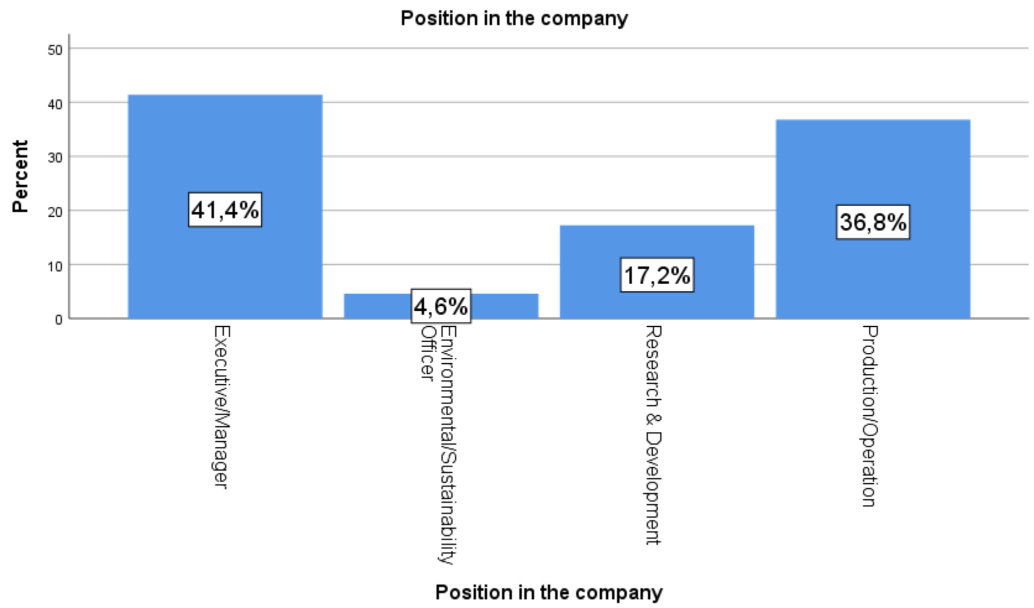
Regarding gender, 58.6% (n = 51) of the participants were men, and 41.4% (n = 36) were women (Graph 1). As for the age distribution, 27.6% (n = 24) of respondents were up to 30 years old, 39.1% (n = 34) were between 31 and 40 years old, 25.3% (n = 22) were between 41 and 50 years old, and 8.0% (n = 7) were over 51 years old (Graph 2). With respect to their position within the company, 41.4% (n = 36) were executives or managers, 4.6% (n = 4) were environmental or sustainability officers, 17.2% (n = 15) worked in research and development, and 36.8% (n = 32) were employed in production or operational roles (Graph 3). Concerning work experience in the chemical industry, 44.8% (n = 39) had less than 5 years of experience, 32.2% (n = 28) had 5 to 10 years of experience, 14.9% (n = 13) had worked for 11 to 20 years, and 8.0% (n = 7) had more than 20 years of experience (Graph 4).



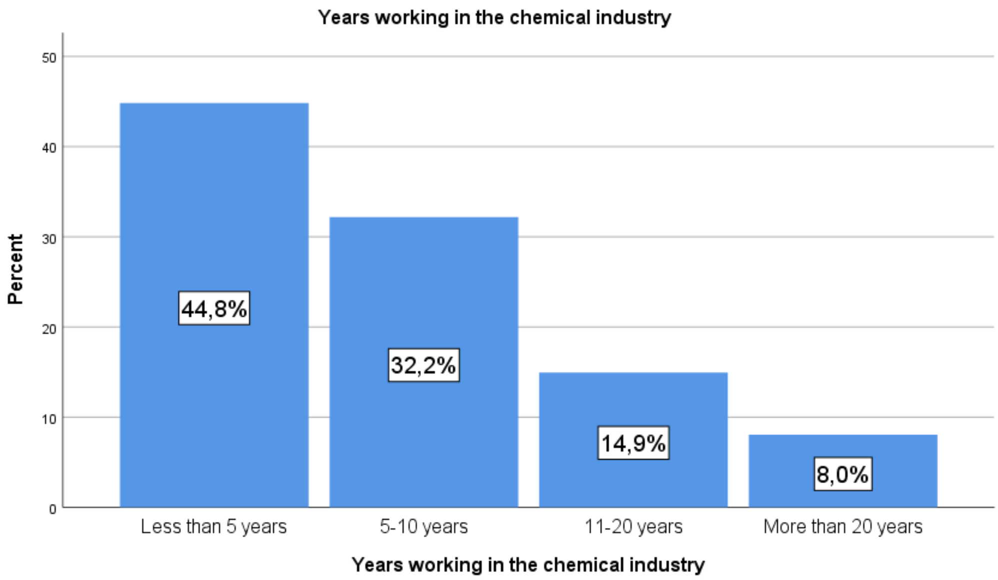
Graph 1. Gender



Graph 2. Age

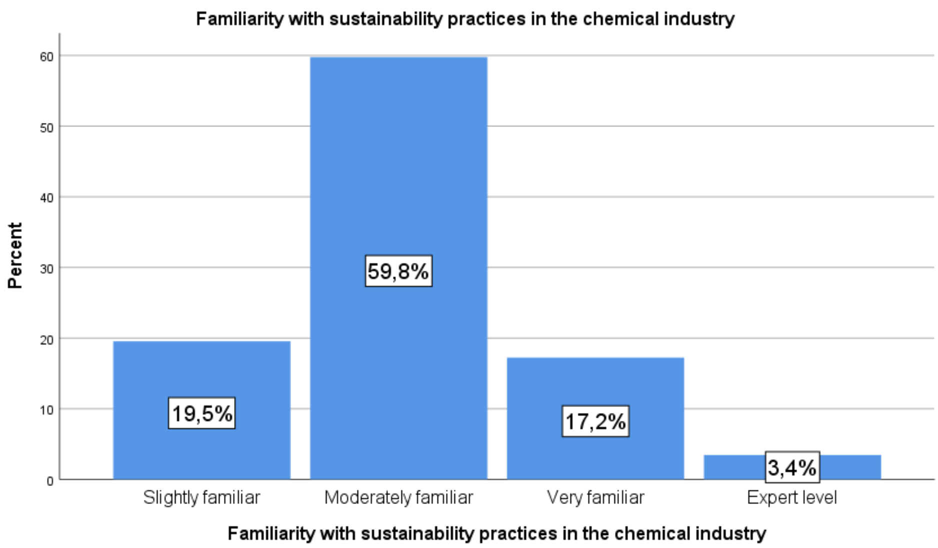


Graph 3. Position in the company



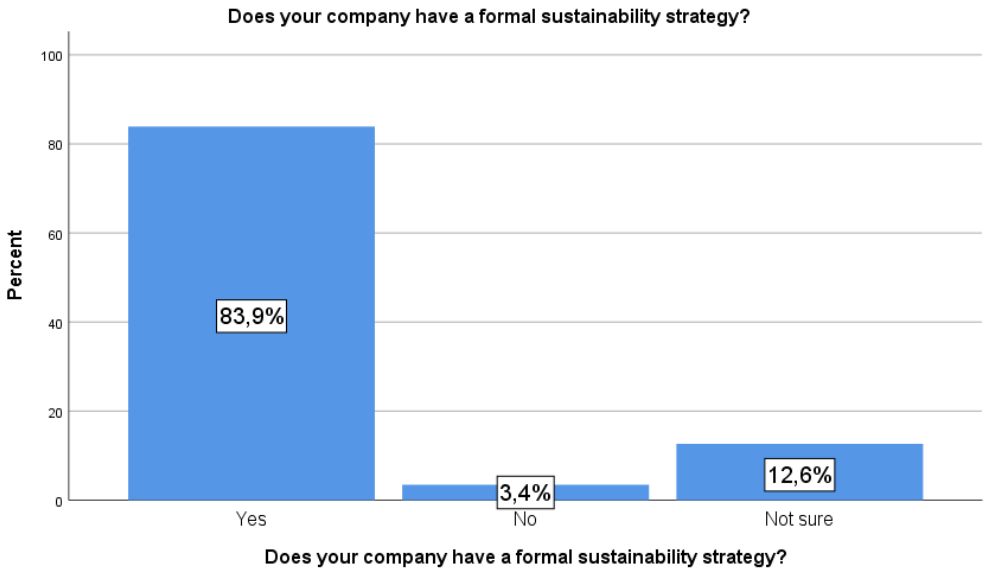
Graph 4. Years working in the chemical industry

In terms of familiarity with sustainability practices in the chemical industry, 19.5% (n = 17) of respondents reported being slightly familiar, 59.8% (n = 52) moderately familiar, 17.2% (n = 15) very familiar, and 3.4% (n = 3) identified as having expert-level familiarity (Graph 5).



