



A comprehensive framework for enhancing environmental sustainability in the chemical industry

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ABSTRACT

The chemical industry, essential to economic growth and innovation, faces critical environmental sustainability challenges, notably pollution, emissions, and intensive resource use. Motivated by the need for practical tools to address these issues, this research develops a structured, comprehensive framework to assess and enhance environmental sustainability within the chemical sector. The framework employs clearly defined Key Performance Indicators (KPIs) related to emissions, resource consumption, and pollutants, providing systematic methods for their identification, measurement, benchmarking, and improvement. It was developed through a structured literature review and sectoral data analysis, followed by the formulation of benchmark construction and a tiered rating approach to assess relative performance. Benchmark values are established using competitive market data, enabling accurate performance comparisons. The framework's effectiveness and practicality are demonstrated through two illustrative case studies, a detailed process-level analysis (steam cracking) and an indicator-level analysis (NOx emissions), which highlight clear opportunities for improvement. This study contributes a scalable, actionable approach that enables chemical companies to achieve measurable sustainability improvements, align with regulatory requirements, and strategically advance their environmental performance.

1. Introduction

The chemical industry, spanning over two centuries, has undergone dynamic changes driven by technology, feedstocks, companies, government policies, and globalisation (Stokes, 2022). Initially rooted in the production of petrochemicals from natural gas and crude oil, it has evolved to encompass a wide array of chemical products and bulk fractions derived from these sources (Speight, 2022). Throughout history, the industry has played a crucial role in meeting human needs, driving economic growth, and creating jobs, albeit with environmental challenges like pollution and resource depletion (Martin, 2016). The industry's significance lies in its ability to innovate processes, utilise raw materials efficiently, and contribute to various sectors by providing essential products through the heavy use of chemicals (Hussain et al., 2022). Embracing concepts like green chemistry and exploring alternative energy sources, the chemical industry faces the challenge of sustainability while continuing to be a cornerstone of industrial development.

Unlike many other sectors, the chemical industry's sustainability challenges are deeply linked to process intensity, high energy demand,

and the handling of hazardous intermediates. These characteristics make environmental performance improvements more complex and capital-intensive. While global initiatives such as the European Green Deal (The European Green Deal - European Commission 2025) have encouraged progress, persistent issues remain around emissions control, resource circularity, and pollution prevention. Evidence consistently shows that the chemical industry faces substantial environmental challenges across air, water, and land domains (Alfarsi et al., 2022). Globally, the sector accounts for around 6–8 % of total anthropogenic greenhouse gas emissions, with approximately 925 million tonnes of CO₂ emitted in 2021 (International Energy Agency 2023). As regulatory and societal expectations continue to rise, the industry faces growing pressure to adopt cleaner technologies, improve resource efficiency, and align operations with evolving sustainability legislation (Scott, 2022). Meeting these expectations requires a proactive approach to environmental risk management through robust environmental management systems that emphasise structured planning, implementation, and continuous improvement (Green et al., 2023).

Existing sustainability tools provide valuable insights but often fall short in practical implementation due to high data requirements and

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complexity (Borschewski et al., 2024; Liu et al., 2024). Additionally, existing environmental performance frameworks for the chemical industry tend to focus either on broad strategies or highly technical assessments without consideration for innovative methods, leaving a gap in accessible, actionable tools for industrial decision-making (Moles et al., 2024). Collaborative efforts involving researchers, industry, regulators, and policymakers are crucial to navigate these challenges and ensure sustainable practices for the chemical industry (Nikolaeva and Khusnutdinova, 2021).

The development of a sustainability framework specifically addressing environmental performance in the chemical industry is motivated by a range of factors. These include the need to encourage employees for environmental improvement (Govindarajulu and Daily, 2004), the desire for a systematic framework for defining quantifiable environmental performance metrics in industrial operations (Sherif et al., 2022), the necessity of data-centric frameworks for assessing environmental sustainability (Peças et al., 2023), and the motivations for corporate sustainability initiatives (Brockhaus et al., 2017). These studies collectively highlight the importance of integrating top management commitment, employee empowerment, feedback and review in environmental performance, as well as the need for a systematic, sector-focused framework for measuring and improving environmental sustainability in manufacturing.

While sustainability encompasses environmental, social, and economic dimensions, this study focuses specifically on the environmental pillar. This choice reflects the immediacy and measurability of environmental impacts within the chemical industry, where emissions, waste, and resource use can be directly quantified and improved through process-level analysis. The social and economic pillars remain vital to long-term sustainability but are beyond the present study's scope and will be addressed in future extensions of the framework. Clarifying this focus helps ensure depth of analysis and aligns the identified research gaps with the central aim of developing an operational framework for environmental performance improvement.

This research aims to address these gaps by developing a structured, dual-level framework that enables chemical manufacturing companies to systematically measure, benchmark, and improve their environmental sustainability. By integrating both indicator-based assessments and process-level evaluations, the framework provides a robust, metric-driven approach to identify performance gaps and guide continuous improvement through a closed-loop process.

The novelty of this work lies in the structured integration of KPI selection, benchmarking against industry standards, and actionable improvement strategies, providing a practical methodology for decision-making in chemical companies. The framework enables organisations to make evidence-based decisions, prioritise sustainability initiatives, improve compliance with regulatory requirements, and follow a clear pathway for continuous improvement. Beyond addressing literature gaps that emphasise only high-level indicators, the study offers a scalable tool that chemical manufacturers can apply to navigate sustainability challenges efficiently. In alignment with Sustainable Development Goal 9 (Industry, Innovation and Infrastructure), this work contributes to the broader objective of sustainable industrial transformation (Goal 9 | Department of Economic and Social Affairs 2025).

This study specifically focuses on the manufacturing stage of the chemical value chain, where most process-related emissions, energy use, and material inefficiencies occur. The framework and KPIs have been designed to be sufficiently generic to cover multiple chemical sub-sectors, enabling comparability across diverse production processes. While the case studies illustrate specific applications, the approach itself remains sector-wide in scope, providing flexibility for adoption by different types of chemical manufacturing operations.

The paper is structured as follows: Section 2 presents the literature review was performed as part of the study. Section 3 describes the framework's development. Section 4 presents the framework using case studies. The conclusion and recommendations for further research are

covered in Section 5.

2. Literature review

The chemical industry, a cornerstone of modern economies accounting for 5.7 trillion U.S. dollars in revenue in 2022 (Moore et al., 2023), is heavily reliant on various raw materials, including fossil fuels, to produce a wide array of products. This reliance brings a multitude of environmental sustainability concerns, prompting nations worldwide to impose regulations and penalties on unsustainable practices (Smith et al., 2024). Such measures have spurred extensive exploration into alternative, clean methods and approaches to reduce fossil fuel dependency (Galán-Martín et al., 2021; Schiffer and Manthiram, 2017; Gabrielli et al., 2020).

Despite these efforts, achieving environmental sustainability in the chemical industry remains challenging due to complex production processes, diverse pollutant emissions and sector-specific sustainability trade-offs. Existing sustainability assessment approaches provide important insights, but many fail to translate into practical, industry-wide solutions. This section reviews the environmental impacts of the chemical industry, explores existing sustainability assessment frameworks, and examines current KPI-driven methodologies before identifying gaps that this research seeks to address.

