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Replication assessment "In a nutshell"

The replication assessment of WaterProof in Colombia finds strong potential for electrochemical CO_2-to-formic acid conversion, leveraging the country's low-carbon electricity mix and strategic CO_2 sources in cement plants, with textile and leather industries as key off-takers. Main barriers include weak policy incentives, lack of Carbon Capture, Use and Storage (CCUS) regulation, and low domestic green chemical production. Scenario planning for 2035 highlights that high policy support and rapid industrial adoption are critical for success. Recommended actions focus on integrating carbon capture and utilization CCU into mitigation programs, enabling green procurement, fostering industrial symbiosis, and securing pilot-scale production with renewable power, carbon market revenue, and international certification compliance.

Publishable executive summary

The WaterProof (urban WAste and water Treatment Emission Reduction by utilizing CO_2 for the PROduction Of Formate derived chemicals) technology concept is based on a process of electrochemical conversion of CO_2, originating from solid waste incineration and wastewater treatment processes, into commercially valuable substances such as formic acid, which can be used as an input to produce cleaning detergents, leather tanning processes, and for the synthesis of Acid Deep Eutectic Solvents (ADES), this last used for the recovery of precious metals from wastewater sludge and incineration ash. Additionally, by-products such as peroxides, generated by the electrochemical conversion process, can be used to remove contaminants from wastewater, re-entering the waste treatment cycle. This technological alternative contributes to the reduction of GHG (greenhouse gas) emissions, specifically CO_2, using carbon, while also generating an alternative to fossil raw materials with the production of formic acid in a sustainable route.

The WaterProof project focus is ensuring transferability and replication with a multidisciplinary research approach, needed for enhance technical efficiency of CO_2 conversion to Formic acid (FA), by assessing scientific, environment, social and economic impacts, and scale-up replication potential in different contexts. To this end, **Work Package 4 (WP4) – Impact and Transfer of the Concept**, led by nova-Institute GmbH, evaluates the environmental, economic, and social impacts of the process and fosters knowledge transfer to accelerate scientific progress. Within WP4, **Task 4.5 – Replication Potential Assessment**, led by CTA, analyses the opportunities for replication and adoption of WaterProof technologies in developing economies, with Colombia as a case study. This task also explores pathways for broader dissemination and social appropriation of the technologies in similar contexts. This assessment is based on the results of environmental, social, market, and economic analyses **Tasks 4.1 to 4.4** projected impact and a prospective assessment for the target replication context included in this derivable **D.4.4 Full replication assessment.**

This report presents a full replication assessment of the WaterProof technology in Colombia, focusing on electrochemical CO_2 conversion to formic acid. The analysis combines Life Cycle Thinking (LCT), gap analysis, and prospective scenario planning to evaluate technical, economic, environmental, and social feasibility. The study identifies critical barriers, including the lack of CO_2 utilization incentives, as subsidies for chemical products generated by CCU technologies, the absence of specific CCUS regulation, and low domestic production of green chemicals. Benchmarking against global Life Cycle Assessment results shows that Colombia's low-carbon electricity mix (0.11 kg CO_2/kWh) enables competitive Global Warming Potential (GWP) performance if process efficiency and product concentration targets are met. Scenario planning for 2035 explores four possible future scenarios based on the level of policy support and industrial adoption rate: Green Acceleration, Slow Lock-in, Tech-led Niche, and Regulatory Drag. The cement industry, exemplified by Argos Cartagena, is identified as a strategic CO_2 source due to its high-volume, stationary emissions, while the textile and leather sectors present potential as off-takers, driven by export-market compliance requirements. Colombia's regulatory framework is progressing through instruments such as the Colombian Strategy for Climate-Resilient Low-Carbon Development (ECDBC), Law 2099/2021, and the Draft CCUS Decree; however, delays in implementation remain a significant challenge. Recommendations include integrating CCU into national mitigation programs, enabling green procurement, fostering industrial symbiosis agreements, developing high-purity formic acid pilot plants with renewable power purchase agreements, and leveraging carbon market monetization and international certification schemes such as Carbon Border Adjustment Mechanism (CBAM) and Registration, Evaluation, Authorisation and Restriction of Chemicals (REACH) to enhance competitiveness in global markets.

Methodological approach

The general methodology of this assessment combines a structured review of Colombia's policy and industrial context with analytical tools to evaluate the feasibility of WaterProof technologies. Three main approaches were applied: (i) a gap analysis to identify regulatory, technical, and market barriers; (ii) Life Cycle Thinking (LCT) to assess environmental and resource trade-offs; and (iii) prospective scenario planning to explore alternative future scenarios up to 2035. Together, these methods provide a robust basis to guide decision-making and support the design of a business case for CO_2 utilization in Colombia.

Step-by-step, the applied methodology included the following steps:

1. Context review
    - Analysis of Colombia's regulatory, industrial, and market frameworks.
    - Sources included national climate strategies (ECDBC, Law 1931/2018, Law 2099/2021), sectoral roadmaps, trade data, and expert consultations.
2. Gap analysis
    - Identification of barriers and enablers (policy, technical, industrial, and social).
    - Applied structured tools such as the Vester matrix and expert interviews to prioritize critical gaps.
3. Life Cycle Thinking (LCT)
    - Benchmarking with international Life Cycle Assessment (LCA) studies.
    - Evaluation of environmental performance, energy demand, and potential trade-offs.
4. Prospective scenario planning (horizon 2035)
    - Definition of key uncertainty axes based on gap analysis.
    - Development of four contrasting futures to test the robustness of WaterProof implementation in Colombia.

1 Introduction: Why does this technology matter for Medellín?

This derivable focuses on the analysis of the current situation in Colombia, specifically in Medellín, regarding solid waste, wastewater, and CO_2 emissions generation and management for assess the potential for replication and appropriation of WaterProof technology, based on the electrochemical CO_2 conversion into value-added carbon-based substances such as Formic acid (FA), this acid is used in eco-friendly products like cleaning agents and fish leather tanning, and further processed into deep eutectic solvents (ADES) for recovering metals from sludge and ash. Powered by renewable energy, the system supports a clean, circular, and climate-neutral water cycle. A pilot plant will be built to scale the technology. Projects such as WaterProof illustrate how international cooperation can accelerate the integration of CCU systems into real-world wastewater facilities, creating synergies across climate, environmental, and economic objectives. By closing carbon loops within municipal infrastructure, these initiatives contribute to both local resilience and global decarbonization efforts, closing the productive process cycle.

Some projected impact and prospective assessment for the target replication context as a comparative analysis with the technical specifications required for the technology installations in the demo sites selected in The Netherlands and conditions in Colombia, specifically in Medellín, a city recognized as national leader in water management, purification, wastewater treatment systems, and urban solid waste management, sustainable transportation, and commerce, among other areas.

Due to all these advantages offered by the city, access to these quality services, and growing technological, scientific, and innovation development, Medellín is a city that has experienced greater urban growth in recent years, and, as a result, greater generation of waste and emissions. This has led to a crisis in the final disposal of solid waste in landfills that are exceeding their storage and treatment capacity, creating a medium-term risk to the health and economy of its inhabitants due to the generation of emissions, leachate, pest problems, diseases, and waste transportation.

This document presents an integrated approach of dimensions of the technology and applied to the individual situation in Colombian and Medellín context.

(1) The overview of the CO_2 emissions, research, and availability of CCU technologies, projects in Colombia and Medellín, based on screening

publications, database information, international CCU experts and the knowledge of experts interviewed.

(2) Analysis of gaps and opportunities (political-legal, technological, social, and economic) to understand the potential benefits and the work required to close the gap with WaterProof technologies.

(3) Assess the sustainability of introducing the technologies developed under the WaterProof project into the Medellín market, with the aim of obtaining insights into the relevance and sustainability of such transfer.

1.1 Carbon capture and usage overview

The Carbon Capture, Utilization and Storage (CCUS) framework encompasses a broad spectrum of technologies aimed at mitigating anthropogenic CO_2 emissions, either through long-term geological storage or by converting captured carbon into commercially valuable products. While Carbon Capture and Storage (CCS) plays a key role in hard-to-abate industrial sectors, increasing attention is being directed toward Carbon Capture and Utilization (CCU), due to its potential to not only mitigate emissions but also replace fossil-based raw materials across diverse value chains.

In CCU, CO_2 is captured and used either directly (i.e. not chemically altered) or indirectly (i.e. transformed) into various products (Emmanuel et al., 2025). Indirectly CCU technologies enable the transformation of CO_2 into a variety of carbon-based products, including fuels (e.g., methanol, methane, syngas), platform chemicals (e.g., formic acid, urea, ethylene), polymers, and construction materials. Around 230 Mt of CO_2 are currently used each year worldwide mainly in direct use pathways in the fertiliser industry for urea manufacturing (~130 Mt) and for enhanced oil recovery (~80 Mt) (Emmanuel et al., 2025) (IEA, 2024).

These processes rely on several conversion pathways—thermochemical, biochemical, photochemical, and particularly electrochemical methods, the latter gaining momentum due to their compatibility with renewable electricity sources and operation under mild conditions (Dziejarski et al., 2023). Among these**, the electrochemical reduction of CO_2 to formic acid (HCOOH) stands out as a promising pathway**, as Converts in a more direct way CO_2 from point sources (e.g. incineration, wastewater treatment) into a valuable commodity chemical, coupling emission reduction with resource recovery, also needs mild conditions (ambient temperature and pressure), reducing infrastructure and operational costs compared to thermochemical routes, and in the case of Formic acid, the synthesis route is one of the simplest and most efficient electrochemical CO_2 reduction pathways. **This compound can be applied in textile, pharmaceutical, cleaning, and leather tanning industries.** However, formic acid production from CO_2 is still at low-to-medium Technology Readiness Levels (TRLs), requiring further optimization to enhance catalyst performance, energy efficiency, and product selectivity (Duarah et al., 2021).

CO_2 utilization for synthetic fuels, chemicals, and construction materials is expanding rapidly. By 2030, planned projects could capture nearly 15 Mt of CO_2 per year, with 8 Mt used for synthetic fuels—globally about two-thirds of what's needed under the Net Zero 2050 scenario (IEA, 2021). Yet, only a small share, just over 4 Mt, would come from biogenic or atmospheric sources, which is essential for meeting climate goals.

The urgency of CCU adoption is particularly evident in the context of waste management systems, which include solid waste, wastewater, and Green House Gas Emissions GHG. These systems are highly influenced by demographic, socioeconomic, and technological variables—such as population growth, industrial activity, and infrastructure—which directly impact the volume and complexity of waste streams (Vaverková, 2019)(Zhou et al., 2025). Efforts to adopt this technology in the world are shown in Figure 1-1.

According to IEA, 2025:

- **United States leads in CCU** deployment with the highest number of industrial CO_2 utilization facilities, and accounted for **33% of global CO_2 consumption in 2015** for applications like methanol, fertilizers, and ethanol production.
- **China ranks second** in scientific output on CCU and **contributed to 22% of global CO_2 consumption** in 2015**,** with strong activity in methanol synthesis and chemical conversion.
- Europe, particularly the **UK, Germany, the Netherlands, and Norway, supports large-scale CCU project**s with coordinated funding and policy efforts, **representing 16% of global CO_2 consumption** in 2015 and significant scientific leadership

Figure 1-1. CCU global actions.

Facilities like landfills, composting plants, incinerators, and wastewater treatment plants (WWTPs), initially conceived to address pollution, have become significant sources of CO_2 and CH_4 emissions (Zhou et al., 2025). These systems also produce secondary residues such as sludge, leachate, and off-gases, which often lack value-added utilization pathways. This **calls for a shift from waste "treatment" to waste valorization, in line with circular economy principles and international frameworks** such as the European Green Deal and carbon neutrality targets by 2050 (European Commission, 2020).

CCU offers a promising route to address this challenge. For instance, **electrochemical CO_2 conversion in WWTPs or incineration plants can produce formic acid, which can be further transformed into acidic deep eutectic solvents (ADES) for precious metal recovery from incinerator ash or sewage sludge.** Additionally, peroxides, another byproduct, have shown utility in degrading pharmaceuticals and pesticides in wastewater (Cuéllar-Franca & Azapagic, 2015). In parallel with the critical need to transition from fossil-derived chemicals.