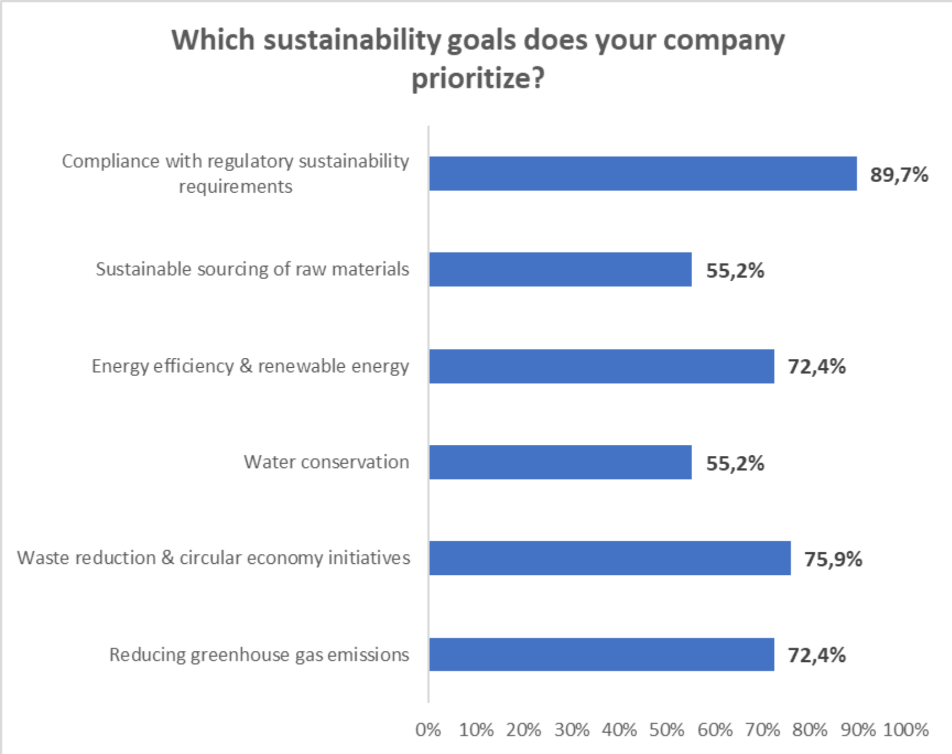
Graph 5. Familiarity with sustainability in the chemical industry

Finally, when asked whether their company has a formal sustainability strategy, 83.9% (n = 73) responded "Yes", 3.4% (n = 3) answered "No", and 12.6% (n = 11) reported that they were not sure (Graph 6).



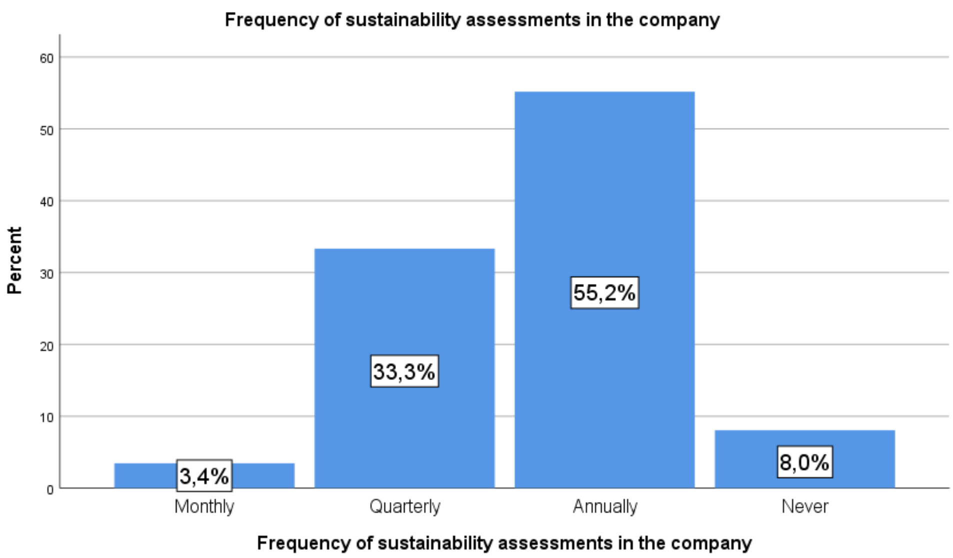
Graph 6. Former sustainability strategy

Regarding the sustainability goals prioritized by the companies, the most frequently reported focus was on compliance with regulatory sustainability requirements, with 89.7% (n = 78) of participants stating their company actively prioritizes this. This was followed by waste reduction and circular economy initiatives at 75.9% (n = 66), and reducing greenhouse gas emissions and energy efficiency and renewable energy, both at 72.4% (n = 63). Water conservation and sustainable sourcing of raw materials were each cited by 55.2% (n = 48) of respondents (Graph 7).



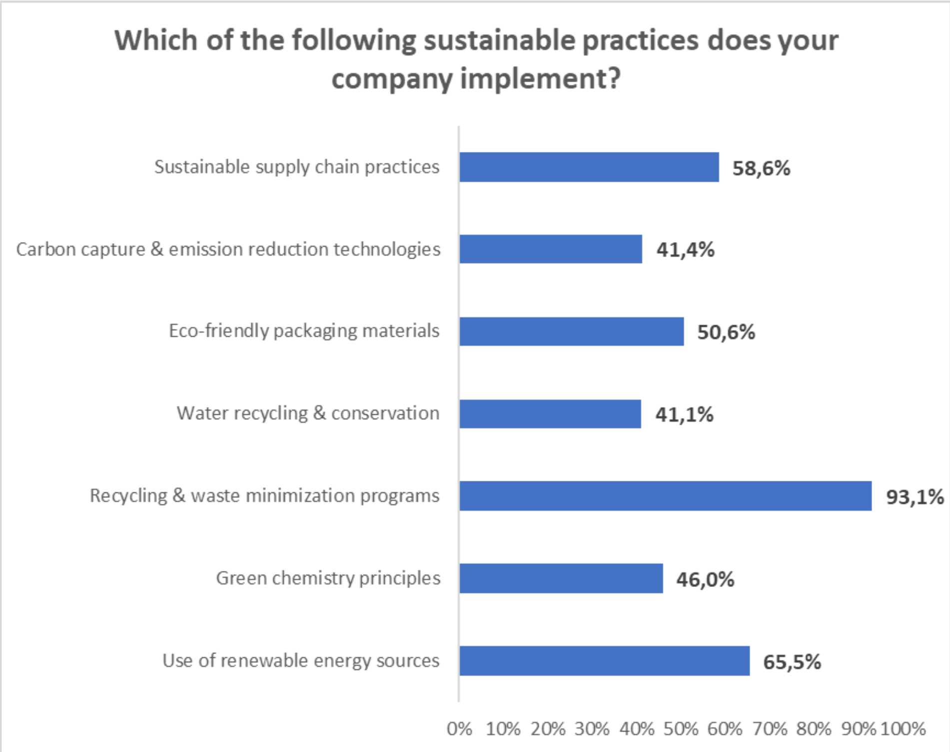
Graph 7. Sustainability goals

When asked about the frequency of sustainability assessments conducted in their companies, 55.2% (n = 48) reported that assessments occur annually, 33.3% (n = 29) said quarterly, 8.0% (n = 7) indicated never, and only 3.4% (n = 3) said monthly (Graph 8).



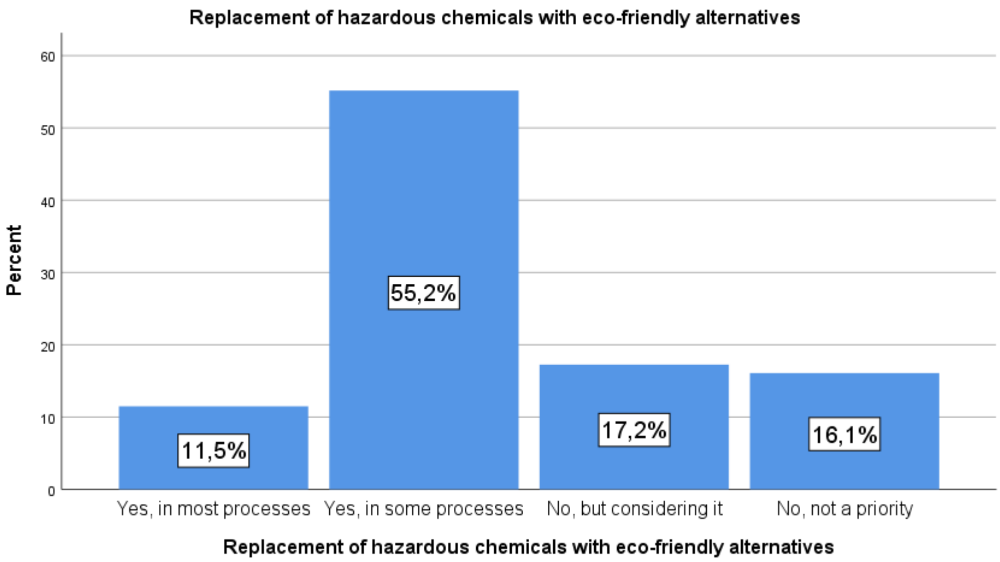
Graph 8. Frequency of sustainability assessments in the company

As for the sustainable practices currently implemented by companies, the most commonly reported practice was recycling and waste minimization programs, implemented by 93.1% (n = 81) of respondents' organizations. This was followed by the use of renewable energy sources, cited by 65.5% (n = 57), and sustainable supply chain practices, reported by 58.6% (n = 51). Other practices included eco-friendly packaging materials (50.6%, n = 44), green chemistry principles (46.0%, n = 40), carbon capture and emission reduction technologies (41.4%, n = 36), and water recycling and conservation (41.4%, n = 36) (Graph 9).