2.1. Overview of the chemical sector

The chemical industry covers a broad range of sectors and products, including basic chemicals, organic and inorganic chemicals, fertilisers, pharmaceuticals, polymers, solvents, agricultural products, and specialty chemicals. Each of these sectors involves complex manufacturing processes, often characterised by interconnected production networks and multiple operational stages such as procurement, production, storage, logistics, and distribution. These supply chains typically comprise suppliers, clustered production facilities, warehouses, distribution centres, and end markets, functioning in a make-to-stock mode due to longer production lead times relative to market demands (Häberle et al., 2015; Sahay and Ierapetritou, 2014).

Due to this operational complexity and product diversity, the chemical industry's environmental impacts are substantial and varied across different supply chain stages, influencing resource use, emissions, waste generation, and pollution risks. The industry is notably energy-intensive, accounting for approximately 10 % of global final energy consumption and about 7 % of industrial greenhouse gas emissions (Griffin et al., 2018). Moreover, the manufacturing processes often require multiple energy sources and resources simultaneously, reinforcing the critical importance of energy efficiency, process optimisation and pollution control (Nicholson et al., 2021).

2.2. Environmental impacts in the chemical sector

Environmental impacts vary significantly across chemical sectors. For example, ethylene production contributes substantially to air pollution, whereas oil and gas activities frequently affect water quality through effluent discharge (Alfarsi et al., 2022). The stage of the supply chain also influences the environmental impacts. For instance, the extraction and procurement stages (such as mining and raw materials sourcing) primarily cause land degradation, soil contamination, and loss of biodiversity due to waste accumulation and resource extraction activities (Vadian et al., 2022; Agboola et al., 2020). Distribution and logistics activities, on the other hand, tend to contribute significantly to air pollution through transportation-related emissions. This drives the adoption of closed-loop supply chains and greener technologies aimed at pollution reduction (Sudhakar et al., 2023). However, the manufacturing stage typically represents the most critical point of environmental concern, given its intensive resource consumption, emissions, and waste generation. The global chemical industry is among

the largest industrial energy consumers, using approximately 42 EJ of energy annually, or around 10 percent of global industrial energy demand, and accounting for roughly 5 percent of global CO₂ emissions (Gabrielli et al., 2023; Fiorentino et al., 2019). These figures highlight the sector's substantial environmental footprint and reinforce the importance of targeted sustainability measures. These impacts extend across the chemical industry's broad influence on vital components of the environment: land, water, and air. Each serves as a significant pathway by which the chemical industry interacts with and affects its sustainability. This underscores the urgent need for effective sustainability practices, targeted environmental assessments, and continuous improvement initiatives.

Land: The chemical industry significantly impacts land quality due to the disposal of solid and liquid waste. Soil is one of the elements of the industrial environment most vulnerable to environmental pollution. For instance, spills and the disposal of toxic waste are major causes of soil contamination in the chemical industry, affecting the soil's structure and depleting nutrients and organic matter essential for fertility and health (Singha and Chatterjee, 2022). Harmful substances like hydrocarbons and heavy metals impair the soil's ability to sustain plant life and disrupt the balance of soil microbes (Alengebawy et al., 2021). Additionally, contaminated soil can lead to land-use changes, making it prone to erosion and further degradation which not only hinder plant growth but also reduce the effectiveness and population of essential soil microbes (Amooshahi et al., 2018). The industry's infrastructure and operations often mix with contaminated soil, exacerbating these problems and leading to long-term soil degradation (Kh Khalilova, 2019).

Water: The chemical industry's water pollution arises primarily through chemical discharges, industrial effluents, and spills, posing risks to aquatic ecosystems. Water pollution has become a noteworthy concern due to high concentrations of various industrial chemicals. These can include industrial salts, solvents, and other toxic substances, which extend their harmful effects to aquatic environments, damaging the seabed, groundwater, and the broader hydrological system (Abed Yaha et al., 2022). Frequent chemical spills linked to industry activities have immediate and long-term negative impacts on freshwater and marine environments (Herrera-Franco et al., 2021).

Air: Chemical industry operations significantly affect air quality through the emission of greenhouse gases, volatile organic compounds, and hazardous substances, posing substantial risks to human health and the environment (Wang et al., 2023). In 2021, the chemical industry's global emissions totalled approximately 925 million metric tons (MT) of CO₂ (International Energy Agency 2023) of which the majority (67%) of GHG emissions from the chemical industry came from fuel combustion, while 33% were linked to industrial processes and product use (EEA 2024). It is worth noting that human health is significantly impacted by air emissions containing sulphur oxides, nitrogen oxides, dust, and carbon monoxide. Short-term exposure to VOCs can cause symptoms like fatigue, depression, and dizziness, while prolonged exposure has been linked to severe effects, including carcinogenic and mutagenic risks (Ragothaman and Anderson, 2017). The industry also emits other hazardous substances, including sulphur oxides, nitrogen oxides, and particulate matter, which exacerbate environmental pollution (Manisalidis et al., 2020). Emissions from chemical industry activities can lead to acid rain, further worsening air quality and contributing to global warming (Bishop, 2022).

2.3. Environmental sustainability frameworks in the chemical industry

This section reviews and compares existing environmental sustainability frameworks developed for the chemical industry. The aim is to identify their methodological focus, practical limitations, and relevance to process-level performance improvement. While a variety of frameworks have been proposed, they differ substantially in scope, data intensity, and operational applicability.

Environmental sustainability frameworks for chemical industries

encompass various key components and pursue a wide variety of applications and use cases. These frameworks aim to integrate technical, economic, environmental, and safety considerations (Tahmid and Syeda, 2023; Makarova et al., 2019). One crucial aspect involves quantifying chemical thresholds on ecosystems, determining ecosystem carrying capacity, and establishing a "safe space" where chemical impact remains within limits to prevent irreversible ecological harm (Kosnik et al., 2022). Additionally, sustainability considerations in chemical industries involve general components like stakeholder engagement, financial resources, and cleaner production strategies, as well as operational components such as raw material supply, synthesis processes, and emission abatement (Aryanasl et al., 2017). To measure environmental sustainability across chemical products, the Chemical Environmental Sustainability Index (ChemESI) metric evaluates the risks and hazards of chemical inventories, emphasising the need for detailed chemical characterisation data (Plugge, 2022). Furthermore, a systematic framework for sustainability assessments in chemical processes integrates economic performance, health, safety, and environmental impact assessments, stressing the importance of early-stage evaluations to avoid costly retrofits (Teh et al., 2019).

In terms of chemical production assessment, indicator-based models have been widely used to evaluate sustainability within the chemical industry, integrating environmental, economic, and social dimensions. Several studies have introduced quantitative metrics to assess sustainability performance and provide a holistic understanding of the sector's progress toward sustainable operations (Hasheminasab et al., 2021; Sierra et al., 2018). While these frameworks mark an important step towards comprehensive assessment, their reliance on extensive data inputs and advanced analysis techniques may limit applicability in contexts where data availability or technical expertise is constrained. Another study (Barbosa and Gomes, 2015) developed a methodology for the continuous evaluation of efficiency and sustainability in the chemical industry. Using nonparametric techniques, analytic hierarchy process (AHP) and Goal Programming, the study identified and prioritised critical variables and action plans to meet set targets, leveraging historical data and industry benchmarks for performance improvement. The study's strengths lie in its systematic approach to defining and measuring KPIs and its practical application in a case study, demonstrating the model's efficacy. However, it lacks a detailed exploration of long-term impacts and the adaptability of the methodology to diverse industrial contexts.