Despite these opportunities, technical and economic barriers remain. Electrochemical and catalytic pathways often involve high energy consumption, while low CO_2 concentrations in waste streams and scaling limitations further restrict deployment. The economic viability of CCU is tightly linked to renewable energy availability, CO_2 feedstock purity, and the market value of derived products (Dziejarski et al., 2023).

In conclusion, CCU technologies, especially those based on electrochemical conversion, represent a transformative opportunity in the valorization of emissions in the waste sector. Their capacity to turn emission liabilities into economic assets aligns them with core principles of industrial sustainability and the transition toward a low-carbon economy. **Ongoing investments in research, demonstration, and policy support will be essential to realize their full potential at scale**, some key insights for CCUS technologies applications are shown in Figure 1-2.

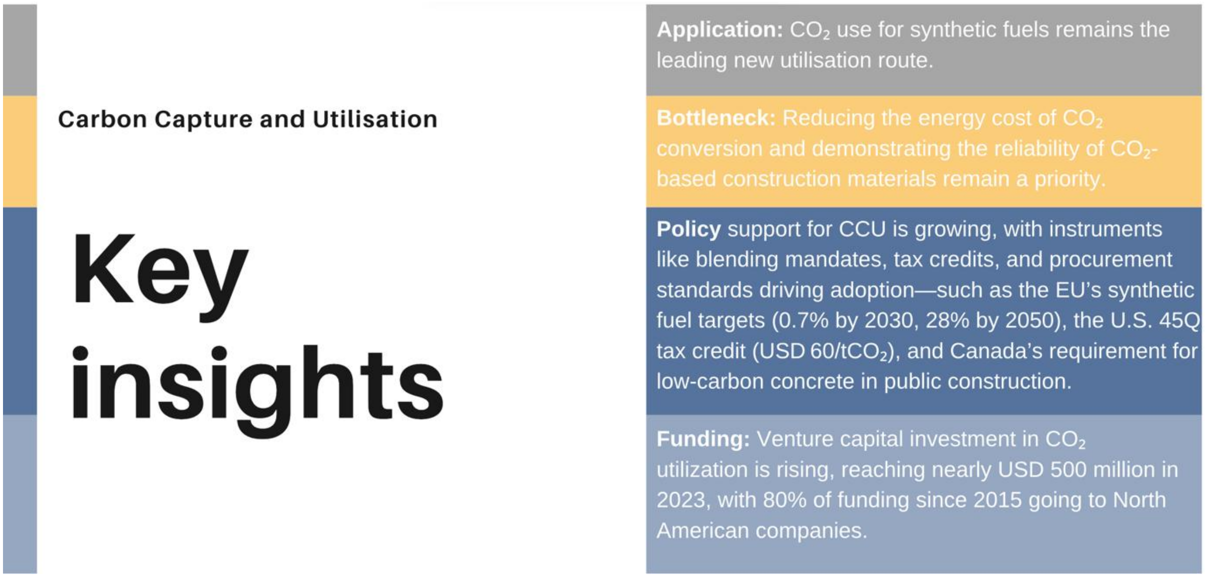

Figure 1-2. CCU Key insights

The Netherlands is a key player in advancing CCU technologies in Europe, particularly through large-scale research and innovation projects. While it does not yet host commercial electrochemical CO_2 conversion from wastewater, Dutch institutions are active in developing solutions like bioelectrochemical systems, membrane technologies, and microalgae-based CO_2 utilization.

A flagship initiative is the WaterProof project, funded by Horizon Europe, which utilizes an electrochemical process to convert CO_2 captured from wastewater and waste incineration into formic acid.

To maximize its impact, the project must develop a strong business case and explore opportunities to apply the technology in new regions—such as Medellín.

1.2 Medellin's scenario

At the national level, **Colombia is laying the foundation for carbon capture, utilization, and storage (CCUS) through a draft regulatory framework proposed by the Ministry of Mines and Energy** (Minenergía, 2022). This framework outlines procedures for CO_2 capture, transport, utilization, and storage, aiming to enable future deployment. **The government has also identified a key storage cluster across Santander, Antioquia, and Norte de Santander, with a capture potential of 4.3 Mt CO_2/year, mainly linked to oil, power, and cement industries—sectors with a strong presence in Medellín** (IEA, 2023).

Medellín, Colombia's second-largest city and a hub for science, technology, and innovation, presents a compelling context for the implementation of Carbon Capture and Utilization (CCU) technologies. With a population of over 2.5 million and a growth rate nearing 0.86% per year (Jordan et al., 2017), the city faces mounting pressure on its waste management and emissions systems due to accelerated urban expansion. In 2020 alone, Medellín generated 1.77 million tons of urban solid waste (Castro Guamán & Vargas Sáenz, 2021), of which approximately 672,740 tons were disposed of at the La Pradera landfill, producing over 850,000 tons of CO_2, plus additional emissions from methane combustion (Rendón et al., 2021). The landfill also generates 333,750 m^3/year of leachate, which requires further treatment and results in sludge production (Emvarias, 2020).

The wastewater sector further adds to the emissions landscape. **The Aguas Claras and San Fernando wastewater treatment plants, operated by Grupo EPM, collectively serve nearly 2.8 million inhabitants and process 128 million m^3/year of wastewater** (EPM, 2022). In 2021, CO_2 emissions from wastewater treatment processes in the Aburrá Valley reached 98,278 tCO_2-eq, with 27,686 tons of sludge generated (Grupo EPM, 2021). Although EPM has implemented mitigation measures such as biogas recovery and green hydrogen production—avoiding nearly 16,800 tCO_2-eq—residual emissions and material waste remain significant.

CCU technologies offer Medellín an opportunity to close these materials and carbon loops. By capturing CO_2 from wastewater and landfill operations and converting it into valuable products such as formic acid, solvents, or bio-based materials, the city could reduce its climate impact while generating new economic value. The city's geographic and institutional advantages—such as its designation as Colombia's Science, Technology, and Innovation District, and its active public utility sector—create favorable conditions for piloting CCU systems. Moreover, the integration of CCU aligns with national goals for circular economy, climate neutrality, and emission reduction under regulatory frameworks like Resolución 909 de 2008 (Minambiente, 2008).

In Medellín, the implementation of Carbon Capture and Utilization (CCU) and Carbon Capture, Utilization, and Storage (CCUS) technologies is still in the early stages, with current efforts mainly focused on academic research and development. One notable example is the work carried out by the Petroleum and Gas Engineering Research Group (Michael Polanyi) at the National University of Colombia – Medellín campus. The group is investigating enhanced oil recovery (EOR) using chemically modified gases, aiming to both increase hydrocarbon production and mitigate CO_2 emissions. Their approach emphasizes minimizing potential formation damage typically associated with gas injection techniques (UNAL Medellín). Additionally, Universidad EAFIT has developed a lab-scale plant capable of selectively removing CO_2 from combustion gas mixtures. This project, led by a student research group, seeks to contribute to emission reduction through innovative capture technologies (EAFIT, 2018). While these initiatives represent meaningful progress in research and policy, no large-scale commercial CCU or CCUS projects have yet been identified in Medellín. Scaling up such technologies will require stronger collaboration between academia, government, and the private sector to advance applied research and technology transfer.

Cementos Argos, one of the leading cement producers in Colombia and Latin America, has integrated carbon capture and utilization (CCU) into its broader decarbonization strategy. Given that over 60% of cement sector emissions come from the clinker production process, Argos has launched a pilot project to capture CO_2 for potential use in biofuel production. The company has also supported research involving microalgae for biological CO_2 capture, aiming to transform emissions into useful biomass for bio-based products. Additionally, Argos has aligned its climate goals with the Science-Based Targets initiative (SBTi) and is recognized for its leadership in climate reporting and mitigation. These initiatives highlight the growing role of the private sector in Medellín in advancing CCU technologies and underscore Argos' potential to act as a key partner in scaling industrial decarbonization solutions in collaboration with public utilities, academia, and city policymakers.

To scale these technologies, Medellín must now develop a strong business case that demonstrates the technical, environmental, and economic viability of CCU, potentially serving as a model for similar urban regions in Latin America. As part of the study focused on Colombia, a set of recommendations has been developed to address the local context. These recommendations are intended to guide the implementation of CCU (Carbon Capture and Utilization) technologies in Colombia and are visually summarized in Figure 1-3 of the document.

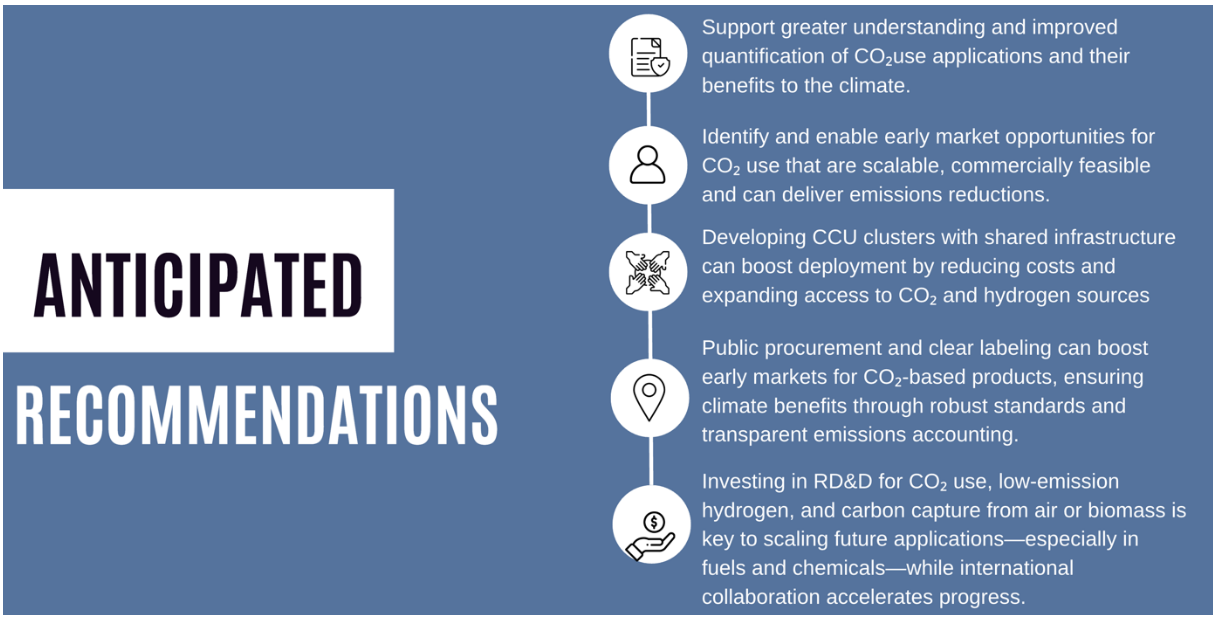

Figure 1-3. Anticipated recommendations for Colombian context

2 Gap analysis and replicability assessment

This chapter aims to identify and analyze the key technical, regulatory, economic, and social gaps, that could hinder the implementation of CCU technologies such as WaterProof in Medellín, Colombia. Given that formic acid synthesis from CO_2 remains an emerging technology with low readiness levels (Kang et al., 2021) it is essential to assess local enabling conditions and constraints that affect its transferability and scale-up. By validating these gaps through engagement with stakeholders, this section also explores actionable pathways to close them, ensuring that the WaterProof concept can be meaningfully adapted and replicated in Colombia. Ultimately, this analysis supports the broader goal of fostering a sustainable circular economy and advancing the strategic objectives of the HORIZON Europe Action Plan beyond Europe.

2.1 Baseline: understanding the current landscape

To assess the replicability of WaterProof technologies in Colombia, it is necessary to understand first the broader landscape in which these innovations would be implemented. This section provides a baseline analysis that includes, on one hand, the current state of emissions and waste generation and management—both globally and specifically in Colombia and Medellín—and, on the other, the enabling conditions that support circular technologies like CCU. These include technological maturity, economic drivers, regulatory frameworks, and social acceptance. Together, these two dimensions help identify the starting point for replication, highlight existing gaps, and frame the opportunities for adaptation of the WaterProof model in the local context.