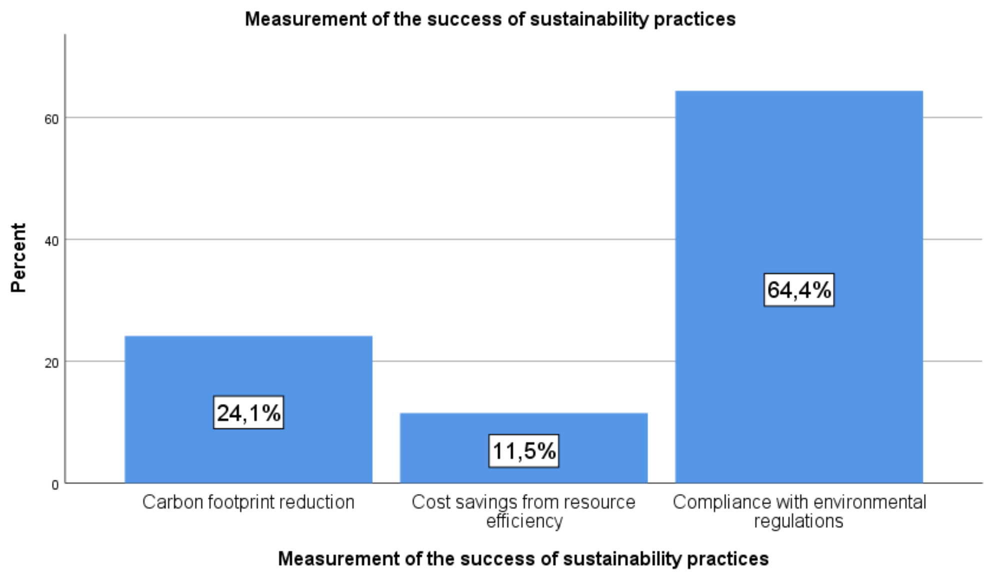
Graph 9. Sustainable practices

Regarding the replacement of hazardous chemicals with eco-friendly alternatives, 11.5% (n = 10) reported that their company has done so in most processes, 55.2% (n = 48) stated it has been done in some processes, 17.2% (n = 15) said this was under consideration, while 16.1% (n = 14) noted it was not a priority (Graph 10).



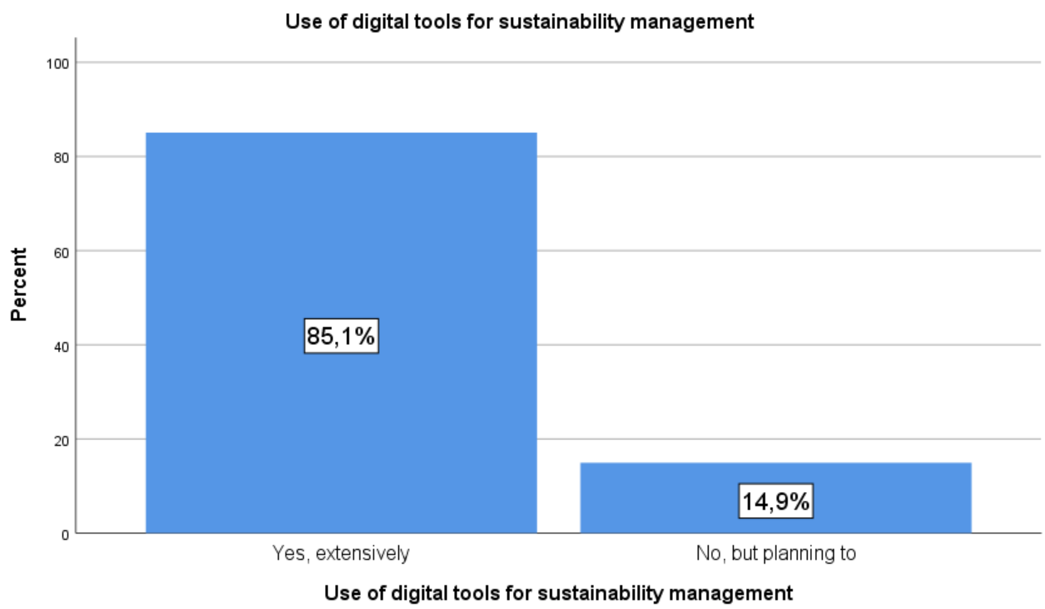
Graph 10. Replacement of hazardous chemicals with eco-friendly alternatives

With regard to how sustainability success is evaluated within companies, the majority of respondents (64.4%, n = 56) indicated that compliance with environmental regulations serves as the primary metric. A smaller proportion of participants noted other indicators, with 24.1% (n = 21) reporting that success is measured by reductions in carbon footprint, while 11.5% (n = 10) referred to cost savings derived from resource efficiency (Graph 11).

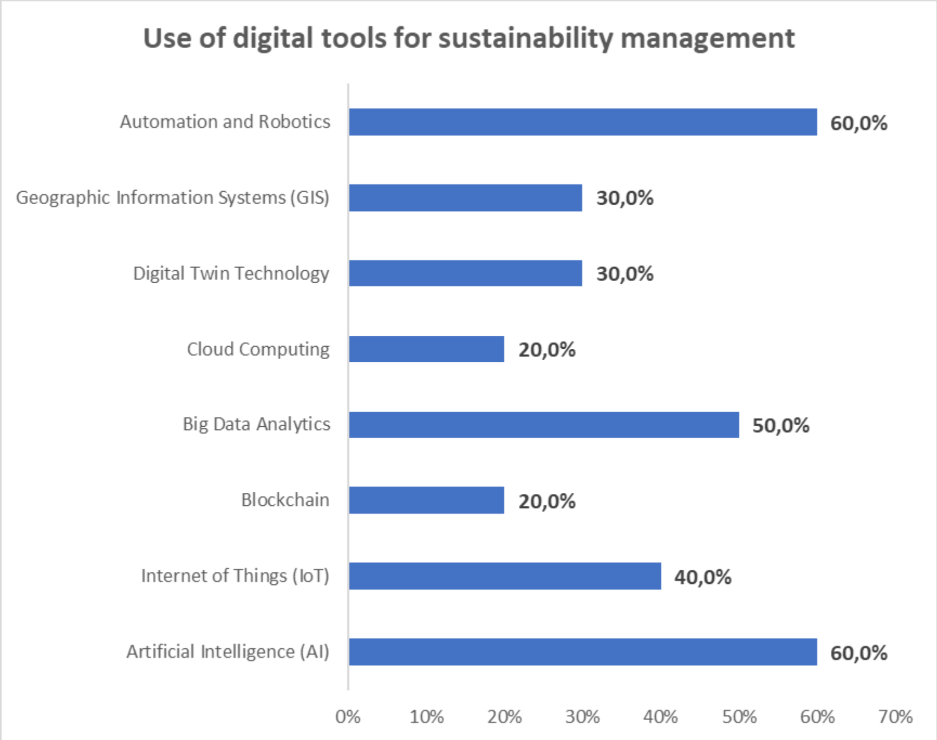


Graph 11. Measurement of the success of sustainability practice

Concerning the use of digital tools in sustainability management, a significant portion of the sample (85.1%, n = 74) confirmed that such tools are actively utilized within their organizations. The remaining 14.9% (n = 13) noted that although digital tools were not currently in use, plans were in place to implement them in the near future (Graph 12). Among the 40 respondents who provided additional information about specific digital tools employed in their companies, the most frequently cited technologies were Artificial Intelligence (AI) and Automation and Robotics, each mentioned by 60.0% (n = 24) of participants. Big Data Analytics was used by 50.0% (n = 20), while 40.0% (n = 16) reported using Internet of Things (IoT) systems. Digital Twin Technology and Geographic Information Systems (GIS) were each used by 30.0% (n = 12), and 20.0% (n = 8) of respondents stated that Blockchain and Cloud Computing technologies were part of their companies' sustainability infrastructure (Graph 13).