Across these frameworks, differences can be observed in both methodological focus and usability. Some models are strategic in orientation, guiding policy or corporate sustainability planning, whereas others are process-specific, focusing on optimisation at the operational level. At the strategic level, Aryee and Kanda (Aryee and Kanda, 2024) developed a framework linking circular economy practices to firm performance, highlighting the importance of structured assessment tools for translating sustainability initiatives into measurable organisational outcomes. However, few effectively bridge these two perspectives, limiting their capacity to translate high-level sustainability objectives into actionable, process-level improvements. Furthermore, frameworks such as ChemESI focus primarily on chemical risk assessment, while others employ performance metrics that are often not standardised, hindering comparability across facilities or sub-sectors. Additionally, existing frameworks often prioritise broad strategic alignment or regulatory compliance without clearly defined, actionable pathways for improving identified performance gaps. Studies by Hristov and Chirico (Hristov and Chirico, 2019) and Marrucci et al. (Marrucci et al., 2024) have highlighted the strategic relevance of KPIs yet frequently omit practical implementation guidance explicitly tailored to industry constraints.

To summarise, the literature clearly illustrates an evolution towards more integrated, indicator-based sustainability frameworks, reflecting the chemical industry's need for quantitative and holistic assessments. Despite these advancements, critical gaps remain. Existing frameworks

often rely heavily on extensive data collection and complex methodologies, limiting their practical application in industrial contexts. Additionally, while these frameworks frequently include indicators for measuring environmental performance, these are often lagging indicators, meaning they primarily confirm past outcomes rather than inform proactive actions. Consequently, without clearly defined targets and stakeholder-specific actionable recommendations, their potential for driving operational improvements is significantly reduced. There remains a need for a structured, actionable sustainability framework explicitly addressing these gaps by offering clear, scalable benchmarks and practical recommendations tailored to the chemical industry's unique challenges, enhancing the practical utility of lagging indicators for continuous environmental improvement.

2.4. KPIs for environmental sustainability in the chemical industry

KPIs play a crucial role in quantifying and simplifying sustainability data for decision-making (Panagiotopoulou et al., 2023). Trigo et al. (Trigo et al., 2023) emphasise that “you can't manage what you don't measure”, underscoring the need for clear, trackable indicators in sustainability assessments. These indicators help companies monitor progress, set benchmarks, and implement targeted improvements to reduce their environmental footprint.

A review of existing literature reveals a wide range of KPI systems applied in the chemical industry, yet significant variation exists in their scope, integration level, and operational usability. Several traditional KPIs have been widely used in industrial sustainability assessments. Material and energy flow analysis is commonly applied to track resource efficiency; however, it does not integrate emissions data, limiting its effectiveness in environmental benchmarking (Borschewski et al., 2024). Similarly, Life Cycle-Based Environmental Indicators provide valuable insights into environmental impact but are not designed for real-time decision-making, making them impractical for many operational contexts (Cerchione et al., 2025). These limitations indicate a need for a more structured, decision-oriented KPI framework that links environmental performance to measurable, achievable improvement strategies. In response, recent KPI-driven methodologies have emerged within the chemical industry, incorporating individual and composite indicators, LCA, and environmental accounting approaches (Angelakoglou and Gaidajis, 2015). For example, Pereira (Pereira et al., 2018) introduced an eco-efficiency index specifically designed for petrochemical plants, focusing on optimising energy and resource use. Recent work by Nikolakis et al. (Nikolakis et al., 2024) further reinforces the relevance of process-level eco-efficiency assessment by proposing a structured methodology to evaluate circular economy strategies in manufacturing, demonstrating how energy and resource efficiency indicators can be operationalised to support sustainability decision-making. Aryanasl (Aryanasl et al., 2017) proposed a KPI-based sustainability model tailored to chemical production management, integrating environmental, economic, and social dimensions. Ruiz-Mercado et al. (Ruiz-Mercado et al., 2014) developed a process performance indicator framework that helps design and assess sustainable chemical processes. While these studies represent major steps toward quantification, they vary considerably in indicator selection, data requirements, and applicability across chemical sub-sectors. Some prioritise energy and material efficiency, while others focus on emissions and pollutant control. However, few provide a unified or standardised structure that enables comparison across different facilities or process types.

In synthesis, the most recurrent KPIs identified in the literature relate to energy intensity, material consumption, waste generation, emissions (CO₂, NO_x, SO_x, VOCs), and water use (Peças et al., 2014; Ruiz-Mercado et al., 2012; Yang et al., 2016). However, these indicators are often used independently, without integration into a cohesive decision-support framework. Moreover, industry confidentiality constraints and the lack of publicly accessible benchmarking data pose major challenges,

hindering standardisation across various regions and organisations.

The framework proposed in this research directly addresses these shortcomings by consolidating the most relevant KPI categories for chemical manufacturing (emissions reduction, resource efficiency, and pollutant control) into a structured, industry-specific benchmarking model. It integrates both performance evaluation and improvement guidance, enabling companies to assess, compare, and enhance their environmental sustainability, even when data is limited. Unlike previous approaches, this framework explicitly operationalises KPI use through a stepwise methodology linking measurement, benchmarking, and improvement. This structure ensures that the previously identified gaps, such as fragmentation of indicators, lack of comparability, and limited practical usability, are methodically mitigated within a unified analytical framework.

3. Framework development

This section outlines the development of the framework aimed at enhancing environmental sustainability within the chemical industry. The development of the framework followed a structured methodological process grounded in the literature review and supported by comparative benchmarking practices. The process began with a systematic identification of relevant sustainability assessment methods and KPIs within the chemical industry. These insights were synthesised to define the core dimensions of environmental performance (emissions, resource consumption, and pollutants) and to establish measurable evaluation criteria. Building upon these findings, the framework was designed to integrate both indicator-based and process-based analyses, ensuring alignment with established benchmarking practices such as the EU Best Available Techniques (BAT) reference. This methodological foundation ensures that each stage of the framework is directly traceable to the underlying evidence gathered during the literature and data synthesis phases.

The framework provides a structured, dual-level methodology that enables chemical manufacturing companies to systematically measure, benchmark, and enhance their environmental performance. It integrates indicator-based assessments and process-level evaluations to ensure both practicality and analytical depth. Central to this approach is the identification of a set of environmental KPIs encompassing emissions, resource consumption, and pollutants, supported by a structured scoring system for performance evaluation. The framework consists of four distinct stages, depicted in Fig. 1, which guide industry stakeholders through a systematic approach of identifying areas of interest, analysing them to determine performance then establishing an improvement strategy. The framework was developed through a synthesis of existing sustainability assessment methodologies, industry benchmarking practices, and key findings from the literature review. The following subsections present the stages of its development, detailing the rationale, structure, and methods used to define and operationalise each component.

The framework's components are grounded in established methods. The threshold branch adapts the U.S. Department of Energy bandwidth methodology to quantify typical practice, Best Available Techniques, and R&D potential for process performance (Energy EEand R 2015). The closed-loop structure for selecting KPIs, reviewing results, and feeding actions back into practice follows the continuous sustainability approach of Sherif et al. for manufacturing operations (Sherif et al., 2022). The categorical rating of indicators into discrete performance bands is consistent with sustainability assessment literature that normalises indicators to aid benchmarking and management decisions (Azapagic, 2003; Singh et al., 2007).