2.1.1 Emissions and wastes management context

Global greenhouse gas (GHG) emissions are dominated by a few key sectors, with CO_2 as the principal contributor (IEA, 2020; Statista, 2023). As of 2023, the power generation sector is the largest emitter, responsible for 26% of global emissions, primarily due to coal-fired electricity production. This is followed by transportation, which contributes 15%, mainly from road vehicles, and industrial processes, accounting for 11%, including emissions from manufacturing and construction activities Figure 2-1. These top three sectors underscore the central role of fossil fuels in the global emissions landscape and highlight where decarbonization efforts are most urgently needed.

Although waste management and treatment represent a smaller share—approximately 4% of global emissions (Figure 2-1**)—this sector is especially relevant due to its release of methane (CH_4) and CO_2 from landfills, wastewater treatment, and waste incineration**. These emissions are particularly challenging to mitigate due to their dispersed nature and the organic content of waste streams. Nonetheless, they present a valuable opportunity for innovation through CCU technologies, which can capture CO_2 from these processes and transform it into valuable products, contributing both to emission reduction and the development of a circular economy.

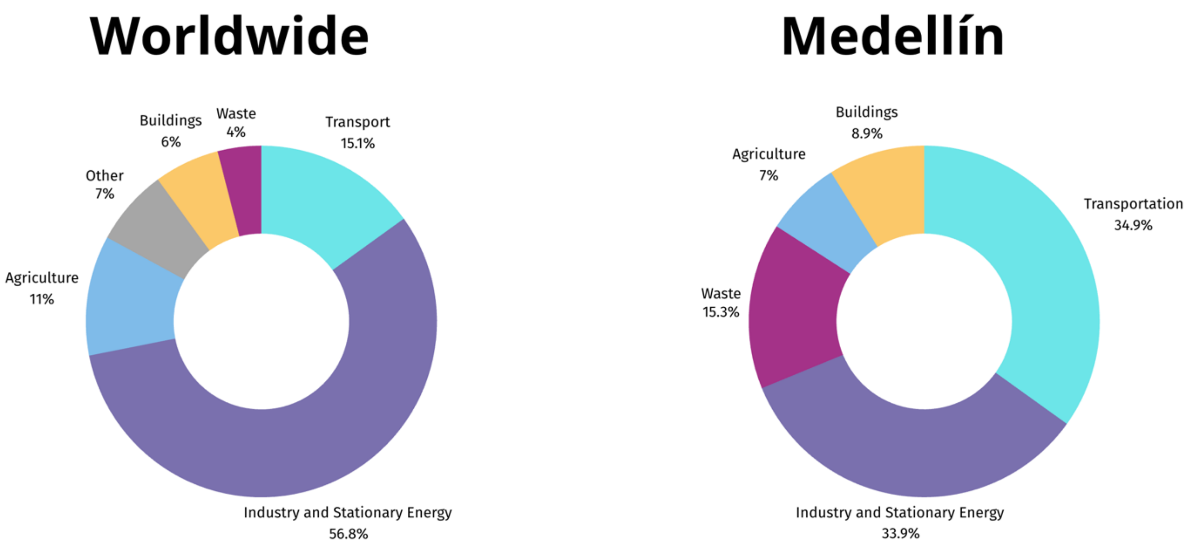

Figure 2-1.Comparison of the greenhouse gas emissions distribution worldwide (left) (Statista, 2023) and Medellín, Colombia (right) (Quiceno & Arcila Marin, 2023).

Globally, carbon emissions regarding waste treatment are 4% for the total emissions (Figure 2-1), the mitigation and utilization of carbon emissions rely on a range of strategies including energy efficiency improvements, fuel switching, electrification, and the expansion of renewable energy. Among these, **Carbon Capture, Utilization, and Storage (CCUS) is increasingly recognized as a key solution for reducing emissions in hard-to-abate sectors such as cement, steel, and chemicals** (IEA, 2020). According to the International Energy Agency (IEA), achieving net-zero emissions by 2050 will require CCUS to capture and store approximately 6.2 gigatonnes (Gt) of CO_2 annually by mid-century (IEA, 2021b), a volume roughly equivalent to the combined annual emissions of the United States and the European Union.

High-profile examples of CCUS projects include Sleipner (Norway), the world's first offshore CO_2 storage project operating since 1996; Boundary Dam (Canada), the first commercial-scale CCS facility at a coal power plant; and the Port of Rotterdam CCUS Hub (Netherlands), which captures industrial CO_2 for offshore storage under the North Sea (IEA, 2024). In the U.S., the Petra Nova project and fiscal incentives under the Inflation Reduction Act have further accelerated CCUS investment and deployment (U.S. Department of Energy (DOE), 2023).

In Medellín and the Aburrá Valley, the waste management sector, including solid waste and wastewater treatment, accounts for approximately 15.3% of total regional greenhouse gas emissions, highlighting its relevance as a target for carbon capture and utilization (CCU) technologies (Figure 2-1). In 2021, emissions from urban waste management reached around 923,484 tCO_2-, with La Pradera landfill alone responsible for 856,934 tCO_2-eq, mainly due to the decomposition of organic matter and methane combustion (Grupo EPM, 2022). Additionally, the Aguas Claras and San Fernando wastewater treatment plants, operated by Grupo EPM, contributed 98,278 tCO_2-eq and generated over 27,000 tons of sludge annually (Grupo EPM, 2022). While emissions from this sector are smaller compared to energy or transportation, they offer strategic advantages: **emissions are concentrated in fixed locations, facilitating capture; the sector produces methane (CH_4), a greenhouse gas with 25 times the global warming potential of CO_2; and it generates valuable by-products such as sludge, leachate, and gas streams, which can be transformed through circular approaches like those proposed in the WaterProof project.** These factors position Medellín's waste sector as a key entry point for CCU deployment, supported by the city's infrastructure, environmental urgency, and technical capacity for innovation.

In Medellín and the Aburrá Valley, the waste management sector—including solid waste and wastewater treatment—accounts for approximately 15.3% of total regional greenhouse gas emissions, highlighting its relevance as a target for carbon capture and utilization (CCU) technologies.

Colombia has adopted a multi-sectoral approach to reduce GHG emissions, aligned with its commitment under the Paris Agreement and its Nationally Determined Contributions (NDCs). **The country has pledged to reduce 51% of its GHG emissions by 2030 compared to the business-as-usual scenario, and to reach carbon neutrality by**

2050 (Minambiente, 2017)**.** Medellín has implemented a range of mitigation strategies targeting key emission sectors such as transport, energy, and waste (Figure 2-2). **Medellín is a member of the C40 Cities Climate Leadership Group**, a network of the world's megacities committed to addressing climate change (C40 cities, 2025). The city has been recognized for its leadership in public transport electrification, green urban infrastructure, and its Climate Action Plan aligned with the Paris Agreement. The initiatives highlighted below reflect the city's transition toward cleaner technologies and circular solutions, positioning Medellín as a regional leader in urban climate action.

National

01 **Carbon Neutrality Roadmap 2050**
Defines long-term mitigation pathways for energy, transport, waste, industry, and land-use sectors.

02 **Carbon Tax and Offset System**
In place since 2017, Colombia imposes a tax on fossil fuel CO_2 emissions, allowing companies to compensate emissions through approved mitigation projects (Decree 926 of 2017).

03 **Energy Transition Law (Law 2099 of 2021)**
Promotes clean energy, hydrogen development, and carbon capture technologies.

04 **CCUS Regulatory Proposal (2023)**
Draft regulation by the Ministry of Mines and Energy to enable CCUS projects covering capture, transport, utilization, and storage of CO_2.

Medellín

01 **Plan de Acción Climática del Valle de Aburrá (PACVA)**
Aims to reduce GHG emissions in the region by 20% by 2030 and 35% by 2050. Focus areas include transport, energy, and solid waste.

02 **Electrification of Public Transport**
Medellín has retrofitted over 500 buses with electric engines, reducing ~4,000 tons of CO_2 annually.

03 **EPM: Green Hydrogen Pilot and Biogas Recovery**
EPM's Aguas Claras wastewater treatment plant implements biogas-to-energy systems and launched a green hydrogen production pilot, which avoided ~16,800 tCO_2-eq in 2021.

04 **Emvarias: La Pradera Landfill Gas Management**
Responsible for over 850,000 tCO_2-eq annually, this site employs methane capture and combustion systems to reduce emissions from organic waste decomposition.

National Policies and Local Strategies for Carbon Mitigation

Figure 2-2 National Policies and Local Strategies for Carbon Mitigation. Own construction, multiple sources.

2.1.2 WaterProof technology description

The WaterProof project develops a novel electrochemical pathway for CCU that transforms CO_2 emissions from urban waste incineration and wastewater treatment plants into formic acid (HCOOH), a versatile green chemical with applications in the cleaning, leather tanning, and chemical recovery sectors (Figure 2-3).

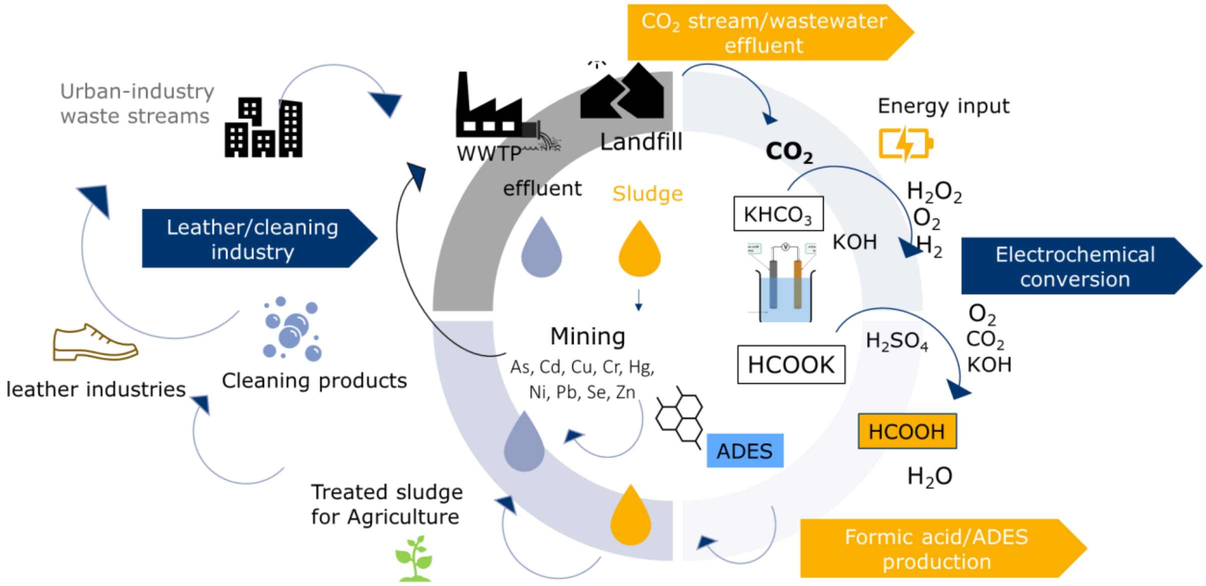

Figure 2-3.WaterProof concept adapted from (WaterProof project, 2023)

The system is designed for integration into urban-industrial infrastructures, with a pilot plant in the Netherlands already operating at a TRL 6 level that demonstrates real-world feasibility. Within the WaterProof project, analyses have been carried out using information of CO_2 captured from biomethane production at the Waternet wastewater treatment plant in Amsterdam, as well as from CO_2 captured at the HVC bio-energy plant in Alkmaar. The latter serves as the location of the pilot plant, where the captured CO_2 will be converted into formic acid.

WaterProof represents a circular process that transforms unavoidable CO_2 emissions into valuable chemical products. In doing so, it not only contributes to decarbonization targets but also enhances resource efficiency and promotes industrial symbiosis. The formic acid produced has broad potential applications, ranging from wastewater treatment, metal recovery, and agriculture to the chemical industry, leather processing, and cleaning products—highlighting the versatility and cross-sector relevance of the technology.