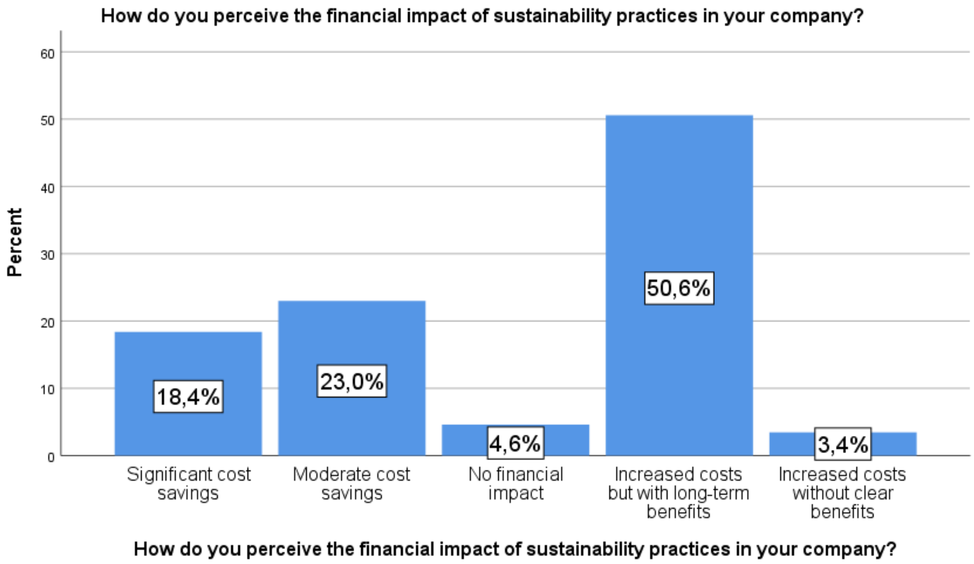


Graph 12. Use of digital tools for sustainability management



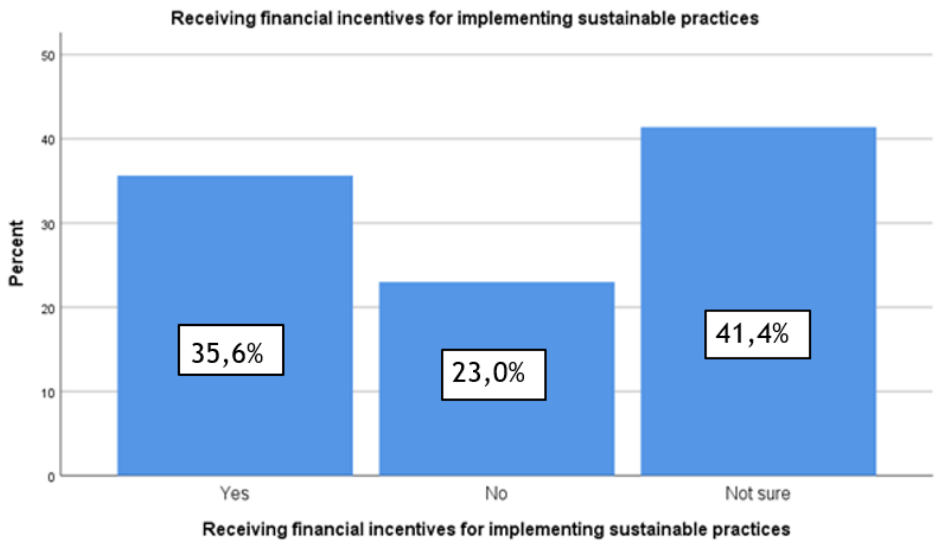
Graph 13. Types of digital tools for sustainability management

As for the perceived financial impact of adopting sustainable practices, 50.6% (n = 44) of respondents believed that while such practices increased costs, they also generated long-term benefits. A further 23.0% (n = 20) experienced moderate cost savings, and 18.4% (n = 16) reported significant financial gains. In contrast, 4.6% (n = 4) indicated that sustainability initiatives had no financial impact, and 3.4% (n = 3) expressed the view that such practices had led to increased costs without delivering clear benefits (Graph 14).



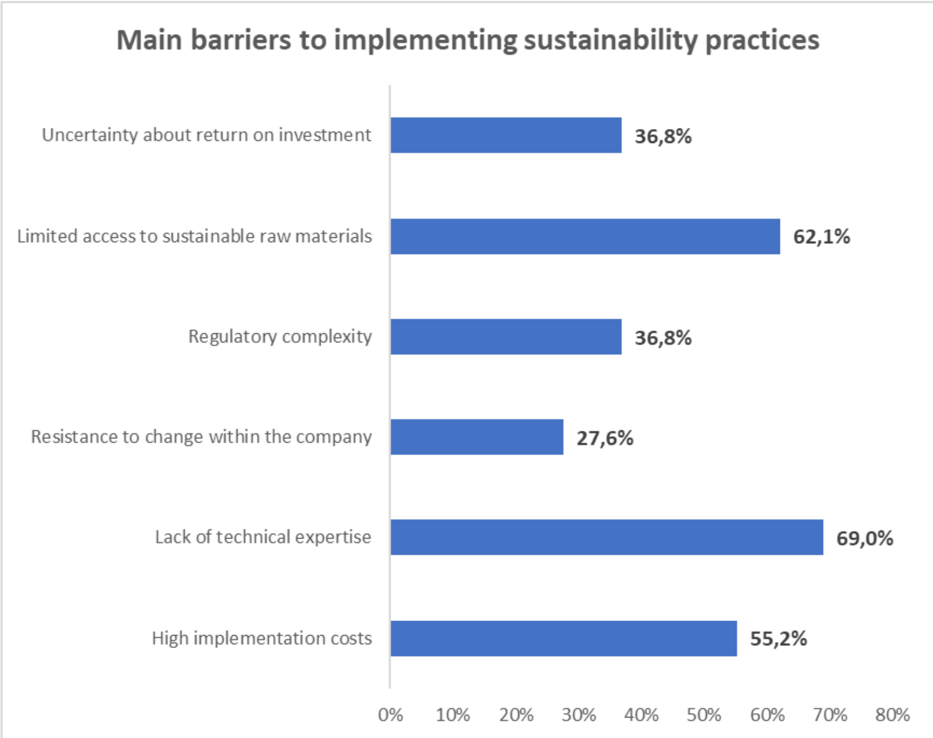
Graph 14. Financial impact of sustainability practices in the company

When asked about financial incentives, 35.6% (n = 31) of participants confirmed that their companies had received incentives for the implementation of sustainable practices. Meanwhile, 23.0% (n = 20) stated that no such incentives were provided, and 41.4% (n = 36) reported being unsure (Graph 15).



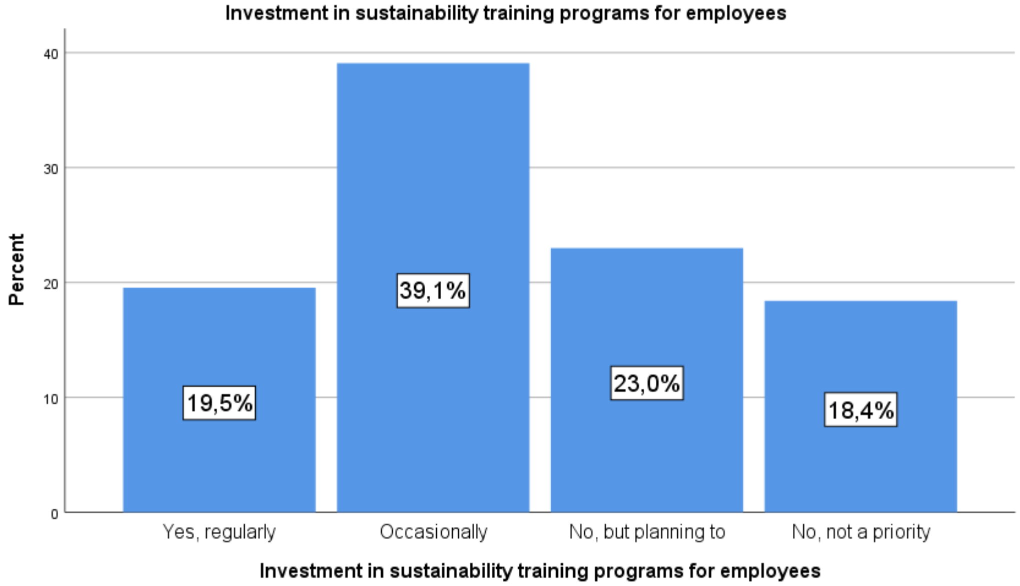
Graph 15. Receiving financial incentive for implementing sustainable practices

Participants were also asked to identify the main barriers their companies face in implementing sustainability strategies. The most frequently cited challenge was a lack of technical expertise, identified by 69.0% (n = 60) of respondents. This was followed by limited access to sustainable raw materials (62.1%, n = 54), high implementation costs (55.2%, n = 48), and regulatory complexity (36.8%, n = 32). An equal percentage of respondents (36.8%, n = 32) pointed to uncertainty regarding the return on investment as a significant barrier, while 27.6% (n = 24) noted internal resistance to change within their organizations as a further limiting factor (Graph 16).