This approach not only refines existing models but also integrates benchmarks and improvement recommendations to foster continuous enhancement in environmental performance. By adopting a structured and methodical approach, this framework seeks to empower the chemical industry to navigate sustainability challenges effectively. It

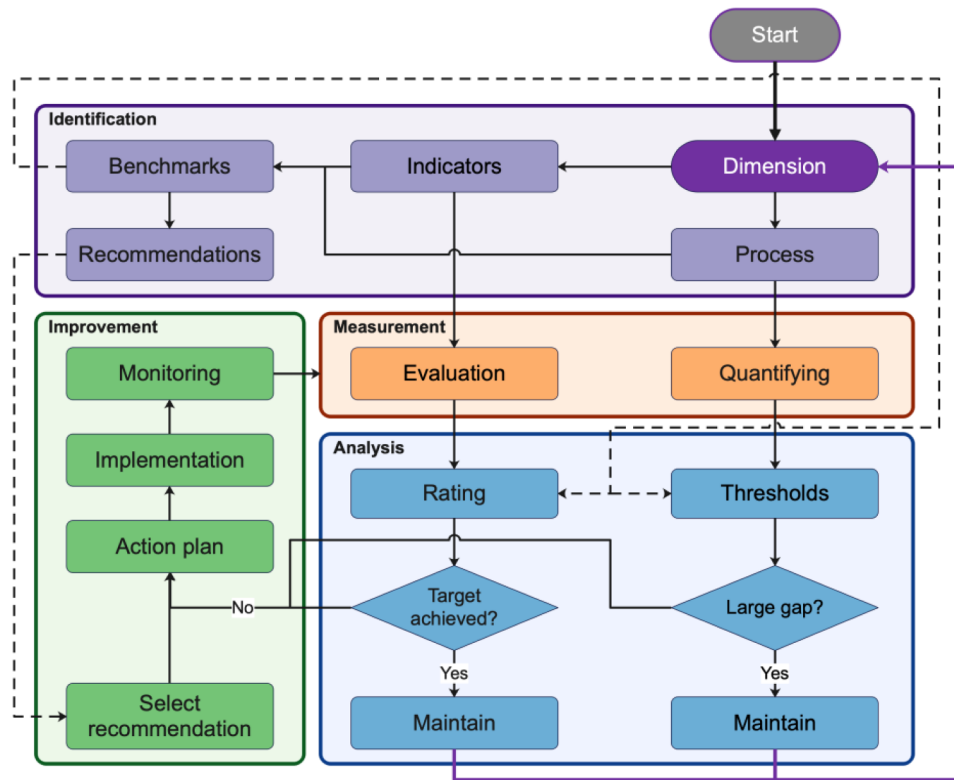


Fig. 1. Environmental sustainability analysis framework for the chemical industry, structured across four main stages: Identification, Measurement, Analysis, and Improvement. The framework includes two analytical pathways: indicator-based and process-based, supported by benchmarking, KPI evaluation, threshold quantification and a feedback-driven improvement cycle.

aligns KPI selection with organisational sustainability objectives, such as emissions reduction and efficiency targets, and with relevant industry standards including regulatory benchmarks (EU BAT) and sector-specific guidelines.

3.1. Analytical pathways

The proposed framework incorporates two distinct analytical pathways. Each approach offers specific benefits tailored to different organisational needs.

Indicator-based Analysis: A flexible evaluation utilising KPIs, where current performance is directly compared against established benchmarks acting as targets. This method is applicable across various scales, from individual processes to entire companies, allowing organisations to pinpoint improvement areas clearly and systematically.

Process-based Analysis (Threshold Approach): A targeted analysis evaluating individual processes against clearly defined thresholds: typical industry values, BAT and future-oriented R&D potentials. This detailed approach provides precise insights into process-level performance gaps, enabling focused interventions specifically aimed at emissions or energy optimisation.

The development of each stage of the framework for both pathways

is detailed in [Table 1](#).

3.2. Stage 1: identification of KPIs

The process involved a systematic search of academic databases using a well-defined search string designed to capture a broad range of studies related to KPIs in environmental sustainability within the chemical industry. The search string used was: (“environmental indicators” OR “KPIs” OR “sustainability indicators” OR “environmental metrics”) AND (“chemical industr*” OR “chemical sector*” OR “chemical manufactur*” OR “chemical produc*” OR “chemical process*”). The search was conducted across Scopus and ScienceDirect databases, covering studies published in the past 20 years. The search yielded 188 unique papers, which then underwent an initial screening to determine their relevance based on titles and abstracts. This initial filtering was crucial to ensure that only papers explicitly addressing KPIs in the context of environmental sustainability were retained for further analysis. After the initial screening, papers were further filtered based on specific criteria to ensure their relevance to the chemical industry, their environmental focus, and the presence of measurable KPIs. The specific criteria used for filtering are detailed in [Table 2](#). These criteria were designed to ensure the relevance and quality of the studies. Papers that did not meet these criteria were excluded, resulting in a refined list of papers that directly addressed the development, implementation, or evaluation of KPIs in the chemical industry.

From the selected papers, KPIs were extracted and compiled into an initial list. The extracted KPIs were screened to remove duplicates, ensuring that each KPI in the final list was unique. This list was further refined through a thorough evaluation process based on predefined selection criteria to identify the most appropriate and effective KPIs ([Murad M de et al., 2021](#)). This comprehensive evaluation considered multiple aspects to ensure that the final KPIs would provide meaningful insights and drive meaningful improvements in environmental

Table 1
Summary of Framework Stages for Analytical Pathways.

Stage	Indicator based	Process-based
Identification	KPI identification criteria clearly defined	
Measurement	KPI definition (units, measurement) and target recognition	Threshold definitions and computations are clearly explained
Analysis	KPI rating system establishment	Current process performance compared to defined thresholds.
Improvement	Structured, actionable recommendations linked to identified gaps	

Table 2

Filtration criteria used for the identification of relevant literature on environmental KPIs.

No.	Criteria	Rationale
1	Published in peer-reviewed journals/conferences; Written in English	Ensures credibility and accessibility of sources
2	Mention of KPIs in title or abstract; Focus on development, implementation, or evaluation of KPIs	Identifies papers directly related to KPIs
3	Original research or case studies on KPIs; Detailed methodologies for KPI development or implementation	Ensures depth and relevance of content
4	Robust findings relevant to research questions; Novel insights or approaches to KPI development or evaluation	Ensures selection of high-quality, impactful papers
5	Recent publication date (20 years)	Incorporates currency and impact of research
6	Alignment with specific research objectives; Contribution to broader literature	Ensures direct relevance and significance of selected papers

performance. The list of criteria used for this evaluation is presented in Table 3.

An overview of the flow and the count of papers and KPIs included and excluded is displayed in the flowchart in Fig. 2. Overall, this methodology facilitated the identification of a robust set of KPIs tailored to the specific needs and objectives of the chemical industry in advancing environmental sustainability practices. The systematic approach adopted in this study lays a solid foundation for future research and implementation efforts aimed at enhancing environmental performance in the chemical sector.

The full list of final KPIs is presented in Table A1 in Appendix A. In developing the framework, the dimensions of environmental performance were identified, and the specific KPIs were selected. The framework includes indicators across various aspects such as energy consumption, greenhouse gas emissions (including Carbon Dioxide, CO₂), water usage and waste generation. These indicators were chosen for their relevance to the industry and their potential impact on sustainability. Following this, they were classified into three dimensions: (1) Emission to Air, (2) Pollutants Release to Land and Water, and (3) Resources Utilisation. Effective classification of KPIs is crucial for overseeing organisational performance. Clear categorisation enhances internal communication about essential metrics, facilitating discussions on performance and improvements.

Moreover, to improve clarity in assessment and address the critiques from Heink & Kowarik (Heink and Kowarik, 2010) and Joung et al. (Joung et al., 2013) regarding the unclear definitions and unspecified measurement units of indicators, detailed characteristics have been included. Additionally, each indicator can be characterised by the following attributes:

- **Name:** The word(s) for the distinctive designation of an indicator.
- **Guideword:** Refer to the sustainability aims of the indicators.
- **Definition:** Provide definitions of the indicator's measurement units.
- **Unit:** Unit of the value of the indicator.