2.1.3 How does the socio-technical ecosystem in Medellín support circularity?

Medellín offers a highly promising socio-technical ecosystem for the deployment of circular technologies such as WaterProof. The city combines robust urban infrastructure, anchored by some of the largest wastewater treatment facilities in Colombia, with a strong public utility system (EPM), and an emerging innovation landscape reinforced by its designation as a Science, Technology, and Innovation District. Public institutions like the Área Metropolitana del Valle de Aburrá, along with universities and research centers (e.g., UdeA, EAFIT, UPB), play a key role in environmental governance, R&D, and technology transfer.

At the policy level, Medellín's Climate Action Plan and the region's Circular Economy Strategy provide strong institutional support for defossilisation and resource recovery. In parallel, industrial stakeholders, particularly in the cleaning products, leather tanning, and bio-based materials sectors, are increasingly seeking low-carbon, biodegradable alternatives to traditional petrochemical inputs. This trend positions **Medellín as a promising emerging market for sustainable chemical solutions such as formic acid derived from captured CO_2. With an established industrial base and growing interest in circular value chains,** the city offers multiple entry points for integrating CO_2-derived compounds into its local economy in alignment with environmental and climate goals.

On the social front, the city hosts an active network of environmental organizations and citizen groups that have historically participated in sustainability dialogues and infrastructure planning.

While challenges remain, such as regulatory gaps for CO_2-based products, and the need for stronger private sector alignment, **the convergence of institutional commitment, technical capacity, and market interest makes Medellín a fertile ground for piloting and scaling CCU innovations**. This potential will be further analyzed through a multi-dimensional lens in the following sections.

Sustainability expert's roundtable

A group of sustainability experts from diverse industries and sectors was convened to share their perceptions of technologies like WaterProof. They discussed how to transform CO_2 emissions into valuable products in Colombia, agreeing that beyond the technology itself, WaterProof's success hinges on aligning economic incentives, regulatory commitments, environmental education, and robust value chains that engage all stakeholders. Some important conclusions are:

- **Citizen and corporate education**: Although large companies (e.g., EPM) have carbon-neutrality targets, most citizens and Small and Medium-sized Enterprises SMEs do not view CO_2 capture as an everyday priority. Ongoing environmental education is needed to move the topic from "background" to daily practice.
- **Supply-chain design and governance**: Creating CO_2-derived products is not enough: the entire value chain, from capture to delivery, requires clear regulation and governance to prevent initiatives from faltering on the route.
- **Local demonstrations and business cases**: Companies need tangible results (e.g., pilots in boilers, workshops, or plants) showing real operational savings, such as reduced fuel consumption by reusing CO_2, before committing investment.
- **Economic incentives and subsidies**: With SMEs comprising 92% of the market, CO_2-based products must be supported by subsidies or cost-benefit mechanisms to ensure accessibility; otherwise, mass adoption will be unfeasible.
- **Consumer culture and gamification**: As demonstrated by other programs like Medellín's Metro Cívica card, incentives (e.g., redeemable points, recognition) can embed sustainable product use into consumers' and employees' routines, amplifying impact.

"A product can be outstanding, but without supportive regulation, it will die along the way"

Sustainability expert

2.2 Assessment in capabilities, technologies and circularity models in place

2.2.1 Legislation: what policies hinder implementation?

Although Colombia has a solid regulatory framework covering CO_2 emissions, wastewater discharges, and solid waste management (Figure 2-4), **the country still lacks specific operational and technical regulations for Carbon Capture, Utilization, and Storage (CCUS) technologies**. Existing standards, such as emission limits for stationary sources (Resolution 909 of 2008, (Minambiente, 2008), biosolid reuse (Decree 1287 of 2014, (Minambiente, 2014), and effluent discharge control (Resolution 631 of 2015, (Minambiente, 2015), are enforced through licensing mechanisms and oversight by environmental authorities. However, while these regulations help set the baseline for environmental compliance, they do not yet provide a comprehensive framework to support the safe, scalable deployment of CCUS or electrochemical conversion technologies like WaterProof.

While Colombia's National Circular Economy Strategy-ENEC (Minambiente, 2019) offers a broad policy vision that encourages cleaner production and using renewable, biodegradable, or secondary raw materials, it falls short of addressing the regulatory needs of emerging technologies such as CO_2 utilization. ENEC aligns conceptually with the goals of projects like WaterProof, particularly through its promotion of eco-efficient industrial models and support for value chains like biomass, water, and energy, but it does not provide enforceable standards for integrating CO_2-derived products into existing regulatory frameworks.

The primary regulatory gap lies in the **absence of technical standards for CO_2 utilization**, particularly regarding the use of CO_2-derived compounds such as formic acid, hydrogen peroxide, or deep eutectic solvents (ADES). This void creates uncertainty for innovators and investors. **Although Law 2099 of 2021 (Función pública, 2021)**mandates the development of CCUS regulation and **Decree 1597 of 2024 (Función pública, 2024)** outlines high-level policy guidelines for hydrogen and CO_2 use, **no enforceable procedures currently exist for CO_2 capture from waste streams, its conversion via electrochemical processes, or the downstream application of resulting chemicals**.

Furthermore, product use in industries like leather, cleaning, agriculture, and paper is governed by diverse regulations for chemical safety, heavy metal content, and water discharge quality (e.g., DQO, chlorides, sulfates), but **does not yet account for CO_2-based alternatives**. For example, while peroxides and acids like formic acid are regulated under transport and labeling laws, there is no specific pathway for circular products derived from captured CO_2.

From a market perspective, **Colombia offers incentives for CCUS-related investments (e.g., tax benefits for capital equipment),** and the National Development Plan references CCUS as a strategic technology. Yet, **the absence of binding norms on monitoring, quality standards, and permitting for CCU processes remains the key barrier to national deployment**. In cities like Medellín, where industrial and environmental conditions make CCU applications highly viable, this gap could hinder innovation unless proactive regulatory development accompanies technological pilots.

In conclusion, while Colombia is advancing in climate commitments and environmental control, **the regulatory void around CCUS implementation, particularly for utilization**, represents a strategic bottleneck. Addressing this gap would not only enable WaterProof's success but also unlock broader opportunities for circular and decarbonizing technologies aligned with the country's carbon neutrality and industrial modernization goals.

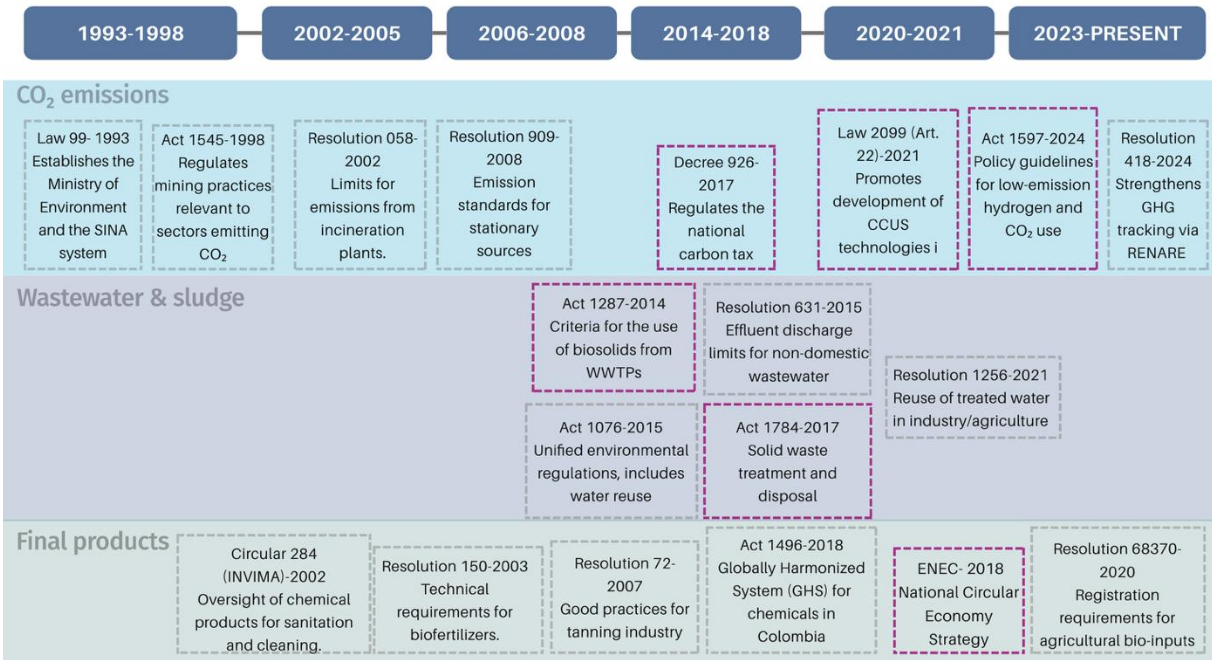

Figure 2-4. Regulation timeline for CCUS and related technologies in Colombia

As countries around the world scale up efforts to reach net-zero emissions, many have established advanced regulatory and policy frameworks to support the development and deployment of Carbon Capture, Utilization, and Storage (CCUS) technologies. These frameworks not only provide legal certainty and safety standards but also include targeted incentives that help reduce investment risks and accelerate innovation. Several Latin American countries have begun to develop regulatory and policy frameworks to support CCUS, showing early but promising steps toward low-carbon transitions. **Brazil stands out as the first country in South America to pass a comprehensive CCS law** (Bill 1425/2022) (Congresso nacional, 2022) assigning regulatory authority to the ANP and enabling commercial CO_2 storage projects, while Petrobras has already injected over 10 million tons of CO_2 through enhanced oil recovery initiatives (Argus media, 2024; Global

CCCS Institute, 2024). **Mexico has included CCS in its General Climate Change Law and developed a CCUS roadmap with World Bank support** (Global CCS Institute, 2015). Meanwhile, **Chile has introduced a carbon tax and passed a climate change law in 2022** that sets sector-specific emissions targets, creating an enabling environment for future CCUS applications (White & Case, 2022).

By analyzing international best practices (Figure 2-5**)—ranging from tax credit schemes and public-private partnerships in the United States** (Carbon capture coalition, 2022) **and Canada** (Natural resources Canadá, 2023)**, to comprehensive emissions trading systems and infrastructure planning in the European Union** (European Commission, 2025) **and the UK** (HM Government, 2018)—Colombia can identify critical elements for designing an enabling environment.