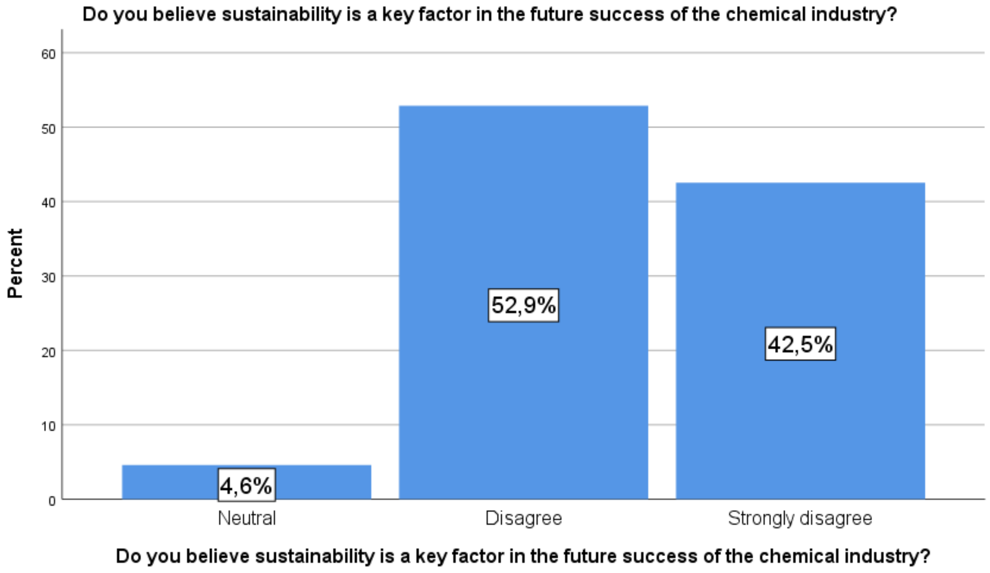
Graph 16. Main barriers to implementing sustainability practices

In relation to employee development, participants were asked whether their company invests in sustainability training programs. A total of 19.5% (n = 17) of respondents stated that their company invests in such programs regularly, while 39.1% (n = 34) reported occasional training efforts. An additional 23.0% (n = 20) indicated that although their company currently does not offer training, there are plans to do so. Meanwhile, 18.4% (n = 16) noted that sustainability training is not considered a priority within their organization (Graph 17).

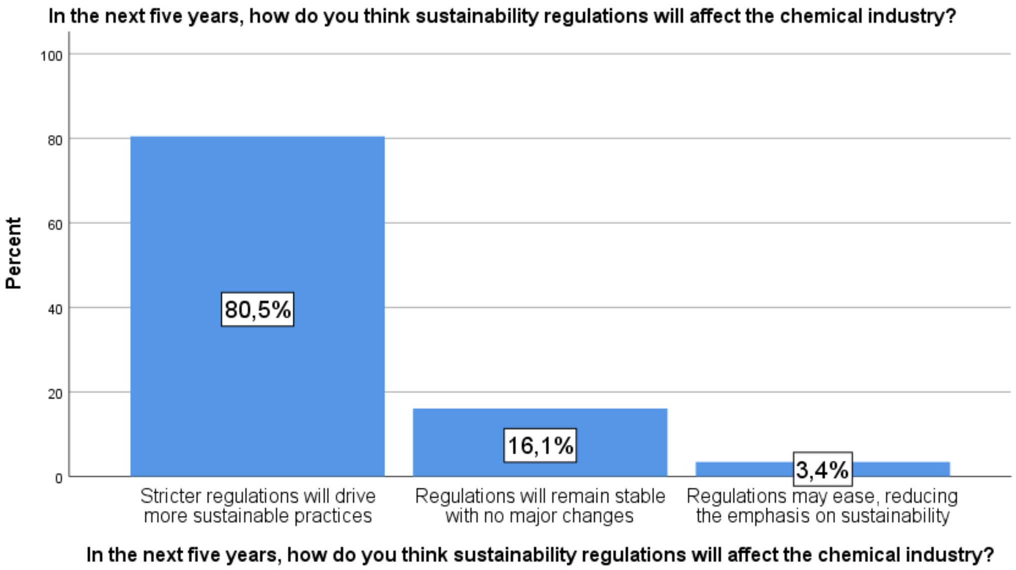


Graph 17. Investment in sustainability training programs for employees

When asked whether they believe sustainability is a key factor in the future success of the chemical industry, a surprising majority expressed skepticism. Specifically, 52.9% (n = 46) of participants disagreed with the statement, and 42.5% (n = 37) strongly disagreed. Only 4.6% (n = 4) maintained a neutral stance. Notably, no respondents expressed agreement or strong agreement, suggesting a prevailing doubt among employees regarding the centrality of sustainability to the industry's future (Graph 18). Participants were also asked to anticipate how sustainability regulations are likely to evolve over the next five years. A strong majority (80.5%, n = 70) predicted that regulations will become stricter and will drive more sustainable practices in the chemical sector. In contrast, 16.1% (n = 14) believed that regulatory conditions will remain stable, while only 3.4% (n = 3) foresaw a relaxation of regulations (Graph 19).

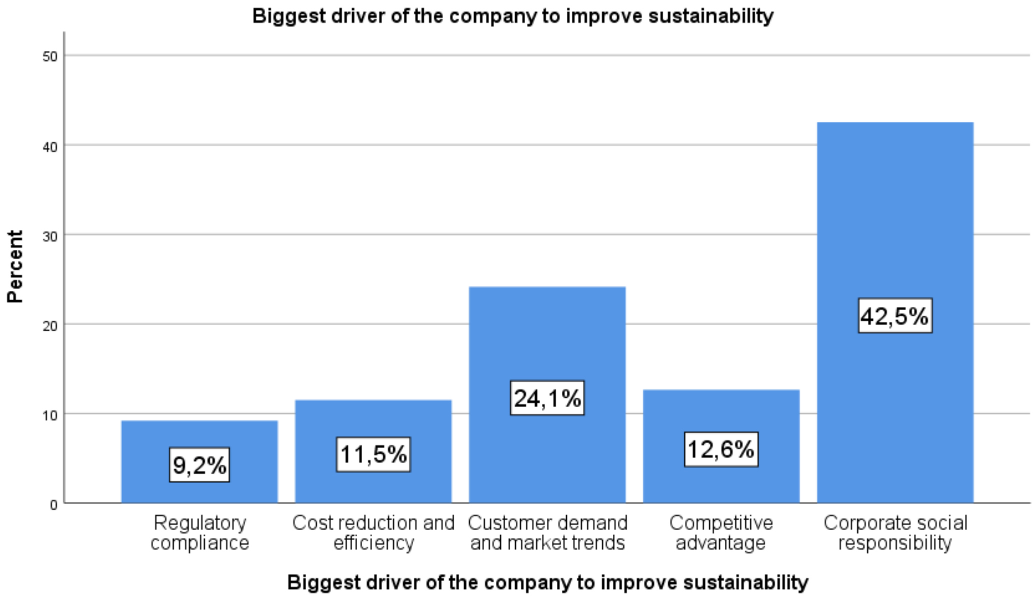


Graph 18. Sustainability as a key factor in the future success of the chemical industry



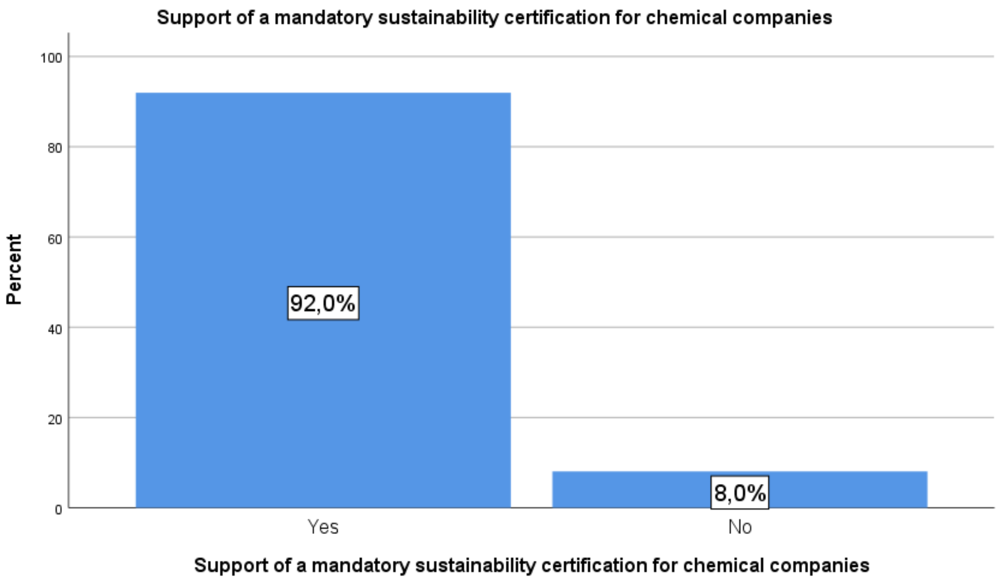
Graph 19. Future of sustainability regulations

In terms of the primary motivations driving their companies to improve sustainability, 42.5% (n = 37) identified corporate social responsibility (CSR) as the leading driver. This was followed by customer demand and market trends (24.1%, n = 21), competitive advantage (12.6%, n = 11), cost reduction and operational efficiency (11.5%, n = 10), and compliance with regulations (9.2%, n = 8). These findings suggest that moral and reputational incentives are more influential than purely economic or legal ones in motivating sustainable action (Graph 20).



Graph 20. Biggest driver of the company to improve sustainability

Finally, respondents were asked whether they support the introduction of a mandatory sustainability certification for chemical companies. An overwhelming 92.0% (n = 80) expressed support for such a measure, while only 8.0% (n = 7) opposed it. This strong consensus indicates a general willingness within the industry to embrace formal accountability mechanisms in support of sustainable development (Graph 21).