Table 3

Selection criteria for filtering KPIs from the collected initial list.

No.	Criteria	Explanation
1	Relevance	Measures how directly the KPI relates to the desired outcome or performance area
2	Measurability	Evaluate whether the KPI is quantifiable and can be effectively measured
3	Feasibility	Considers the practicality of collecting data and monitoring the KPI over time
4	Impact	Examines the potential impact of improving performance on the organisation

- **Method of Measurement:** Methodologies used to measure the corresponding indicators.

After companies adopting the framework identify which dimension they aim to target and the indicators to track, they are responsible for identifying benchmarks specific to their processes and recommending improvements. The framework ensures that companies can focus on the most relevant and impactful environmental metrics. This enables more effective monitoring, reporting, and improvement of environmental performance, ultimately contributing to the sustainability goals of the chemical industry.

3.3. Stage 2: measurement

Consistent and reliable data collection is crucial for accurate assessment. Specific measurement methods are advised to ensure data accuracy and reliability. These methods include direct measurements using sensors, data logging from operational systems, and periodic manual data collection. The KPI should ideally be measured in a time series in which the longer the period, the more accurately the performance is presented. In terms of process-level analysis, the current value of energy consumption or emissions should be computed.

3.4. Stage 3: analysis

3.4.1. KPI analysis and rating

The analysis phase involves a comparative evaluation of the collected KPI data against established benchmarks. This comparative analysis helps contextualise performance metrics, offering a clear picture of how well chemical processes align with sustainability goals. Measured KPIs are evaluated against three reference thresholds: target, average, and baseline values. These reference values are determined using one of two complementary methods, depending on data availability.

Method One: Utilisation of Recognised Reference Values and Competitors

Target and Baseline Values: Set using reference values from local associations or authorities.

When official benchmark data exist, such as BAT or industry association reference values, they are used to define the target (best-performing) and baseline (least-performing) thresholds. The average value is then calculated from competitor data in the same sector, as shown in Eq. (3.1):

$$\text{Average Value} = \frac{\sum \text{Collected Values}}{\sum \text{Companies}} \quad (3.1)$$

Method Two: Data Collection from Industry Competitors Alone

When no official reference data exist, benchmark values are derived directly from the performance of comparable facilities:

- Target Value: The best-performing value among competitors.
- Baseline Value: The least-performing value.
- Average Value: Calculated using Eq. (3.1).

In recognition of the potential absence of competitor or reference data, the framework remains adaptable. Where external benchmarks are unavailable, users are encouraged to rely on internal historical records, aggregated literature data, or sustainability disclosures. This ensures the framework remains usable in data-constrained contexts while supporting continuous performance evaluation and improvement.

Since the indicators often have different units and scales, the measured values must be normalised to a common range (0–1) before they can be compared or aggregated at the dimension level. The framework employs a min–max normalisation approach, adjusted for the indicator type (cost-type or benefit-type).

For benefit-type indicators (where a higher value represents better

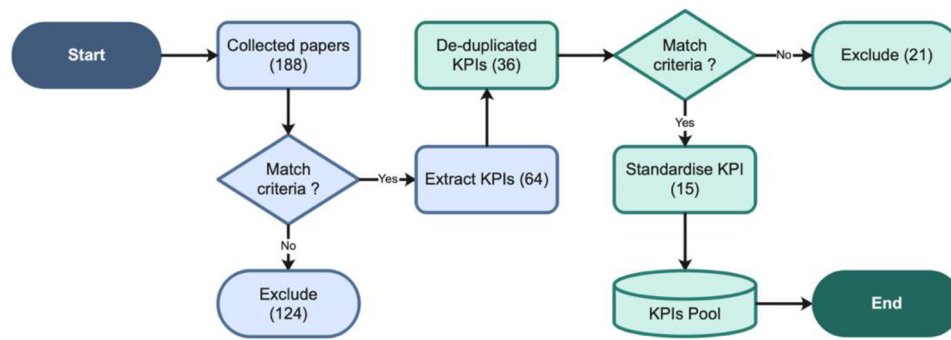


Fig. 2. Flow diagram illustrating the methodology used for identifying, screening and selecting relevant KPIs from the literature. The diagram outlines key steps, including paper collection, eligibility screening, KPI extraction, de-duplication, and standardisation. The counts shown at each step represent the numbers processed in each step.

performance):

$$x_i^* = \frac{x_i - \min(x)}{\max(x) - \min(x)} \quad x_i^* \in [0, 1] \quad (3.2)$$

For cost-type indicators (where a lower value represents better performance):

$$x_i^* = \frac{\max(x) - x_i}{\max(x) - \min(x)} \quad x_i^* \in [0, 1] \quad (3.3)$$

Here $\min(x)$ and $\max(x)$ are the minimum and maximum benchmark values for each indicator. When $\max(x) = \min(x)$ the normalised value is set to zero to avoid division errors.

In addition to rating individual KPIs, companies can opt for a dimension-based evaluation. This approach provides a broader view of performance by assessing groups of related indicators under a common dimension, such as emissions or resource use. To do this meaningfully, the values of individual indicators must first be normalised to a common scale (e.g., 0 to 1), since they typically have different units. After normalisation, the average value can be calculated to represent overall performance within that dimension. This enables a more holistic understanding of performance trends across multiple indicators, without compromising mathematical validity, as described in Eq. (3.2):

$$\text{Dimension Value} = \frac{\sum_{i=1}^n \text{Normalised Indicators}_i}{n} \quad (3.4)$$

Here, $\sum_{i=1}^n \text{Normalised Indicators}_i$ represents the sum of all 'n' normalised indicators within a particular dimension, with 'n' being the total number of indicators in that dimension.

The ensuing analysis involves comparing the measured indicators against the values derived from Eqs. (3.1), (3.2), and (3.3). This comparison results in a tiered rating system, detailed in Table 4, which classifies the performance of each indicator.

In cases where the achieved rating aligns with the company's sustainability aims, the next step is to maintain current performance levels. If the rating falls below the desired level, the company proceeds to the improvement stage.

The analysis process is critical for understanding the environmental impact of chemical processes and identifying specific areas for improvement. By using a straightforward comparative method, the framework provides a detailed and nuanced understanding of

environmental performance, enabling targeted and effective interventions. This analysis helps identify trends and pinpoint areas requiring improvement, which is essential for developing effective strategies to enhance environmental sustainability.

It is important to note that the benchmark values defined in this framework are intended to serve as guidance ranges rather than definitive or statistically fixed targets. Given that available data often originate from a limited number of comparable facilities, the calculated averages or "best" values may reflect contextual variations such as operating conditions, feedstock, or reporting practices. The purpose of these reference values is therefore to support comparative assessment and improvement prioritisation, not to prescribe exact performance thresholds. Users are encouraged to interpret them alongside their own operational data and local conditions, recognising that inherent variability and uncertainty may exist within the benchmark dataset. It is also recognised that the availability and comparability of market or competitor data can be limited due to confidentiality restrictions and differing reporting methodologies. However, the increasing transparency of corporate sustainability reporting has significantly improved access to environmental performance data, with many chemical companies now disclosing key KPIs such as emissions intensity and resource efficiency in annual or ESG reports. In cases where direct benchmark data are unavailable, the framework supports the use of internal historical records, aggregated industry averages, or anonymised datasets provided by trade associations or regulatory agencies to maintain consistency and practical applicability.