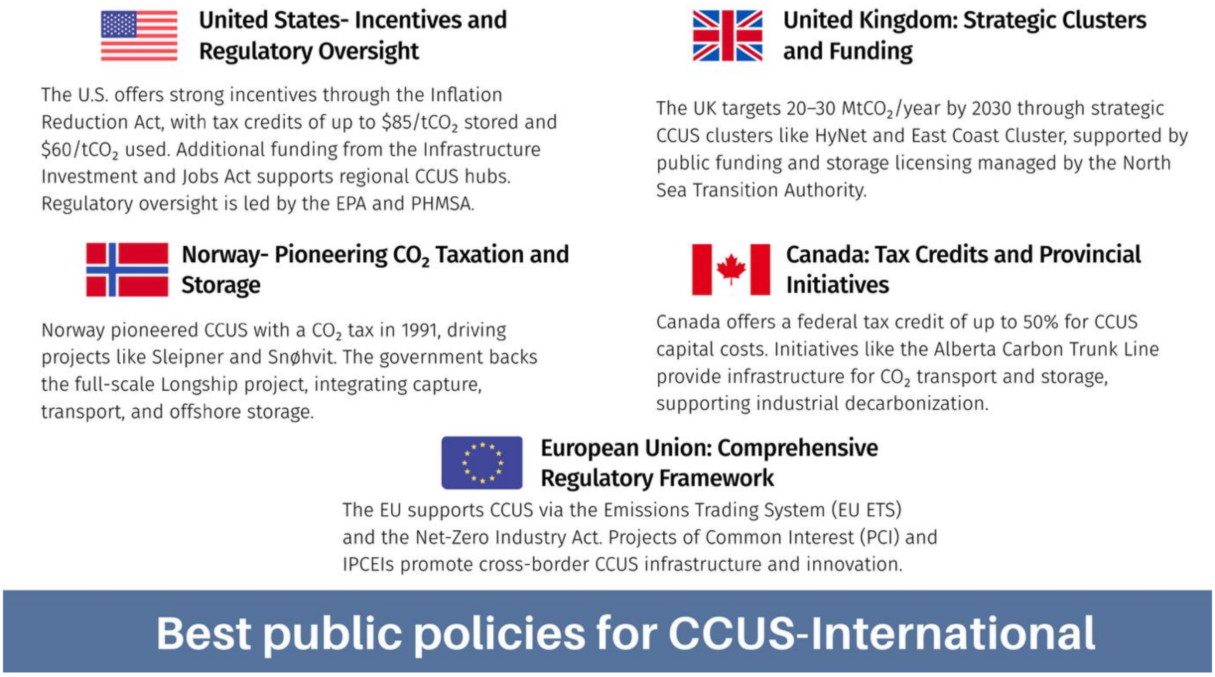

Figure 2-5. Best public policies for CCUS Worldwide

Finally, the main gaps and opportunities for the CCUS technologies in Colombia are listed below:

Table 2-1. Main Gaps and opportunities regarding public policies for CCUS in Colombia

Gaps	Opportunities
Lack of specific CCUS regulation: While CCUS is mentioned in overarching policies (e.g., Law 2099 of 2021), Colombia still lacks clear technical and operational regulations for CO_2 capture, transport, utilization, and storage.	**Recognition in the National Development Plan**: CCUS is identified as a strategic technology, offering long-term policy alignment for sustainable innovation.
Limited focus in Colombia's 2030 Agenda: National efforts are primarily centered on energy transition, with less emphasis on emerging technologies like electrochemical CO_2 conversion.	**Existing tax incentives**: Companies investing in CCUS equipment and technologies may benefit from income tax deductions.
Low prioritization of industrial CCUS innovation: Innovation indicators are mostly focused on ICT, leaving a gap in support for low-carbon industrial technologies.	**Alignment with national climate goals**: Colombia's carbon neutrality and climate resilience strategies provide a supportive framework for CCU solutions.
Generic regulation of CCUS-related products (formic acid, ADES, hydrogen peroxide): Existing laws focus on chemical safety under major accident prevention frameworks, without differentiation for circular or CO_2-based products.	**Potential for public-private partnerships**: Like leading countries, Colombia can leverage multi-sectoral collaborations to develop CCUS infrastructure.
Dependence on political continuity: The advancement of CCUS policies and incentives is subject to shifts in political priorities and administrative agendas.	**Opportunity to become a regional leader:** Projects like WaterProof support material reuse, carbon loop closure, and align with circular economy objectives in Antioquia and Medellín. Implementing WaterProof in Medellín could position Colombia as an early mover and innovation hub for CO_2 utilization technologies in Latin America.

Colombia's government partner interview

The interview with representative of government, technical advisor at the Ministry of Environment and Sustainable Development (Minambiente), provided key insights into the policy, regulatory, and strategic positioning of CCUS technologies in the national climate agenda. Some important takeaways include:

- **Recognition in policy frameworks**: CCUS is mentioned in key national regulatory instruments. Resolution 1447 (Minambiente, 2018b) includes it among the mitigation measures subject to monitoring. The upcoming modification of Decree 1073 of 2015 (Función pública, 2015) is expected to formally include a dedicated chapter on CO_2 capture and utilization.

• **Strategic visibility in the National Development Plan**: Under Law 2294 of 2023, Article 6 explicitly includes CCUS as a mitigation tool aligned with Colombia's decarbonization strategy (Presidencia de la República, 2023). CCUS is grouped alongside hydrogen and SAF (sustainable aviation fuels) as part of the country's transition technology portfolio.

• **Electrochemical gap**: While CCUS is gaining policy traction, electrochemical pathways are largely absent from current planning. EOR (Enhanced Oil Recovery) continues to be prioritized in early project considerations.

• **Unstructured pilot ecosystem**: Colombia currently lacks a coherent pipeline of CCU demonstration pilots. There is recognition within the ministry that enabling these pilots is essential to validate technical assumptions and generate the regulatory and financial inputs needed for scale-up.

• **Carbon markets and MRV challenges**: Although CCUS could theoretically integrate into carbon trading systems, Colombia is still in the early stages of generating the data and instruments (MRV, baselines) required for traceability and integration into domestic or international carbon markets.

• **Fiscal and financial levers under discussion**: The ministry is working jointly with Minenergía and Hacienda to define fiscal incentives. Laws such as 1715 of 2014 and Article 428 of the Tax Statute (IVA exemptions for emissions-reducing technologies) are seen as potential entry points for CCUS-related benefits (Función pública, 2014).

• **Governance gaps**: While Minambiente is involved in discussions, the leadership of the CCUS agenda is on the Minenergía side. There is a clear need for cross-sectoral coordination and stronger leadership to unlock financing and regulatory clarity.

"We're still generating the building blocks—there's no clear leadership on CCUS, but it's gaining traction. The challenge now is structuring traceability and incentives."

Environmental Ministry of Colombia

2.2.2 Technological capacities: are they ready for integration?

Technical requirements: purity

The WaterProof technology is built around an innovative electrochemical process that **transforms captured CO_2 into value-added products, primarily formic acid, using**

renewable electricity. Designed to integrate into urban waste incineration and wastewater treatment facilities, the system captures CO_2 emissions.

Electrochemical CO_2 reduction is emerging as a promising pathway to convert waste carbon into useful chemicals under mild operational conditions. It enables the production of compounds such as **formate, syngas, methanol, and hydrocarbons** by combining CO_2 with water and renewable energy, effectively linking carbon mitigation strategies with clean energy transitions. Among these products, **formic acid stands out due to its high volumetric hydrogen density, broad industrial versatility, and potential applications in hydrogen storage and green solvents** (W. Bin Li et al., 2022; Z. Zhang et al., 2020). Despite its potential, several technical challenges remain for the widespread deployment of CO_2 reduction. These include low product selectivity, high energy demands, and the degradation of electrodes and membranes over time. **One of the most critical bottlenecks is the sensitivity of the process to impurities in the CO_2 feedstream.** Trace components such as Sulfur Oxides (SOx), Nitrogen Oxides (NOx), Hydrogen Sulfide (H_2S), and particulate matter can poison catalysts, reduce reaction efficiency, and limit the system's stability and scalability (Ali et al., 2025). Therefore, **ensuring a high-purity CO_2 supply is essential**. In the WaterProof project's Dutch demo sites, CO_2 streams from both the Waternet WWTP and the HVC incineration plant exhibited purities above 98%, with only minimal contaminants detected, making them suitable for electrochemical conversion without significant pretreatment (Table 2-2).

In Colombia, and particularly in Medellín, wastewater treatment plants (WWTPs) and sanitary landfills represent key fixed sources of greenhouse gas emissions, mainly composed of methane (CH_4) and carbon dioxide (CO_2). However, **detailed characterization of the gas streams from these facilities, especially regarding CO_2 purity, contaminant traces, or suitability for utilization processes such as electrochemical conversion, is limited**. In the case of WWTPs, biogas typically contains ~60–70% methane and ~30–40% CO_2, along with trace contaminants such as H_2S, NH_3, siloxanes, and moisture. Despite significant infrastructure, like the Aguas Claras and San Fernando WWTPs operated by Grupo EPM in Medellín, **there is no public data on the chemical composition or purification levels of CO_2 streams post-biogas separation**. Similarly, **in Medellín's La Pradera landfill, emissions are dominated by methane and CO_2, but the captured biogas is flared, and no purification process is reported for CO_2 recovery or characterization**

According to emissions inventories, **the waste sector in the Aburrá Valley produced approximately 923,484 tCO_2eq in 2021, with 856,934 tCO_2eq attributed to La Pradera landfill and 98,278 tCO_2eq to WWTP operations**. However, these figures reflect emission quantities, not gas quality or processing potential (Yáñez et al., 2020). Moreover, Colombia's national reporting system (RENARE) and regulatory instruments such as Resolution 418 of 2024 (Minambiente, 2024) mandate GHG reporting but do not include specifications for CO_2 stream characterization relevant to utilization technologies. This absence of detailed data on gas purity and composition from fixed sources poses a major bottleneck for the replication of technologies like WaterProof, which require high-purity CO_2 with minimal impurities to operate effectively and safely (Grupo EPM, 2022; Quiceno & Arcila Marin, 2023).

Establishing reliable data on emission profiles and conducting pre-assessments of CO_2 quality is therefore a prerequisite for evaluating technological feasibility and planning future pilot-scale implementation in Colombia (Table 2-2).

Table 2-2. Comparative CO_2 production and samples between demo plants in Amsterdam and Medellín

Aspects	Amsterdam	Medellín and Metropolitan area	Observations
WWTP			
Gas stream	• Flow: 3,066 tCO_2/yr • Purity: 98%	• Flow: 98,278-tCO_2 eq /yr 201. • **Purity: Not reported.** • 480-t CO_2 eq/yr biogas burning (CH_4).	• Waternet: ISO-6974 normativity parameters for gas characterization. This is the selected portion of CO_2 available for electrochemical conversion, not the total emissions of the plant. • Medellín WWTP reported quantity not quality. Those are the total emissions reported.
Solid waste treatment plant			
Wastes	• Biomass: 180 kt/yr. • Dried sewage sludge: 10 kt/yr.	• Biomass: 403,6 kt /yr • Mixed urban waste: 269,096 kt /yr.	• Medellín has not urban waste incineration plants
Gas stream	• flow: about 350 kg/h • Purity: 99.8%	• Flow: 923,483 t CO_2 eq/yr. • **Purity: Not reported.** • 54,857 t CO_2 eq/yr from the combustion of biogas burning (CH_4)	• HVC: NEN-EN-ISO/IEC 17025 normativity. This is the selected portion of CO_2 available for electrochemical conversion, not the total emissions of the plant. • Medellín Landfill reported quantity not quality Those are the total emissions reported.

Research and development capacities

Regarding technology maturity at the global level, the state of the art in carbon capture and utilization (CCU) technologies is summarized in Table 2-3. It provides a concise overview of recent academic advances over the past five years, highlighting key applications, ranging from electrochemical conversion to mineralization and integrated systems, along with major insights, technological challenges, and representative sources. This synthesis reflects the diversity and maturity of international CCU research and emphasizes the critical areas where innovation is advancing scalable, low-carbon solutions.

Table 2-3. State of the art of CCU technologies

Technology	Application	Key Insights	Challenges	Source
Electrochemical Conversion	Fuels and chemicals (CO, CH_4, formic acid, ethanol)	Highly selective electrocatalysts are being developed; direct electrochemical reduction from capture media is emerging.	Energy efficiency, catalyst stability, scalability	(Pei et al., 2023)
Solvent-Based Capture & Conversion	Integrated CO_2 capture and chemical conversion	Combining capture and conversion in solvents can reduce cost and improve efficiency	Process integration, new solvent development	(Heldebrant et al., 2022)
Mineralization	Conversion of CO_2 to stable carbonates using seawater or Mg-rich materials	Can yield high-purity products like $NaHCO_3$ and $MgCO_3$	Process kinetics, scalability	(Kim et al., 2020)
Reactive Carbon Capture (RCC)	Electrochemical reduction of CO_2 directly from capture solutions	Dissolved CO_2 is the main reactive species; integrated systems are promising	Speciation control, energy input	(Shen et al., 2023)
Integrated CCU Systems	CO, formic acid, n-propanol from fossil fuel CO_2 emissions	Some CCU pathways are economically and environmentally superior to CCS	Product selection, policy and economic drivers	(X. G. Zhang et al., 2024)

Internationally, CCU is rapidly advancing at the commercial level, with several large-scale projects around the world converting CO_2 into valuable chemicals like methanol, ethanol, and formic acid. Table 2-4 highlights the top 10 global CCU initiatives focused on producing chemical bases and solvents for commercial use. Leading the way are CRI's methanol plants in China, LanzaTech's ethanol facilities in the U.S., and multiple EU-backed projects in Germany, Sweden, and Belgium, showcasing the growing viability of CCU as part of a low-carbon industrial future.