Graph 21. Mandatory sustainability certification

5.1.2 Inductive Statistics

In order to examine whether demographic characteristics correlated with familiarity with sustainability practices and attitudes towards future perspectives and industry trends within chemical sector, chi-square tests were performed, as all the variables were qualitative. The results indicated that gender did not correlate significantly with familiarity with sustainability practices in the chemical industry (p = .083), belief in sustainability as a key factor for the future success of the chemical industry (p = .167), expectations regarding future regulatory changes (p = .280), or support for a mandatory sustainability certification for chemical companies (p = .311). Similarly, age was not significantly associated with familiarity with sustainability practices (p = .164), perceived importance of sustainability for the industry's future (p = .069), expectations about regulatory evolution (p = .091), or support for mandatory certification (p = .074). The position in the company also showed no statistically significant relationship with familiarity with sustainability practices (p = .098), belief in sustainability's future relevance (p = .815), perceived impact of upcoming regulations (p = .397), or support for certification (p = .471). Lastly, years of experience in the chemical industry did not correlate significantly with any of the examined sustainability-related variables: familiarity with sustainability practices (p = .166), perception of sustainability as a success factor (p = .285), anticipated regulatory change (p = .246), or support for certification (p = .457). These results suggest that demographic characteristics do not significantly influence respondents' attitudes or expectations regarding sustainability in the chemical sector.

Table 1. Chi-square tests between demographic characteristics and attitudes or expectations regarding sustainability in the chemical sector

	Gender	Age	Position in the company	Years working in the chemical industry
	p-value			
Familiarity with sustainability practices in the chemical industry	,083	,164	,098	,166
Do you believe sustainability is a key factor in the future success of the chemical industry?	,167	,069	,815	,285
In the next five years, how do you think sustainability regulations will affect the chemical industry?	,280	,091	,397	,246
Support of a mandatory sustainability certification for chemical companies	,311	,074	,471	,457

Further chi-square analyses were conducted to examine whether participants' perceptions of the financial impact of sustainability practices and the receipt of financial incentives were associated with key organizational actions and practices. The perception of sustainability as a financial factor was not significantly associated with whether the company has a formal sustainability strategy (p = .070), nor with the implementation of specific sustainability practices such as the use of renewable energy sources (p = .115), green chemistry principles (p = .235), recycling and waste minimization programs (p = .724), water recycling and conservation (p = .815), eco-friendly packaging materials (p = .822), carbon capture and emission reduction technologies (p = .146), or sustainable supply chain practices (p = .190). Additionally, no significant relationship was found between perceived financial impact and the replacement of hazardous chemicals with eco-friendly alternatives (p = .160), or the use of digital tools for sustainability management (p = .106). Likewise, the receipt of financial incentives for implementing sustainable practices did not show a statistically significant association with the presence of a formal sustainability strategy (p = .098). Similarly, it was not significantly correlated with the adoption of renewable energy sources (p = .438), green chemistry principles (p = .743), recycling and waste minimization programs (p = .782), water conservation (p = .584), eco-friendly packaging (p = .274), carbon emission reduction technologies (p = .842), or sustainable supply chains (p = .144). Furthermore, financial incentives did not significantly relate to the replacement of hazardous substances with environmentally friendly alternatives (p = .135), or the integration of digital tools for sustainability management (p = .535). Overall, these findings suggest that neither the perceived financial impact of sustainability practices nor the provision of financial incentives is a determining factor in the adoption of specific sustainability initiatives among the surveyed chemical companies.

Table 2. Chi-square tests between perceptions of the financial impact of sustainability practices and receipt of financial incentives and key organizational actions and practices

	How do you perceive the financial impact of sustainability practices in your company?	**Receiving financial incentives for implementing sustainable practices**
	p-value	
Does your company have a formal sustainability strategy?	,070	,098
Use of renewable energy	,115	,438

sources		
Green chemistry principles	,235	,743
Recycling & waste minimization programs	,724	,782
Water recycling & conservation	,815	,584
Eco-friendly packaging materials	,822	,274
Carbon capture & emission reduction technologies	,146	,842
Sustainable supply chain practices	,190	,144
Replacement of hazardous chemicals with eco-friendly alternatives	,160	.135
Use of digital tools for sustainability management	,106	,535

5.2 Discussion

The present study provides an important snapshot of sustainability perceptions, practices, and challenges in the Greek chemical industry. The findings contribute to the growing body of research on how industrial sectors are adapting to environmental, social, and regulatory pressures. Several key themes emerge from the results, which both align with and diverge from existing literature.

A central finding is the widespread adoption of environmental practices among surveyed companies. High rates of implementation were reported for waste minimization programs (93.1%), use of renewable energy sources (65.5%), and sustainable supply chain initiatives (58.6%). These results mirror the global trend toward greener industrial operations as emphasized by Genovese et al. (2017), who argue that transitioning to circular models is becoming increasingly mainstream in sectors with high environmental footprints. Moreover, the application of renewable technologies and recycling initiatives is in line with the green chemistry principles proposed by Anastas and Warner (1998), underscoring the role of process redesign and materials substitution in mitigating environmental harm.

Despite this reported implementation, the most paradoxical and concerning finding was that the overwhelming majority of participants—over 95%—either disagreed or strongly disagreed with the idea that sustainability is a critical success factor for the future of the chemical industry. This sharply contrasts with studies that portray sustainability as a strategic imperative. For example, Epstein and Buhovac (2014) assert that sustainability is not only a risk management tool but also a source of innovation, customer trust, and long-term profitability. Similarly, McKinsey & Company (2022) have highlighted how leading chemical firms are leveraging sustainability to secure investor interest and maintain regulatory compliance. The disconnect between practice and perception evident in the present study could be attributed to several factors: a limited understanding of sustainability's strategic potential, a narrow focus on regulatory compliance over proactive innovation, or a perception that sustainability is externally imposed rather than internally valued.

Another important observation is the absence of statistically significant relationships between demographic variables (gender, age, years of experience, and job position) and sustainability-related attitudes or behaviors. This suggests that sustainability perceptions are not strongly shaped by individual background characteristics, echoing the findings of Wang and Wang (2021), who argue that structural and institutional factors—such as leadership commitment, regulatory pressures, and organizational culture—play a far greater role in sustainability adoption than personal attributes. This could imply that, regardless of demographic diversity, what ultimately determines sustainability progress is how embedded it is in company policy and culture.

The results also cast doubt on the commonly held assumption that financial incentives are key drivers of sustainable behavior. Although 50.6% of respondents acknowledged that sustainability practices incur higher costs, with long-term benefits, no significant associations were found between financial perceptions and the actual adoption of sustainability measures. Similarly, whether or not a company received financial incentives did not correlate with implementation of practices such as green chemistry, digital tools, or emissions reduction. These findings contrast with much of the literature emphasizing cost-benefit rationale in sustainability decisions (Del Río González, 2005; Rennings, 2000), and suggest that compliance with legal requirements and reputational concerns may be more prominent motivators—at least within the Greek context.

This is further supported by the data on motivational factors. Corporate Social Responsibility (CSR) was the most commonly cited driver for sustainability initiatives (42.5%), followed by customer demand and market trends (24.1%). Cost savings and competitive advantage were far less frequently mentioned. These findings support the argument made by Engert and Baumgartner (2016) that CSR often serves as a bridge between regulatory compliance and voluntary action, particularly in industries seeking legitimacy among increasingly eco-conscious stakeholders. However, the limited role of cost and competitiveness in driving sustainability adoption also suggests that many firms have yet to fully realize the potential of sustainability as a value-generating mechanism, rather than simply a compliance or image-enhancing activity.

The study’s findings regarding digitalization reveal a similar contradiction. While a high proportion of participants (85.1%) indicated that digital tools were used for managing sustainability, this did not translate into statistically significant associations with strategic sustainability integration. Jabbour et al. (2020) have noted that many companies deploy digital tools in isolated, operational ways (e.g., emissions monitoring, reporting compliance) without fully integrating them into broader environmental strategies. The findings from this thesis suggest that the Greek chemical industry may be in a transitional phase, where digital solutions are available but not yet harnessed to drive innovation or strategic differentiation in sustainability performance.

Perhaps one of the most encouraging findings is the nearly unanimous support (92.0%) for the implementation of a mandatory sustainability certification system for chemical companies. This consensus highlights a latent demand for standardization, benchmarking, and external validation of sustainability efforts. According to KPMG (2020), companies increasingly view third-party certification as essential for maintaining credibility with regulators, investors, and the public. The Greek chemical sector’s support for certification could reflect a recognition that voluntary efforts alone are insufficient to drive systemic change, and that standardized frameworks are needed to ensure consistency, comparability, and long-term accountability.

Taken together, the results of this study reflect a complex picture. On one hand, there is evidence of widespread implementation of environmental practices and receptiveness to institutional mechanisms such as certification. On the other hand, perceptions of sustainability's strategic relevance remain underdeveloped, and internal motivators appear to be weak compared to external pressures. This combination points to a sustainability landscape that is externally driven and operationally reactive, rather than strategically integrated. If Greek chemical companies are to fully leverage the benefits of sustainable development—whether in terms of market competitiveness, innovation capacity, or environmental stewardship—they must evolve from a compliance mindset toward a proactive, value-oriented approach.