By measuring and analysing KPIs, companies can gain valuable insights into their environmental performance, allowing for data-driven decision-making and continuous improvement in sustainability practices. This stage ensures that the chemical industry can make informed decisions to minimise its environmental footprint and enhance its overall sustainability.

3.4.2. Thresholds analysis

When the data collection phase is completed, they are then analysed by establishing meaningful insights focusing on the identified thresholds. This stage compares current process performance values directly against the identified benchmarks (Typical, BAT and R&D potential). This highlights whether the company's performance is better, equal to, or worse than these reference values. This analytical framework was adapted from the bandwidth studies conducted by the U.S. Department of Energy (Energy E&R 2015).

The performance differences are quantified using a unified formula presented in Eq. (3.5):

$$\text{Difference \%} = \frac{\text{Current Value} - \text{Threshold Value}}{\text{Current Value}} \quad (3.5)$$

Where:

Table 4
Definition of the 4-tiered rating system.

Tier	Definition
A	Performance surpasses the target value.
B	Performance is between the target and average values.
C	Performance is between the average and baseline values.
D	Performance is below the baseline value.

- Current Value is the actual measured emissions or resource-use performance of the company's specific process.
- Threshold Value refers to any of the identified benchmarks.

A positive percentage indicates the company's current performance is worse than the threshold, highlighting areas for potential improvement. Conversely, a negative percentage indicates performance is already better than the threshold, reflecting strong environmental performance. By quantifying these differences clearly and consistently, companies can easily determine their current position relative to industry standards, best practices, and potential future innovations.

3.5. Stage 4: improvement

The final stage involves implementing improvements identified through the analysis, with explicit consideration of economic feasibility and operational constraints. This includes developing realistic and actionable plans, carefully evaluating resource requirements, and continuously monitoring progress. The framework features a closed-loop process, ensuring that achieved targets are maintained, while unmet targets are revisited for further assessment and adjustment based on practical considerations. This iterative approach supports balanced decision-making, clearly accounting for economic investments and operational limitations alongside environmental improvements.

Once recommendations are selected for implementation, companies adopting the framework follow a structured guide to develop feasible action plans, considering economic and operational constraints.

1. **Assign Responsibilities:** Delegate specific responsibilities among team members to manage the implementation process effectively.
2. **Outline Detailed Action Steps:** Define step-by-step actions, clearly detailing methods, expected outcomes, and required operational changes, considering existing process constraints and capabilities.
3. **Set Timelines and Milestones:** Establish realistic timelines and key milestones, ensuring alignment with operational schedules and capacity constraints.
4. **Allocate Necessary Resources:** Explicitly evaluate and allocate necessary resources (financial, human, technical) for each action step, balancing environmental benefits against investment costs and resource availability.
5. **Execute Action Steps:** Carry out the defined steps according to the established plan, monitoring closely to ensure adherence to economic and operational constraints.
6. **Continuous Monitoring and Evaluation:** Continuously monitor and evaluate progress against established KPIs using the tiered rating system, adjusting strategies promptly based on economic performance, operational feasibility, and environmental results.

By following this structured framework, companies can systematically integrate environmental KPIs into their daily operations, ensuring that sustainability remains an ongoing organisational focus. The approach guides firms through a detailed process of setting goals, planning actions, allocating resources, and continuously monitoring progress to achieve measurable and lasting improvements while maintaining economic and operational feasibility. The framework is designed to be applicable across different segments of the chemical industry, including petrochemicals, fine chemicals, and speciality production, as it relies on broadly measurable indicators such as energy use, emissions, water consumption, and resource efficiency. It is primarily intended for application at the operational and performance evaluation stages of the manufacturing workflow, where sustainability data can be systematically collected, benchmarked, and acted upon. By structuring KPI identification, measurement, and improvement around emissions, resource consumption, and pollutant control, the framework directly addresses the most critical environmental challenges of the chemical sector, including energy intensity, waste generation, and process-related

emissions. Through its closed-loop design and focus on actionable metrics, the framework supports continuous improvement, regulatory compliance, and the long-term enhancement of environmental performance across diverse industrial contexts.

4. Case studies

The case studies presented in this section demonstrate the application and outcomes of the proposed environmental sustainability framework. They serve to validate its ability to generate meaningful and measurable insights for decision-making within the chemical industry. By applying the framework to real industrial contexts, the analysis highlights how it can quantify performance gaps, benchmark key indicators against industry standards, and identify improvement opportunities that contribute to enhanced environmental performance.

The case studies were selected to represent the two analytical pathways within the framework, each addressing a different level of assessment and data type. The first focuses on process-level analysis using the steam cracking process as a representative example to evaluate energy consumption and identify efficiency thresholds. The second applies the indicator-level pathway to the assessment of nitrogen oxide (NO_x) emissions within the petrochemical industry, demonstrating the framework's capability to support targeted environmental performance evaluation using quantifiable metrics.

Together, these examples provide evidence of how the framework operates in practice, translating data into structured insights and actionable recommendations. The results highlight its flexibility across diverse chemical manufacturing contexts, its ability to support benchmarking and performance improvement, and its contribution to a more transparent and consistent approach to environmental sustainability assessment.

4.1. Process-level application

Steam cracking is a crucial petrochemical process primarily used to produce olefins, such as ethylene and propylene. These olefins are essential building blocks for various products, including synthetic rubber, polymers, and plastics. Naphtha is commonly used as feedstock for steam cracking due to its economic benefits and wide availability. However, growing environmental awareness and energy consumption concerns have prompted the industry to seek more efficient and sustainable alternatives (Griffin et al., 2018).

4.1.1. Energy thresholds for steam cracking of naphtha

In this case study, the process-based analytical approach was applied, computing the defined thresholds for the energy performance of steam cracking.

Typical Energy: Currently, the global average energy intensity for steam cracking using naphtha feedstock is approximately 18 GJ/MT. This value varies based on operational specifics, feedstock characteristics and unit designs (Xu et al., 2023; Ren et al., 2008).

BAT Energy: Employing proven industry best practices can reduce energy intensity to about 13 GJ/MT, representing approximately a 28 % improvement compared to typical practice. Key BAT includes optimising furnace coils to enhance heat transfer and reduce coke formation, improving olefin yields, and integrating front-end separation techniques to lower refrigeration needs (Barthe et al., 2015).

R&D Potential: Emerging technologies, currently under development, have the potential to further lower energy intensity to around 9 GJ/MT, indicating about a 50 % improvement compared to typical performance. Notable technologies include:

- Microwave-enhanced direct cracking, potentially reducing energy requirements by approximately 50 % (Yan et al., 2023).
- Advanced catalysts for catalytic pyrolysis, offering energy efficiency improvements of around 4 % (Bhoi et al., 2020).

- Novel membranes for olefin/paraffin separation, promise energy savings of about 11 % (Roy et al., 2021).

Although these R&D innovations demonstrate noteworthy potential, their commercial viability is still under assessment.

The identified energy thresholds for steam cracking are illustrated in Fig. 3, clearly visualising current typical performance, best practice benchmarks, and R&D potential, facilitating clear identification of opportunities for targeted improvements.

The thresholds identified highlight clear opportunities for improved energy efficiency and reduced emissions. Current BAT already offers practical energy reductions of about 28 percent compared to typical industry practices, making them viable short-term targets. Emerging technologies, although still under research and development, present a greater potential of up to a 50 percent reduction in energy use. Techniques such as microwave-enhanced direct cracking and catalytic pyrolysis hold considerable promise but require further validation before widespread adoption.