Table 2-4. CCU large commercial projects worldwide

Rank	Project / Company	Location	Product	CO_2 Captured (t/year)	Production Capacity	Commercial application	Source
1	Shunli CO_2-to-Methanol Plant (CRI)	China	Methanol	160,000	110,000 t/year	Fuel and feedstock for plastics, coatings, and chemicals	(Carbon Recycling International, 2024c)
2	Sailboat CO_2-to-Methanol Plant (CRI)	China	Methanol	150,000	100,000 t/year	Used in solar panel coatings, plexiglass, and fuel	(Carbon Recycling International, 2024b)
3	George Olah Renewable Methanol Plant (CRI)	Iceland	Methanol	~5,500	5M liters/year	Low-carbon fuel and chemical industry feedstock	(Carbon Recycling International, 2024d)
4	LanzaTech Commercial Facilities	USA (Global ops)	Ethanol, Acetone, Isopropanol	>120,000 (est.)	Varies by site	Cosmetics, packaging, fuels, cleaning agents	(Lanzatech, 2023)
5	BioMCN Renewable Methanol Plant	Netherlands	Methanol	Not disclosed	60,000 t/year	Fuel and feedstock for the chemical sector	(Nouryon, 2019)
6	Liquid Wind e-Methanol Plant	Sweden	Methanol	Not disclosed	50,000 t/year	Marine fuel and sustainable transport	(Liquid Wind, 2025)
7	MefCO_2 Project (CRI)	Germany	Methanol	Pilot scale	1 t/day	Demonstration for grid-to-chemical conversion	(Carbon Recycling International, 2024a)
9	Wacker Chemie RHYME Project	Germany	Methanol	Not disclosed	15,000 t/year	Feedstock for green chemical production	(Grupo Argos, 2025)
10	REUSE Project (Horizon Europe)	Greece	Formic Acid, CO	Pilot scale	80 kWth	Formic acid and CO for industrial chemical applications	(Reuse, 2024)

Technology in Colombia has made promising advances in carbon capture and storage (CCS), with a growing body of research highlighting its potential to contribute meaningfully to the country's climate goals. For instance, integrated CCS projects combined with enhanced oil recovery (EOR) have been estimated to store up to 142 million tons of CO_2 while delivering significant emission reductions from the oil sector (Yáñez et al., 2020). National energy system modeling has also demonstrated that bioenergy with CCS (BECCS) could mitigate up to 41% of cumulative emissions between 2030 and 2050, while low-carbon retrofitting of refineries could play a strategic role in CO_2 capture (Younis et al., 2023). Site-specific analyses, such as the identification of potential geological storage zones in the Sinu-San Jacinto basin, further emphasize Colombia's growing technical capabilities in CCS (Rojas Barrientos, 2023). Additionally, Colombia has explored the carbon sequestration benefits of blue carbon ecosystems like mangroves (Zarate-Barrera & Maldonado, 2015) and agroforestry systems (Hernandez Núñez et al., 2020), showcasing an integrated approach to carbon management. This trend is further reflected in international collaborations such as the Norwegian Energy Initiative, which is supporting CCUS-related studies and pilot frameworks in Colombia and Ecuador, reinforcing the regional potential for deployment of these technologies (University of Bergen, 2021).

However, despite this momentum in CCS, Colombia has not demonstrated the same level of development in carbon capture and utilization (CCU), particularly in emerging technologies like electrochemical CO_2 conversion. The absence of dedicated studies and pilot projects in this area underscores a significant gap that needs to be addressed to build a more holistic carbon management strategy.

Alternative technologies

Alternative technologies to CCUS are currently being adopted by Colombia's highest-emitting industries, such as oil and gas, cement, thermal energy, and manufacturing, as interim solutions to reduce or offset CO_2 emissions from fixed sources. The Oil and gas industry has the technical capacity to incorporate CO_2-enhanced oil recovery (EOR), which can serve as a transitional use case for captured emissions while improving extraction efficiency. **Ecopetrol, the country's leading oil company**, is piloting carbon capture and storage (CCS) while also investing in energy efficiency, reducing gas flaring, and controlling fugitive methane emissions (Ecopetrol, 2024). In the **cement sector**, CO_2 mineralization through integration into concrete and clinker production is gaining attention as a dual-purpose solution for both emissions reduction and material enhancement (Fu et al., 2022); following this trend, **Cementos Argos is advancing its emissions reduction strategy through process innovation, biological CO_2 capture and the use of alternative raw materials** (Argos, 2023). Manufacturing and energy firms such as **Corona** and **Surtigas** are adopting carbon footprint measurement tools, especially for Scope 3 emissions, in partnership with sustainability platforms like **CECODES** (CECODES, 2024). Additionally, participation in **voluntary carbon markets (VCMs)** is growing, with companies purchasing carbon credits to offset emissions and finance ecosystem-based climate solutions (El País, 2025). These strategies are supported by national frameworks such as **Law 2099 of 2021**, which formally recognizes CCUS, and the **Carbon Neutrality Program**, which engages more than 500 companies in mitigation actions (Minambiente, 2022b).

Case studies and technological compatibility

- Ecopetrol

Ecopetrol, Colombia's state-owned oil and gas company, is one of the country's largest greenhouse gas emitters and is actively pursuing a transition strategy to reduce its carbon footprint. The company aims to reach net-zero emissions by 2050, with a 25% reduction in total emissions by 2030 and a 50% reduction in methane emissions by 2025, in line with its participation in the Global Methane Pledge and the Science-Based Targets initiative (SBTi) (Ecopetrol, 2024; IEA, 2021a).

Ecopetrol's decarbonization strategy combines technological innovation and operational transformation to address its role as one of Colombia's largest emitters. **Key efforts include increasing energy efficiency and electrification across operations, implementing flaring and venting reduction programs at upstream facilities, and advancing nature-based solutions such as forest restoration and carbon offsetting through its Biocarbon and conservation initiatives**. The company also actively participates in Voluntary Carbon Markets (VCMs), reporting over 4.4 million tCO_2eq offset in 2022 and has deployed more than 100 MW in solar energy to support the transition to renewables. To enhance emissions monitoring, **Ecopetrol leads in real-time GHG traceability in Latin America by deploying sensor-based methane monitoring systems across oil fields and partnering with satellite platforms such as GHGSat and Kayrros**. This dual infrastructure enables the detection of methane super-emitters and large plumes with high precision, improving transparency and validating emission reductions—critical foundations for CCUS scalability and eligibility for international climate finance. Additionally, **Ecopetrol is spearheading Colombia's green hydrogen agenda**. In 2023, it launched a pilot green hydrogen electrolyzer at its Cartagena refinery, powered by solar energy with a capacity of 50 kg/day. Looking ahead, the company aims to expand hydrogen production for industrial applications and heavy transport, exploring integration with CO_2 utilization pathways such as e-fuels and synthetic methanol. As part of this long-term strategy, Ecopetrol joined the Hydrogen Council in 2022 and published a national roadmap targeting 1 GW of green hydrogen capacity by 2040 (IEA, 2021a).

The infrastructure, emission intensity, and innovation focus of the company, make it a strong candidate for pilot deployment of CCUS technologies such as WaterProof:

- Concentrated CO_2 sources: Refineries and upstream facilities emit large volumes of CO_2.
- Established monitoring systems: Real-time and satellite data enable tracking of performance and co-benefits.
- Industrial readiness: Facilities in Barrancabermeja and Cartagena are well-positioned to integrate electrochemical CO_2 conversion units.

Moreover, Ecopetrol's involvement in R&D programs, alliances with universities, and access to international financing mechanisms (e.g., IFC, IDB, World Bank) enhance its capacity to test and scale up advanced CCU technologies.

- Argos

Grupo Empresarial Argos is a potential candidate for CCUS adoption and pilot implementation of the WaterProof technology, given its ambitious climate goals and carbon-intensive operations. The company has committed to **net-zero emissions by 2050**, with intermediate targets of **46% CO_2eq intensity reduction** and **36% absolute reduction** by 2030 (baseline 2018) (Miranda et al., 2021a).
The decarbonization strategy of the company includes five levels: improving energy efficiency, using alternative fuels and materials, reducing thermal demand in kilns, lowering the clinker/cement ratio, and sourcing 25% of its energy from renewables. **Relevant CCUS-related efforts already underway include CO_2 capture via microalgae at the Cartagena cement plant, waste co-processing, and the production of Green Cement.** The Green Cement is expected to cut down CO_2 emissions by up to 38% and thermal energy use by 30% compared to traditional cement. This is achieved by replacing clinker, the most carbon-intensive component, with natural pozzolans and calcined clays, maintaining strength while lowering the environmental footprint.

Figure 2-6. Microalgae Biomass cultivation for Biocrude Production in Argos. https://estaticos.elcolombiano.com/binrepository/848x565/34c0/780d565/none/11101/TJDW/mcv-4267_44404295_20240213154916.jpg

Since 2008, Argos has been working on a carbon capture project through microalgae. With the support of EAFIT University, Ruta N and the University of Antioquia, the system has allowed different microalgae to absorb CO_2 (they do it 50 times more than plants or trees), capture solar energy and generate biomass, which has great potential as a biofuel (Miranda et al., 2021a). **The company's microalgae-based CO_2 capture project represents one of the most advanced CCU initiatives in Colombia's industrial sector**. (Figure 2-6). This strategy focuses on capturing CO_2 from cement flue gases and transforming the resulting microalgal biomass into renewable fuels via hydrothermal liquefaction (HTL).

Pilot studies showed that using real flue gases from Argos' cement kiln in Cartagena significantly enhanced biomass productivity (up to 2.3 g/L) and improved bio-oil yields by 55% compared to synthetic CO_2, with energy contents near 31 MJ/kg, comparable to conventional fuels (Miranda et al., 2021a). The process also allows for reusing the aqueous phase generated during HTL, reducing wastewater discharge and increasing biocrude yield up to 76% after several water-reuse cycles (Gómez et al., 2022). This innovation addresses one of the main economic and environmental challenges of HTL-based biofuel production. By integrating CO_2 valorization with biofuel generation, Argos not only reduces its carbon footprint but also aligns with national climate goals and opens a pathway for industrial-scale adoption of CCU technologies. Grupo Argos demonstrates several key capabilities that position it as a strong candidate for implementing a project like WaterProof:

Technical and Operational Readiness

- High-emission processes: Cement production offers concentrated CO_2 sources.
- Experience with flue gas: Operates microalgae-based CO_2 capture at Cartagena.
- Suitable infrastructure: Facilities for integration with electrochemical systems.

Research and Innovation Capacity

- Academic partnerships: Active collaboration with University of Antioquia (UdeA) and National University of Colombia (UNAL).
- Award-winning R&D: Nationally recognized work on CO_2-to-biofuel via HTL.
- Process analysis: Experience with LCA and techno-economic evaluation.

Strategic and Environmental Alignment

- Net-zero target: Committed to carbon neutrality by 2050.
- Decarbonization levers: Green cement, alternative fuels, renewable energy.
- CCUS fit: WaterProof aligns with Argos' innovation and climate roadmap.

Ecosystem and Location Advantage

- Public-private collaboration: Track record in sustainability partnerships.
- Local leadership: Based in Medellín, a strategic site for CCU demonstration.