6. Conclusion

6.1 Summary of Key Findings

This study set out to investigate sustainability practices, perceptions, challenges, and motivations within the Greek chemical industry, using empirical data collected through a structured questionnaire distributed to professionals working in various companies across the sector. The findings offer a multi-dimensional view of how sustainability is currently understood and implemented at the organizational level.

This section revisits the research questions posed at the beginning of the thesis and summarizes how each was answered based on the data collected and analyzed. Specifically:

- What is the current level of awareness and organizational commitment to sustainability among professionals in the chemical industry?
  - ➢ The study found moderate awareness of sustainability concepts, with many professionals recognizing its importance, though organizational commitment often remains superficial or compliance-driven rather than strategic.
- Which specific sustainability goals are most commonly prioritized by chemical companies?
  - ➢ The most frequently implemented goals were recycling, reduction of hazardous substances, and energy efficiency, while broader goals such as circular economy adoption and long-term emission targets were less emphasized.
- To what extent are digital tools such as AI, IoT, and Big Data Analytics used to support sustainability initiatives?
  - ➢ Digital tools are in use, but mainly limited to basic applications like monitoring and reporting. Advanced tools like AI and predictive analytics were rarely adopted, particularly among SMEs.
- How do companies perceive the financial impact of adopting sustainable practices?
  - ➢ Perceptions varied; most respondents did not see significant short-term cost savings, and financial incentives were not widely reported. Sustainability was often not viewed as economically beneficial without external support.
- What are the key barriers to implementing sustainability in the chemical industry?

    - The main barriers identified were high implementation costs, lack of expertise, and organizational inertia. These were more prominent in smaller firms with limited resources.
- What do industry professionals perceive as the main drivers for adopting sustainable practices?
    - Corporate social responsibility (CSR) and regulatory compliance were the most cited drivers, whereas innovation and competitive advantage were less commonly viewed as motivators.

More precisely, one of the most notable findings is that many companies in the sample have already adopted a range of sustainability practices. High rates of implementation were reported for recycling and waste minimization programs, the use of renewable energy sources, and sustainable supply chain management. This suggests a growing operational alignment with environmental objectives and demonstrates that sustainability, at least at the practice level, is becoming embedded in daily operations.

Despite this practical engagement, the study revealed a clear disconnect between action and perception. An overwhelming majority of participants expressed skepticism about the strategic importance of sustainability for the future success of the chemical industry. This contradiction indicates that sustainability is often seen as a regulatory or reputational requirement, rather than a source of competitive advantage or long-term value creation.

The research also found no significant correlation between demographic or professional variables—such as gender, age, job role, or years of experience—and familiarity with sustainability, attitudes toward regulation, or support for certification. This suggests that sustainability views are not significantly influenced by personal characteristics, and instead may be shaped more strongly by organizational culture or external factors.

While many participants acknowledged that sustainability initiatives might involve increased short-term costs, financial concerns were not strongly associated with the actual implementation of specific practices. Furthermore, receiving financial incentives did not correlate significantly with greater sustainability adoption. These findings challenge the assumption that financial motivations are the primary drivers of environmental initiatives and suggest that compliance, CSR, and stakeholder expectations may be more influential in the Greek context.

Another key insight is that digital tools are widely used for sustainability management; however, their application does not appear to be strategically integrated. Instead, digitalization may be functioning at a technical or reporting level rather than as a driver of sustainable innovation. Similarly, while many participants identified Corporate Social Responsibility (CSR) and customer demand as the main motivators for sustainability efforts, factors like competitive advantage and operational efficiency were far less emphasized.

Finally, the overwhelming support among respondents for a mandatory sustainability certification system indicates a general openness to structured accountability and standardized performance measurement in the sector. This suggests that many professionals recognize the need for clearer benchmarks and formal validation, even if the perceived strategic value of sustainability remains underdeveloped.

In summary, the study highlights a sector that is engaging in sustainability on a practical level but still lacks a fully developed strategic or cultural commitment to it. The findings underscore the need for greater awareness, leadership engagement, and alignment between sustainability practices and long-term business planning.

6.2 Limitations of the Study

While the present study offers valuable insights into sustainability practices and perceptions within the Greek chemical industry, it is important to acknowledge several limitations that may affect the generalizability and interpretation of the findings.

First, the sample size of 87 participants, although adequate for exploratory research, limits the statistical power of certain analyses and restricts broader generalization to the entire chemical sector in Greece. Additionally, the use of non-probability purposive sampling means that the sample may not be fully representative of the industry's diversity in terms of company size, geographic distribution, and specific sub-sectors. Participants self-selected into the study, which may have introduced response bias, particularly from those more engaged with or informed about sustainability issues.

In addition, the research did not explore the external stakeholder perspective, such as views from regulators, industry associations, customers, or supply chain partners. Since sustainability is increasingly influenced by external expectations—ranging from environmental regulations to consumer behavior and market trends—excluding these actors presents an incomplete picture of the forces shaping sustainability in the chemical sector.

Another limitation relates to the economic and performance outcomes of sustainability initiatives. The study examined perceived financial impacts but did not assess objective performance indicators, such as cost savings, efficiency gains, or emissions reductions over time. As a result, it is not possible to determine whether the reported practices translate into measurable business or environmental benefits.

Finally, the study did not address company-specific variables, such as firm size, ownership structure (e.g., domestic vs. multinational), or market orientation, which could significantly influence the extent and nature of sustainability adoption. These variables might help explain variations in sustainability commitment and investment but were outside the scope of the present research.

6.3 Contributions to Research and Industry

This study contributes to both academic research and industry practice by offering original empirical data on sustainability in the context of the Greek chemical industry—an area that has been underexplored in the existing literature. Its findings enrich our understanding of how sustainability is perceived and operationalized within a critical industrial sector that is both environmentally intensive and economically significant.

From a research perspective, the study fills an important gap by providing data on a national industrial sector that is typically less visible in global sustainability discourse. While much of the existing literature has focused on large multinational corporations or on regions with mature sustainability infrastructures, this study draws attention to the Greek context, where sustainability practices are still evolving and often shaped by external pressures such as EU regulations or corporate social responsibility frameworks.

Moreover, the research contributes to theoretical discussions about the gap between sustainability practices and sustainability perceptions. The finding that companies actively engage in environmental initiatives yet largely dismiss sustainability as a strategic priority raises important questions about how sustainability is framed, communicated, and internalized within organizations. This distinction between practice and mindset offers a valuable area for future theoretical exploration in fields such as organizational behavior, strategic management, and industrial ecology.

Additionally, the study's findings challenge commonly held assumptions in the literature that financial return is the primary motivator for sustainability adoption. By demonstrating that financial incentives and perceived cost savings were not strongly associated with sustainability implementation, the study opens up new research avenues to explore the roles of compliance culture, risk management, and reputational drivers in shaping corporate environmental behavior.

From an industry standpoint, the research offers insights that are directly relevant to decision-makers, sustainability officers, and policymakers operating in or with the chemical sector. The high implementation rates of certain practices suggest that Greek chemical companies have taken meaningful steps toward environmental responsibility, yet the observed skepticism regarding sustainability's strategic value reveals a potential disconnect between operational improvements and long-term business strategy.

By highlighting this disconnect, the study can encourage industry leaders to re-evaluate how sustainability is integrated into core business planning, performance evaluation, and risk management frameworks. Greater alignment between daily practices and strategic objectives could help firms derive more value—both economic and reputational—from their environmental investments.

The study also underscores the importance of capacity-building and education, as many respondents expressed only moderate familiarity with sustainability concepts, and a substantial number of companies did not offer structured sustainability training. This suggests a clear opportunity for industry associations, government bodies, and academic institutions to support knowledge development through targeted training, awareness campaigns, and partnerships that promote sustainability literacy.

Lastly, the strong support for mandatory sustainability certification suggests that industry professionals are open to more formal accountability mechanisms. This insight can inform policy development by reinforcing the need for regulatory clarity, standardized benchmarks, and incentives that are not only available but visible and easily accessible to companies of varying sizes.

In sum, this thesis contributes to the literature by introducing empirical findings from an underrepresented industrial and geographical context, and it supports the advancement of sustainability practice in the chemical industry by identifying areas of progress, contradiction, and opportunity for more strategic engagement.

6.4 Recommendations for Future Research

Building on the findings and limitations of this study, several directions for future research are proposed to deepen and broaden the understanding of sustainability in the chemical industry, particularly in contexts similar to Greece where sustainability transitions are ongoing but not yet fully institutionalized.

First, future research would benefit from a more detailed exploration of managerial perspectives and decision-making dynamics. As this study primarily gathered input from a diverse pool of employees, further investigation into the views of senior executives and sustainability officers could reveal how strategic sustainability priorities are set, resourced, and evaluated at the top levels of organizations. Such insight would help bridge the gap identified in this study between sustainability implementation and its perceived strategic value.