These findings demonstrate how the process-based analytical pathway within the proposed framework can translate complex process data into clear performance benchmarks and improvement potentials. By quantifying energy gaps between typical operations, BAT, and emerging technologies, the analysis provides decision-makers with structured, evidence-based targets for both short-term efficiency measures and long-term technological transitions. Moreover, this approach reinforces the framework's value as a practical tool for linking process-level energy performance to broader environmental sustainability goals, including emissions reduction and resource optimisation.

4.2. Indicator-Level application

An indicator-level analysis has been conducted to demonstrate the proposed framework within the petrochemical industry. The petrochemical sector was selected due to its extensive scale of operations and significant environmental impact (Bathrinath et al., 2021). By applying the framework, its effectiveness in identifying, measuring, analysing, and improving environmental performance is illustrated.

It was performed via the following scope:

1. An indicator was selected from the finalised set of KPIs for evaluation.
2. A specific region with activity of petrochemical production was chosen to be the focus of the study.
3. Companies within the highlighted region were evaluated on the selected indicator.

Following the scope, the framework demonstrated its efficacy. It identified performance gaps and provided actionable steps for improvement. It was executed by evaluating the sustainable performance of a petrochemical company in the Middle East region (GPIC (Gulf Petrochemical Industries Co 2021)). The case study centred on reducing the value of a selected indicator: NO_x. This indicator is

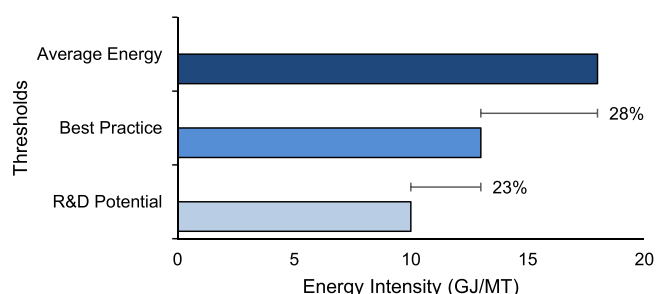


Fig. 3. Energy thresholds and differences for steam cracking.

measured using emissions in kilograms per metric ton of production. It should be noted that the analysed indicator did not have a predefined reference value from a relevant association. Thus, the second data collection method was utilised, which entailed setting the guideline value by gathering information from competitors in the industry.

The first step involved identifying benchmarks and potential improvements. The target, minimum and average values for NO_x were calculated using data acquired from five other petrochemical companies within the region (Saudi Basic Industries Corporation 2023, Qatar Petrochemical Company 2022, Jordanian Petroleum Refinery Co 2022, Sadara Chemical Company 2022, Advanced 2023), presented in Table 5.

Based on data from five regional petrochemical companies, the benchmark thresholds for NO_x emissions were defined as follows:

- Target value = 0.2328 kg NO_x/t product
- Average value = 0.6385 kg NO_x/t product
- Baseline value = 1.2177 kg NO_x/t product

These thresholds formed the basis for the reference lines and rating boundaries shown in Fig. 4. The list of possible improvements is listed in Table B1. in Appendix B.

Using the developed rating approach for the framework, it can be seen that in 2017, the company achieved a B rating for NO_x emissions, indicating that its performance was better than average. However, from 2018 to 2021, they achieved a C rating since they failed to keep their NO_x emissions below the average value. The suitable recommendation from the list in Appendix B offers a solution for lowering NO_x emissions by approximately 30–50 %, based on field-reported results in the literature (Zhang et al., 2017). The measure involves improving the spray lance and nozzle design to optimise the Selective Non-Catalytic Reduction (SNCR) system. It should be noted that the reduction range is indicative and depends on system configuration, reagent conditions, and baseline performance. With the expected improvement in emission reduction and under the assumption that production remains the same as in 2021, the company may be able to reduce its emissions significantly and revert to a rating of B, as presented in Table 6.

The case studies collectively demonstrate the framework's effectiveness in simplifying environmental sustainability assessment and translating results into actionable improvement strategies. In the process-level example, the framework identified a 28 percent gap between typical and best available practice energy performance in steam cracking, with a potential improvement of up to 50 percent based on emerging R&D technologies. In the indicator-level application, the analysis revealed that the case company could achieve a 40 percent reduction in NO_x emissions by implementing an optimised SNCR system.

By narrowing the assessment to targeted KPIs, the framework addresses concerns raised by Al-Sharrah et al. (Al-Sharrah et al., 2010) and De Faria et al. (de Faria et al., 2021) regarding the complexity caused by excessive indicators, facilitating clear and informed decision-making. A key strength lies in its use of market-derived benchmarks, consistent with the comparative approaches discussed by Swarnakar et al. (Swarnakar et al., 2021). This benchmarking method enables precise identification of performance gaps and facilitates targeted resource

Table 5
Summary of company data used for NO_x benchmarking.

(Murad M de et al., 2021) Company	Year	Value (Kg NO _x / t Product)
(Heink and Kowarik, 2010) Advanced Petrochemical Company	2023	0.3805
(Joung et al., 2013) Saudi Basic Industries Corporation	2023	0.5410
(Griffin et al., 2018) Sadara Chemical Company	2023	1.2177
Jordan Petroleum Refinery Company	2023	0.2328
Qatar Petrochemical Company	2023	0.8213

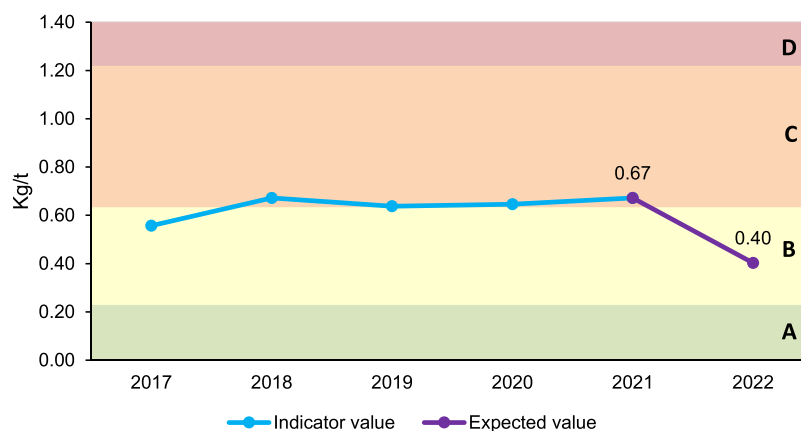


Fig. 4. NOx analysis results highlighting the tiered rating and expected value.

Table 6

Details for NOx case study results, improvement and rating.

Details	2021	Expected Value
NO _x annual emission (kg/MT)	0.66	0.402
Improvement percentage	-	40 %
Rating achieved	C	B

allocation for improvement. Unlike other emission-focused methods (Bathrinath et al., 2022; Cui et al., 2024), the framework provides flexibility for analysis at multiple operational scales depending on the user's objectives. Moreover, its flexible rating system allows continuous tracking and updating as new reference data become available, ensuring ongoing alignment with evolving sustainability goals.

Additionally, unlike many existing frameworks such as those described by Mohamed et al. (Mohamed et al., 2023), the proposed methodology includes specific, actionable recommendations directly linked to identified performance gaps. By focusing explicitly on environmental sustainability, the framework enables measurable progress in reducing the ecological footprint of chemical manufacturing operations. Overall, the results confirm that the framework offers a transparent, scalable, and practical mechanism for assessing and improving environmental performance across the chemical industry, while providing a replicable foundation for cross-sector implementation.