- EPM

Grupo EPM has established itself as a leader in sustainable water management and climate action in Colombia. Its wastewater treatment plants, **particularly San Fernando and Aguas Claras, are central to its environmental strategy.** San Fernando, operational since 2000 in Itagüí, treats approximately 1.6 m^3/s of wastewater, significantly reducing organic pollutants entering the Medellín River. Aguas Claras (Figure 2-7, and Figure 2-8), inaugurated in 2019 in Bello, is the country's largest and most advanced plant, with a capacity of up to 6.5 m^3/s, serving around 2.2 million people. Together, these facilities treat about 84% of the region's wastewater, preventing over 140 tons of organic pollutants being discharged into the river daily.
Beyond wastewater treatment, Grupo EPM is committed to reducing its carbon footprint. **The group aims to achieve carbon neutrality by 2025, with 2016 as the base year. In 2022, EPM's emission factor was 0.0454 tCO_2eq/MWh, below the national average of 0.1124 tCO_2eq/MWh, indicating efficient energy use**. The company

conducts annual greenhouse gas (GHG) inventories, covering scopes 1 and 2, and has obtained external verification for its carbon footprint estimates. **Notably, EPM has certified significant emission reductions from its hydroelectric projects, such as Porce III, and has engaged in carbon credit trading, selling over 1.1 million credits in 2023.**

Figure 2-7. Biofábrica Aguas Claras-EPM Aguas nacionales Photograph by the author. December 2025.

Figure 2-8. Green Hydrogen plant Aguas Claras (EPM, 2023)

"In 2023, the EPM Group continued to emphasize its focus on hydrogen, investing approximately €1.14 million in identifying production and commercialization models, developing a business case for exports, mapping partners, and advancing the Medellín Hydrogen Hub. In partnership with its subsidiary Aguas Nacionales, it invested around €0.58 million in the installation and assembly of a pilot project to produce 5 kg/day of green hydrogen, located at the Aguas Claras wastewater treatment plant."

EPM

Grupo EPM's infrastructure, emissions monitoring systems, and long-standing sustainability leadership make it a strong candidate for piloting electrochemical CO_2 conversion technologies such as those developed in the WaterProof project. Key enabling capacities include:

- Concentrated CO_2 streams: Wastewater treatment plants like Aguas Claras and San Fernando generate significant CO_2 emissions from organic matter degradation and biogas production.
- Operational bio-digesters and sludge processing units: These provide both integration points for CO_2 capture and opportunities for downstream valorization.
- Verified GHG monitoring: Grupo EPM conducts annual GHG inventories (Scopes 1 and 2), with third-party verification—facilitating traceable impact for CCU technologies.
- Generate 85% of their energy from the biogas produced.
- Certified carbon credit generation: The group has experience issuing and selling emission reduction certificates, supporting climate finance integration.
- Advanced sludge valorization: Thermal drying and biosolids transformation infrastructure aligns with WaterProof's by-product potential (e.g., biofertilizers, ADES), with 470 biosolid users and Total production of sludge of 350 tons/day.
- Investmen over 12 billion Colombian pesos COP in odour control, using hydrogen peroxide and sodium hydroxide (Figure 2-7).
- Green Hydrogen Pilot plant coupled with the biogas production (Figure 2-8)
- Climate neutrality commitment: A 2025 carbon neutrality goal, backed by actionable strategies and renewable energy expansion.

- Community engagement and circularity leadership: Projects like UVA Aguas Claras reflect a culture of inclusive sustainability, reinforcing social license for innovative climate technologies.

Human talent

Colombia has at least 18 research groups recognized by Minciencias working in areas relevant to CCUS, including adsorbent materials, photocatalysis, waste-to-energy, and electrochemical CO_2 conversion. Notable examples include the *Electrochemical Engineering Group (GRIEQUI)* at Universidad Nacional Medellín, the *Environmental Catalysis Group* at Universidad de Antioquia, and *GAOX* at Universidad del Valle. While few groups are exclusively focused on CCUS, many possess strong capabilities in catalysis, process engineering, and materials science, forming a solid foundation for scaling up CCUS research. These capacities are distributed across leading institutions such as UDEA, UNAL, UIS, UPTC, and EAFIT, providing a strategic opportunity for interdisciplinary collaboration and technology adaptation in Colombia giving key capacities for adoption of technologies as WaterProof (Figure 2-9).

1 Strong background in CO_2-related research:
Several research groups, such as the Grupo de Catálisis Ambiental at Universidad de Antioquia, GITEM at Universidad Nacional (Manizales), and groups at the Universidad Industrial de Santander (UIS), are actively working on adsorbent materials, photocatalysis, and waste-to-energy conversion—which are relevant to CO_2 capture and utilization technologies.

2 Experience in process simulation and techno-economic modeling
Researchers across universities (e.g., Universidad Nacional, Universidad del Valle, Universidad EIA) have solid experience in modeling chemical and energy processes using Aspen Plus, COMSOL, and other tools, which are essential for scaling CCUS technologies.

3 International collaboration experience
Colombian institutions have participated in joint research initiatives on sustainability, carbon neutrality, and clean energy with organizations like the World Bank, the European Union, and GIZ. These collaborations build capacity for systems-level thinking and multi-stakeholder implementation.

4 Growing interest in climate innovation
Programs such as Minciencias' Bioeconomy and Circular Economy Missions, Ruta N's innovation platforms, and recent Horizon Europe projects like WaterProof are helping orient the national research agenda toward decarbonization—paving the way for CCUS to be integrated as a strategic theme

5 Training programs and advanced degrees
Colombia has master's and PhD programs in energy, environmental sciences, and chemical engineering. These programs produce graduates with the potential to specialize in CCUS-related R&D if given proper orientation and research opportunities.

Key capacities of Colombian researchers for CCUS

Figure 2-9. Key capacities of Colombian researchers for CCUS projects

Key Gaps and Opportunities

Based on the findings in technological capacities in research and industry development the key gaps and opportunities are shown in the Table 2-5.

Table 2-5. Main Gaps and opportunities- Technology

Gaps	Opportunities
Lack of CO_2 purity characterization: Major emission sources like WWTPs and landfills report CO_2 quantities but not composition, which is critical for electrochemical conversion viability.	**Strategic emission sources:** Medellín's Aguas Claras and San Fernando WWTPs, and Argos production plants offer fixed-location CO_2 emissions with operational bio-digesters and sludge valorization units**.**
Absence of gas pretreatment systems: Colombian plants lack infrastructure to remove contaminants (e.g., SOx, NOx, H_2S) that can poison catalysts used in WaterProof technology**.**	**Existing climate commitments:** Institutions like Grupo EPM and Argos have ambitious emission reduction goals and infrastructure aligned with circular technologies.
Limited technical experience in CCU: While Colombia has CCS-related research, there is minimal applied R&D on electrochemical CO_2 utilization or formic acid production.	**Robust research base:** At least 18 research groups across Colombia are engaged in fields relevant to CCU (electrochemistry, materials, catalysis), enabling knowledge transfer.
Insufficient pilot-scale infrastructure: No existing national platforms allow for the demonstration or validation of electrochemical CO_2 conversion under local conditions.	**Growing climate finance and carbon markets:** Active carbon credit trading and verified GHG inventories create a framework for impact monetization and investment.
Shortage of specialized training: Engineering programs and technical talent lack exposure to CCUS system design, operation, or integration.	**Integration with existing systems**: WaterProof's electrochemical modules could link with sludge treatment, biogas valorization, or ADES production chains in existing facilities.

Technical Expert Interviews

To validate the gaps and better understand the real context of a possible implementation of WaterProof in Medellin, some interviews were conducted with key local stakeholders. The interview with a Doctor of Engineering. Expert in Energy and Sustainability, highlighted the technical, economic and regulatory hurdles for deploying the WaterProof CCU technology in Colombia, as well as key levers to build a viable, scalable CO_2 capture-and-utilization business. Some important insights are:

- **Viable CO_2 sources in Colombia**: Cement plants and two municipal wastewater treatment facilities in Medellín (Aguas Claras and San Fernando) are the most promising feedstocks, but the high impurities in their exhaust streams represent a major technical bottleneck.

- **Capture-value gap**: In Europe, the market values CO_2 at € 80–90 per tonne, enough to make CCU projects financially viable, whereas in Colombia the implied price is only about COP 27 000 (≈ €5.75 per tonne), making it far harder to close the business case.
- **Product-driven business model**: Securing end-markets for formic acid, peroxides or deep-eutectic solvents derived from CO_2 is essential; blended financing mechanisms (carbon taxes, border adjustments, extended producer responsibility fees) must be structured around these products. Argos has CO2 capture and utilization technologies based on the use of amines and biological fixation (microalgae) that are already at high TRLs (7-8). Still, the lack of financial viability keeps them relegated.
- **Modular, on-site demonstrations**: Deploying containerized pilot units (e.g. 20 ft modules) allows low-cost, flexible field trials, accelerating investor confidence and easing adaptation to local conditions.
- **Policy and regulatory enablers**: A dedicated carbon tax whose revenues are ring-fenced for CCU projects, combined with proportional border carbon adjustments, would level the playing field and catalyze private investment.

"We risk a technological overflow—what we truly need is to think supply-chain and actively build the market"

Expert in Energy and Sustainability

Some of the previous insights were validated by **Professor from the Process Engineering Department at Universidad EAFIT**. The technical maturity of electrochemical CO_2 capture and conversion technologies was confirmed, alongside the economic, regulatory, and infrastructural barriers hindering their scale-up in Colombia, particularly high energy costs, lack of incentives, and reliance on imported inputs. Some important insights:

- **Technical maturity vs. economic viability**: While laboratory-scale electrochemical routes to formic acid, hydrogen peroxide, and deep-eutectic solvents have reached approximately TRL 4, operating costs, estimated at €226 per tonne of formic acid assuming €50/MWh electricity and 80% system efficiency, make industrial adoption in Colombia unfeasible without strong financial incentives.
- **Need for clear regulatory incentives:** In the absence of a meaningful carbon tax or direct financial support, companies opt to pay emission fines rather than invest

in capture; weak penalties and low regulatory pressure discourage real-world demonstrations.

- **Impurities and compression challenges:** Colombian point-source CO_2 contains impurities (O_2, N_2, SO_2) that impair solubility and poison catalysts. The additional cost of gas compression further escalates overall expenses, undermining competitiveness against imported chemicals or emission penalties.
- **Preference for simpler chemical pathways:** Electrochemical conversion to formic acid—requiring only two proton-electron steps—is technically more straightforward than routes to methane, ethanol, or urea, where catalyst selectivity and development remain major hurdles.
- **Deficit of local infrastructure and capabilities**: Colombia lacks domestic manufacturers of specialized catalysts and has no CO_2 capture-use pilot plants; most critical equipment and reagents must be imported, and existing labs focus on combustion rather than CO_2 electrochemistry

2.2.3 Social appropriation: how can the community be involved?

CCU technologies are gaining global attention as a climate mitigation strategy. While their technical and environmental benefits have been widely studied, the social implications of these innovations remain largely underexplored. Recognizing this gap (Rafiaani et al., 2020) conducted one of the first systematic efforts to identify relevant social indicators for the sustainability assessment of CCU technologies, using a multi-criteria decision-making approach (modified TOPSIS) applied across **three key stakeholder groups: workers, consumers, and local communities.**

Among the most critical findings, experts **prioritized indicators such as *health and safety* (relevant across all groups), *fair salary* and *equal opportunities* (for workers), *end-of-life responsibility* and *transparency* (for consumers), and *local employment* and *secure living conditions* (for communities).** These insights underline the need for a more inclusive approach to innovation that reduces emissions and improves wellbeing, equity, and trust among those affected by CCU deployment. **Despite these advances, the assessment of social impacts of CCU technologies is still in its early stages and requires further empirical studies** to inform policy, guide responsible innovation, and support socially sustainable deployment at scale.

In Colombia, the potential for social impact is closely tied to a growing ecosystem of actors aligned with sustainability and climate action. The following stakeholder map outlines relevant categories and examples that would be critical for enabling and assessing the deployment of CCU technologies in the country (Figure 2-10).