Second, future studies should consider incorporating external stakeholders such as policymakers, regulators, suppliers, and customers. As sustainability is increasingly shaped by external demands—ranging from environmental legislation to investor expectations—understanding the broader ecosystem in which chemical companies operate is essential. A multi-stakeholder approach would offer a more holistic perspective on the pressures, enablers, and barriers to sustainability in the sector.

Third, while this study examined a range of sustainability practices and attitudes, it did not assess quantifiable outcomes, such as emissions reductions, energy savings, or return on environmental investments. Future research should integrate performance-based metrics to evaluate whether and how sustainability practices translate into tangible environmental and economic benefits. This would help validate or challenge perceptions around costs, benefits, and the effectiveness of sustainability programs.

Another recommendation is the inclusion of firm-specific characteristics in future analyses. Variables such as company size, ownership structure (e.g., local vs. multinational), product type, and export orientation may significantly influence sustainability behavior. Comparative studies could reveal whether certain types of firms are more proactive in adopting environmental strategies, and what organizational traits support or hinder progress.

Moreover, further research could explore the role of innovation and R&D in advancing sustainability in the chemical sector. While this study addressed digital tools at a general level, it did not examine investment in cleaner technologies, green product development, or partnerships with research institutions. Given the importance of technological innovation in reducing environmental impacts, studies focusing on innovation ecosystems could provide valuable insights.

It is also recommended that future studies adopt mixed-methods approaches, combining quantitative surveys with qualitative interviews or case studies. Such designs would allow researchers to explore the underlying motivations, cultural dimensions, and contextual nuances that shape sustainability practices—dimensions that are difficult to capture through questionnaires alone.

Finally, cross-national comparative studies could provide a valuable benchmark for the Greek chemical industry. Comparing sustainability practices, perceptions, and regulatory environments across different countries would help identify best practices and contextual constraints, offering insights into how local industries can adapt and compete in an increasingly sustainability-driven global market.

In summary, future research should aim to build on the foundation laid by this study by incorporating strategic, stakeholder, performance, and innovation perspectives, while also broadening the methodological and geographic scope. These directions will contribute to a more comprehensive and actionable understanding of sustainability in the chemical industry and beyond.

6.5 Final Thoughts on Sustainability in the Chemical Industry

The chemical industry occupies a paradoxical position in the global sustainability dialogue. On the one hand, it is indispensable to modern economies, enabling innovations across sectors such as agriculture, pharmaceuticals, energy, and construction. On the other hand, it is one of the most resource- and emission-intensive industries, bearing significant responsibility for environmental degradation and climate change. This dual role underscores the urgency—and the complexity—of embedding sustainability into the core operations, strategies, and values of chemical companies.

The findings of this study reflect this duality within the Greek context. While companies have taken considerable steps toward implementing sustainable practices—particularly in waste management, renewable energy, and supply chain practices—there remains a notable hesitation to recognize sustainability as a central driver of long-term business success. This dissonance between action and perception is not merely theoretical; it represents a critical challenge for the industry's transition to truly sustainable development.

Sustainability must evolve from a reactive, compliance-based approach to a proactive, opportunity-driven mindset. In a rapidly changing global landscape shaped by regulatory tightening, stakeholder activism, technological disruption, and environmental limits, sustainability can no longer be treated as a peripheral concern or a marketing add-on. It must be strategically integrated into how chemical companies design products, manage resources, assess risks, and measure success.

This transformation is not solely the responsibility of individual firms. It requires collaborative effort among industry leaders, policymakers, academic institutions, and civil society. Governments must create enabling environments through clear regulations, incentives, and infrastructure. Industry associations must foster knowledge-sharing and benchmarking. Educational institutions must prepare the next generation of scientists, engineers, and business leaders to think systemically and act responsibly.

Importantly, sustainability is not a destination but a continuous journey—one that demands both technological innovation and cultural change. The industry's future will be shaped not just by how well it reduces emissions or recycles waste, but by how deeply it rethinks its role in society and the economy.

In closing, the findings of this thesis point to both progress and potential. The Greek chemical sector has begun its transition, but much work remains to be done in aligning actions with strategy, perception with purpose, and compliance with innovation. Embracing sustainability not as an obligation but as a source of resilience and competitiveness will be essential for the chemical industry to thrive in the decades ahead.

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Appendix A: Questionnaire

Section 1: General Information

Gender

- ☐ Man
- ☐ Woman
- ☐ Prefer not to answer

Age

- ☐ Up to 30 years old
- ☐ 31-40 years old
- ☐ 41-50 years old
- ☐ 51+ years old

What is your position in the company?

- ☐ Executive/Manager
- ☐ Environmental/Sustainability Officer
- ☐ Research & Development (R&D)
- ☐ Production/Operations
- ☐ Other (Please specify): ____________

How many years have you worked in the chemical industry?

- ☐ Less than 5 years
- ☐ 5–10 years
- ☐ 11–20 years
- ☐ More than 20 years

Section 2: Awareness and Commitment to Sustainability

How familiar are you with sustainability practices in the chemical industry?

- ☐ Not familiar
- ☐ Slightly familiar
- ☐ Moderately familiar
- ☐ Very familiar
- ☐ Expert level

Does your company have a formal sustainability strategy?

- ☐ Yes
- ☐ No
- ☐ Not sure

Which sustainability goals does your company prioritize? (Select all that apply)

- ☐ Reducing greenhouse gas emissions
- ☐ Waste reduction & circular economy initiatives
- ☐ Water conservation
- ☐ Energy efficiency & renewable energy
- ☐ Sustainable sourcing of raw materials
- ☐ Compliance with regulatory sustainability requirements

How often does your company conduct sustainability assessments?

- ☐ Monthly
- ☐ Quarterly
- ☐ Annually
- ☐ Never

Section 3: Implementation of Sustainable Practices

Which of the following sustainable practices does your company implement? (Select all that apply)

- ☐ Use of renewable energy sources
- ☐ Green chemistry principles
- ☐ Recycling & waste minimization programs
- ☐ Water recycling & conservation
- ☐ Eco-friendly packaging materials
- ☐ Carbon capture & emission reduction technologies
- ☐ Sustainable supply chain practices

Has your company replaced hazardous chemicals with eco-friendly alternatives?

- ☐ Yes, in most processes
- ☐ Yes, in some processes
- ☐ No, but considering it
- ☐ No, not a priority

How does your company measure the success of its sustainability practices?

- ☐ Carbon footprint reduction
- ☐ Cost savings from resource efficiency
- ☐ Compliance with environmental regulations
- ☐ Customer and stakeholder feedback
- ☐ Other (Please specify): ____________

Does your company use digital tools (e.g., AI, IoT, blockchain) for sustainability management?

- ☐ Yes, extensively
- ☐ Yes, to some extent
- ☐ No, but planning to
- ☐ No, not a priority

If yes, which of the following digital tools do you use for sustainability management? (Select all that apply)

- ☐ Artificial Intelligence (AI)
- ☐ Internet of Things (IoT)
- ☐ Blockchain
- ☐ Big Data Analytics
- ☐ Cloud Computing
- ☐ Digital Twin Technology
- ☐ Geographic Information Systems (GIS)
- ☐ Automation and Robotics
- ☐ Other: ____________

Section 4: Economic Viability of Sustainability Initiatives

How do you perceive the financial impact of sustainability practices in your company?

- ☐ Significant cost savings
- ☐ Moderate cost savings
- ☐ No financial impact
- ☐ Increased costs but with long-term benefits
- ☐ Increased costs without clear benefits

Does your company receive financial incentives (e.g., government grants, tax benefits) for implementing sustainable practices?

- ☐ Yes
- ☐ No
- ☐ Not sure

What are the main barriers to implementing sustainability practices? (Select all that apply)

- ☐ High implementation costs
- ☐ Lack of technical expertise
- ☐ Resistance to change within the company

- ☐ Regulatory complexity
- ☐ Limited access to sustainable raw materials
- ☐ Uncertainty about return on investment

Does your company invest in sustainability training programs for employees?

- ☐ Yes, regularly
- ☐ Occasionally
- ☐ No, but planning to
- ☐ No, not a priority

Section 5: Future Perspectives and Industry Trends

Do you believe sustainability is a key factor in the future success of the chemical industry?

- ☐ Strongly agree
- ☐ Agree
- ☐ Neutral
- ☐ Disagree
- ☐ Strongly disagree

In the next five years, how do you think sustainability regulations will affect the chemical industry?

- ☐ Stricter regulations will drive more sustainable practices
- ☐ Regulations will remain stable with no major changes
- ☐ Regulations may ease, reducing the emphasis on sustainability

What is the biggest driver for your company to improve sustainability?

- ☐ Regulatory compliance
- ☐ Cost reduction and efficiency
- ☐ Customer demand and market trends
- ☐ Competitive advantage
- ☐ Corporate social responsibility

Would you support a mandatory sustainability certification for chemical companies?

- Yes
- No

Author’s Statement:

I hereby expressly declare that, according to the article 8 of Law 1559/1986, this dissertation is solely the product of my personal work, does not infringe any intellectual property, personality and personal data rights of third parties, does not contain works/contributions from third parties for which the permission of the authors/beneficiaries is required, is not the product of partial or total plagiarism, and that the sources used are limited to the literature references alone and meet the rules of scientific citations.