Beyond these findings, the framework demonstrates flexibility in supporting both indicator-based and process-based assessment paths. The indicator path is best suited for organisations seeking high-level benchmarking of specific environmental metrics (e.g., emissions or resource intensity), whereas the process path is more appropriate for in-depth operational analysis and technology evaluation. In practice, trade-offs may arise—such as between energy efficiency and NOx reduction—highlighting the importance of aligning performance improvement priorities with broader sustainability targets. Although the results were demonstrated in selected petrochemical and chemical processes, the underlying principles remain applicable across sub-sectors, with adjustments based on process configuration and data availability.

5. Conclusion

5.1. Overview

This research presented a structured and systematic approach to addressing critical environmental sustainability challenges within the chemical industry, as identified through an extensive literature review. The primary contributions of this study include the development of a tailored sustainability assessment framework, the identification and refinement of relevant Key Performance Indicators (KPIs) focused on

emissions, resource use, and pollutants, and the introduction of an innovative benchmarking methodology based on competitive market data.

The application of the framework through two illustrative case studies, process-level analysis (steam cracking) and indicator-level analysis (NOx emissions) highlighted clear, measurable opportunities for environmental performance improvements. Key findings indicate that adopting established best practices can result in approximately 28 % improvement in resource efficiency or emission reductions while emerging technologies under research and development could potentially offer up to a 50 % improvement compared to current industry standards.

The implications of this work are substantial, providing chemical companies with practical tools for accurate sustainability assessment, clear benchmarks for continuous monitoring, and structured recommendations enabling targeted improvements. By adopting the proposed framework, organisations within the chemical industry can effectively prioritise and systematically enhance their environmental performance, aligning their operations with global sustainability goals and regulatory expectations.

5.2. Limitations of the research and future considerations

This research has several limitations that must be acknowledged. First, the inherent complexity of chemical manufacturing processes and variability in product types make accurately rating selected indicators challenging, as specific indicators may exhibit broad ranges of values despite consistent production volumes. Second, the limited availability of detailed literature quantifying the specific impacts, costs, and implementation challenges of environmental improvement measures restricts deeper benchmarking and validation. Although many companies report sustainability progress, disclosures often omit methodological details, investment costs, and encountered operational barriers, thereby limiting comparative insight. Furthermore, confidentiality policies and data inconsistency across facilities can constrain benchmarking accuracy, though such challenges are gradually easing as corporate sustainability disclosures become more standardised.

To strengthen the robustness of future applications, sensitivity and uncertainty analyses should be incorporated to assess the influence of data variability, normalisation choices, and benchmark selection on the final results. Future research should also expand the framework to integrate economic and social sustainability dimensions, enabling a more holistic trade-off analysis that explicitly weighs environmental gains against financial and operational implications. Establishing standardised and scientifically grounded reference values that reflect product variability and process complexity remains another key priority. Finally, practical validation of the framework across a wider range of chemical subsectors, supported by quantitative performance tracking

and feedback loops, would enhance its reliability, transparency, and overall decision-support capability.

Dual publication

The results/data/figures in this manuscript have not been published elsewhere, nor are they under consideration (from you or one of our Contributing Authors) by another publisher.

Authorship

We have read the Nature Portfolio journal policies on author responsibilities and submit this manuscript in accordance with those policies.

Third party material

All of the material is owned by the authors and/or no permissions are required.

Ethics declaration

Not Applicable.

Consent to publish declaration

Not applicable.

Appendix A

Table A1

Table A1

Final Environmental KPIs Identified for the Chemical Industry, derived from a structured literature review (64 papers screened, 36 KPIs extracted, and 15 final indicators selected). Representative sources from which these KPIs were identified are listed for each category.

Dimension	Ref.	Name	Guideword	Definition	Unit	Method of Measurement
Emissions (Makarova et al., 2019; Acquaye et al., 2017; Chen et al., 2017)	1	Carbon Dioxide (CO ₂)	Reduce	Total weight of CO ₂ emitted over metric tons of production.	kg/ Mt	Continuous Emission Monitoring Systems (CEMS) or stack sampling
	2	Sulphur Oxides (SO _x)	Reduce	Total weight of SO _x emitted over metric tons of production.	kg/ Mt	Continuous Emission Monitoring Systems (CEMS) or stack sampling
	3	Nitrogen Oxides (NO _x)	Reduce	Total weight of NO _x emitted over metric tons of production.	kg/ Mt	Continuous Emission Monitoring Systems (CEMS) or stack sampling
	4	Volatile Organic Compounds (VOC)	Reduce	Total weight of VOC emitted over metric tons of production.	kg/ Mt	Flame ionisation detectors (FID) or photo-ionisation detectors (PID),
	5	Carbon Monoxide (CO)	Reduce	Total weight of CO emitted over metric tons of production.	kg/ Mt	Non-dispersive infrared (NDIR) sensors or gas filter correlation infrared
	6	Particulate Matter (PM)	Reduce	Total weight of PM emitted over metric tons of production.	kg/ Mt	Gravimetric sampling or optical particle counters
Resource Consumption (Grosse-Sommer et al., 2020; Kim et al., 2018; Saygin et al., 2011)	7	Water Use Intensity	Reduce	Total volume of water usage per metric ton of production.	m ³ / Mt	Flow meters in conjunction with production volume records
	8	Freshwater Withdrawal	Reduce	Amount of freshwater withdrawn from ground or surface water sources	Mm ³	Flow meters at withdrawal points
	9	Water Recycling and Reuse Rate	Increase	Percentage of wastewater that is treated and reused	(%)	Flow meters and water quality analysis to determine reuse levels
	10	Energy Use Intensity	Reduce	Amount of energy consumed per metric ton of production.	GJ/ Mt	Energy meters integrated with production management systems
Pollutants (Park and Behera, 2014; Lamjahdi et al., 2021; Tantisattayakul et al., 2016)	11	Material Use Intensity	Reduce	Total material usage per metric tons of production.	kg/ Mt	Inventory tracking systems and material flow analysis
	12	Hazardous Waste	Reduce	Total weight of hazardous waste directed to disposal over metric tons of production.	kg/ Mt	Weighing scales for solid waste, flow meters for liquid waste

(continued on next page)

Table A1 (continued)

Dimension	Ref.	Name	Guideword	Definition	Unit	Method of Measurement
	13	Solid Waste	Reduce	Total weight of solid waste directed to disposal over metric tons of production.	kg/Mt	Weighing scales at disposal points
	14	Liquid Effluent	Reduce	Total weight of liquid effluent directed to disposal over metric tons of production.	m ³ //Mt	Flow meters combined with pollutant-specific sensors or sampling
	15	Groundwater Contamination	Reduce	Total concentration of contaminants entering groundwater systems.	mg/L	Sample analysis for specific contaminants

Appendix B

Table B1

Table B1
Summary of process and indicator-level improvement options.

Recommendation	Reference	Description	Impact
Selective Non-Catalytic Reduction (SNCR)	(Zhang et al., 2017)	Optimisation of SNCR systems, such as improving spray lance and nozzle design.	30 to 50 %
Selective Catalytic Reduction (SCR)	(He et al., 2022)	Uses SCR technology to reduce NO _x emissions by converting them into nitrogen and water.	Reduce NO _x emissions.
Fluid catalytic cracking (FCC) process	(Barthe et al., 2015)	Specially formulated chemicals added to the FCC to control and minimise NO _x formation during the refining operations.	28 % to 76 %, depending on the operational conditions and initial NO _x levels.

Data availability

All data that support the findings of this study are included within the article.

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