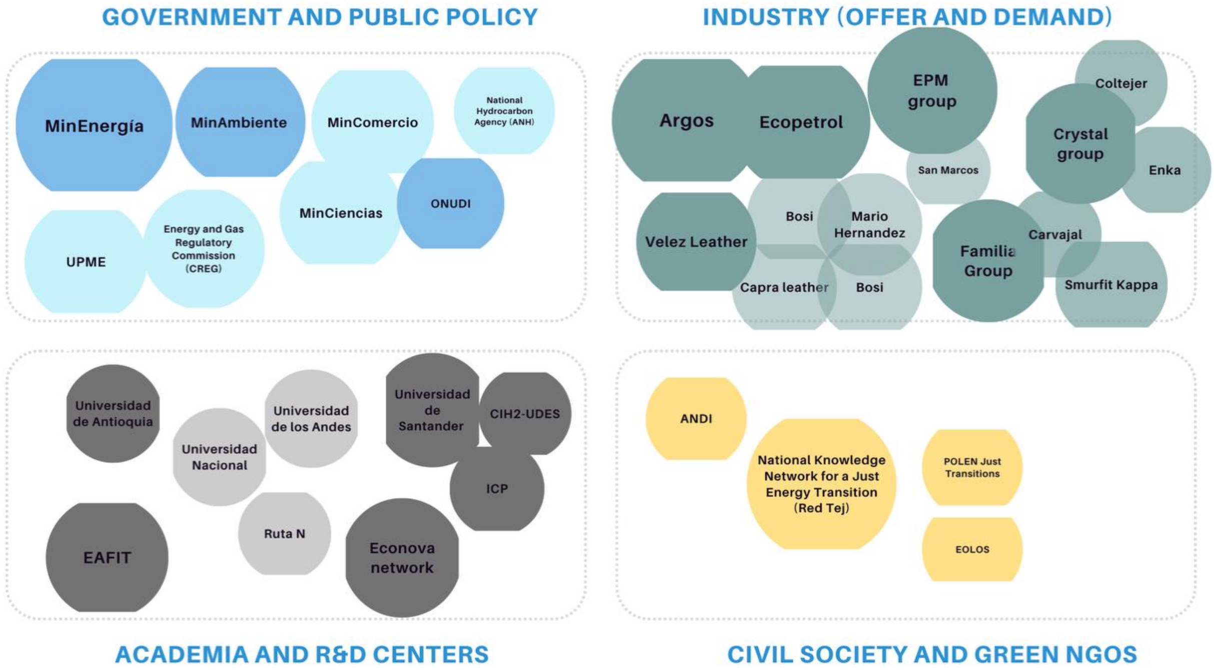

Figure 2-10. Stakeholder map.

Notably, citizen perception in Colombia is evolving according to the DANE's 2023 (ECV), over 70% of Colombians believe companies should adopt cleaner technologies, even if that implies higher costs (DANE, 2023). This reflects a rising societal demand for sustainability, particularly in sectors like fashion, food, and consumer goods, and aligns closely with the transformative goals of CCU technologies.

Beyond perception, CCU deployment, particularly through projects like WaterProof, holds significant promise for tangible social impact. It can strengthen local capacity and **generate high-quality jobs in technical areas such as chemical engineering, environmental management, and green logistics**. Opportunities also arise for micro and small enterprises to integrate into circular value chains, including the recovery and transformation of CO_2 into bio-based chemicals.

In Colombia, the textile and leather sectors exemplify the potential for impact. **The textile industry accounts for more than 600,000 direct and indirect jobs and represents around 30% of Medellín's regional GDP (ProColombia, 2023).** Meanwhile, **the**

leather sector includes approximately 2,680 micro, small, and medium enterprises. Modernizing these industries through CCU-enabled processes could drive job creation, improve working conditions, and promote the shift toward cleaner production. Particularly in traditional manufacturing hubs, CCU may enable the requalification of labor, fostering inclusion in emerging green value chains.

Moreover, reduced industrial emissions through CCU could lead to measurable improvements in the quality of life. In the ECV 2023, 17% of households reported frequent water contamination issues from rivers and canals, and 7.4% said these issues were constant (DANE, 2023). By decreasing pollution and exposure to harmful industrial byproducts, CCU technologies could contribute to healthier environments, lower public health costs, and a greater sense of community wellbeing.

In this context, Colombia's push for clean technology adoption is an environmental necessity and a pathway to more equitable, resilient, and socially inclusive development.

Key Gaps and Opportunities

Key social gaps and opportunities identified for strengthening community engagement and fostering inclusive benefit are shown in Table 2-6.

Table 2-6. Main Gaps and Opportunities- Social

Gaps	Opportunities
Low public awareness of CCU and green chemistry: Most citizens are unfamiliar with the concept or benefits of CCU technologies.	**Over 70% of Colombians support cleaner technologies** even at higher costs, showing high potential for social acceptance.
Limited incorporation of social indicators in sustainability assessments of industrial innovation.	**International frameworks** (e.g., UNEP/SETAC) and recent studies provide tested methodologies and priority indicators for assessing social impact
Weak integration of community participation in industrial technology deployment.	**Local NGOs and sustainability-oriented chambers** (e.g., Cámara Verde, ANDESCO) can support co-design and participatory governance models.
Employment vulnerability in traditional sectors (e.g., leather, textiles) due to pollution and low-tech production models.	**CCU-driven modernization offers reskilling and job creation** in circular value chains for over 600,000 jobs in textiles and ~2,600 SMEs in leather.
Lack of formal training in social dimensions of sustainability for engineers and plant operators.	**Incorporation of SLCA (Social Life Cycle Assessment) tools** into academic programs and partnerships with research centers like Ruta N and CTA.
High levels of industrial pollution affecting water and air quality in urban communities.	**CCU can reduce co-contaminants and improve environmental health**, which is

	responding to 17% of households reporting water pollution and 7.4% reporting it constantly.

As part of the WaterProof project, a study conducted by **IZES gGmbH (Institute for Future Energy and Material Flow Systems)** and distributed by **CTA** (Center for Science and Technology of Antioquia) a **consumer perception survey** was conducted in Colombia March - August 2025 to explore attitudes towards cleaning products made with recycled CO_2. The online survey gathered responses from **66 participants** (58% women, 42% men, aged between 18 and 65+ years) across different educational backgrounds. Participants were asked about their perceptions, purchase intentions, and information needs regarding CO_2-based products.

The preliminary results reveal a generally favorable perception and high purchase intention with 86% of participants indicating that they would buy cleaning products derived from recycled CO_2. The finding of rather high product acceptance is supported by responses on brand support: 89% would support brands using recycled CO_2. Results underline the **importance of environmental product benefits**: The percentage of participants who could imagine purchasing this type of cleaning product is even higher when consumers are assured of environmental superiority over conventional products. 93% of participants would buy the products if they knew that they are better for the environment. Participants' valuation of the products' environmental effects is rather positive: 86% believe such products would be good for the environment, and 91% see them as contributing to climate change mitigation.

Other key insights:

- **Purchase drivers** align with typical cleaning product criteria — price (considered an influencing factor for purchase decisions by 77% of participants), effectiveness (73%), and sustainability (47%). Notably, 52% of participants would still purchase if the product were 20% more expensive, suggesting a willingness to pay for added environmental value.
- **Risk perception** is low, with only 13% associating potential environmental harm and 9% linking possible health risks to CO_2-based products. However, **uncertainty remains around product characteristics such as product smell (45% neutral/don't know) and quality (63% neutral/don't know), indicating the need for targeted communication**.
- **Consumers' wish for information transparency**:79% want clear information on the processes connected to transforming and using CO_2 emissions, 55% on the CO_2

source location, and 48% on the source type (e.g., wastewater). Suggestions include including environmental impact data, energy use comparisons, and QR codes linking to technical details.

- From a **market positioning perspective**, **these findings point to strong early adopter potential in Colombia,** with strategic opportunities to differentiate via transparency, third-party eco-certifications, and branding that emphasizes climate benefits.

Surveys assessing self-reported perceptions and purchase intentions are a common method when studying the acceptability of novel technologies or products, that are typically not yet available to participants. Studies measuring real life behavior and purchase decisions can be used to complement survey results in future research.

2.2.4 Economic context: is the market ready?

The economic viability of WaterProof technology depends on both the cost-effectiveness of implementation for emission-generating industries and the market demand for the CO_2-derived products it produces. From the supply side, the decision to adopt such technology is influenced by the availability of carbon pricing mechanisms, fiscal incentives, and the potential for monetizing emissions through carbon markets. On the demand side, the attractiveness of WaterProof increases if its outputs, formic acid, hydrogen peroxide, and deep eutectic solvents, can access high-growth, high-value markets where cleaner, bio-based, or circular chemical alternatives are in demand. The following sections explore both perspectives to assess WaterProof's economic potential in Colombia.

Supply-Side economics: carbon markets, incentives, and emission monetization

For companies that generate CO_2 emissions, such as wastewater treatment plants, landfills, or industrial sites, adopting WaterProof technology can represent an environmental upgrade and an economic opportunity through carbon markets. These markets are divided into two main types:

- Compliance (regulated) markets, established by governments or international treaties, require companies to reduce or offset emissions under legal mandates. Examples include the European Union Emissions Trading System (EU ETS), where carbon prices averaged around €71 per ton in 2023 and are projected to rise to

€149/tCO_2 by 2030, creating strong incentives for carbon capture and utilization (CCU) investments (Bloomberg, 2024).
- Voluntary carbon markets (VCMs) allow companies or individuals to purchase carbon credits on a non-mandatory basis to meet internal sustainability goals or improve corporate reputation. In these markets, average prices fell to $4.8/t$CO_2$ in 2024, though credits linked to high-impact technologies or nature-based solutions can fetch higher prices (Carboncredits.com, 2025).

Colombia currently operates within a hybrid framework. Since 2017, the country has applied a carbon tax on fossil fuels (Decreto 926, 2017), set at approximately USD 5 per ton of CO_2 emitted, covering gasoline, diesel, fuel oil, and natural gas used for combustion. Although relatively low compared to international benchmarks, this tax establishes a foundational signal for carbon pricing in the economy and is progressing toward establishing a national emissions trading system (ETS). Additionally, **Colombia has implemented a government-administered carbon crediting program, which allows companies to offset up to 50% of their tax liability by purchasing verified carbon credits from domestic projects registered in the National Emissions Reduction Registry (RENARE).** These credits must meet rigorous standards and verification processes, fostering an emerging ecosystem for emissions mitigation and offsetting within the country (World Bank, 2024). However, **no specific regulatory mechanisms or fiscal incentives exist for CO_2 utilization technologies like WaterProof.** This lack of policy clarity presents a key barrier for emitters seeking economic justification for investing in electrochemical conversion systems (UNEP, 2023).

Nonetheless, Colombia is actively engaged in climate finance and carbon offset initiatives, including participation in REDD+ and ART-TREES, and has launched the Carbon Neutral Colombia Program (Minambiente, 2022a)**, which includes over 500 participating companies. These frameworks could offer a pathway to valorize CCU-related emission reductions once verification and certification mechanisms are aligned**. In parallel, global interest in CCU credits is rising, with financial institutions like JPMorgan Chase investing in credits from carbon removal projects at prices exceeding $100–200 per ton (Barrons, 2025).

While Colombia's current carbon prices remain low and the absence of CCU-specific incentives limits short-term profitability, the country is well-positioned to benefit from international demand for high-quality carbon credits. For

WaterProof adopters, economic viability will hinge on the ability to quantify and verify avoided emissions, align with evolving national regulations, and access premium segments of the carbon market.

Demand-side economics: market potential for CO_2-derived products

While WaterProof's value proposition depends on the ability to reduce emissions at the source, its economic viability is equally tied to the market potential of the CO_2-derived products it generates. As global industries shift toward more sustainable and circular alternatives, the demand for cleaner chemical inputs, particularly those derived from captured carbon, is rising. Products such as formic acid, hydrogen peroxide, and acidic deep eutectic solvents (ADES) are essential to multiple industrial sectors, including agriculture, textiles, paper, water treatment, and pharmaceuticals. In recent years, these markets have shown steady or accelerated growth, with increasing interest in green and bio-based alternatives. The following sections summarize key trends, uses, and projected market growth for each of these compounds.

Formic acid

The global formic acid market was valued at approximately USD 2.32 billion in 2024 and is projected to reach around USD 3.78 billion by 2034, growing at a Compound Annual Growth Rate CAGR of 5% (Procedence research, 2024). Its primary applications include agriculture (as a preservative and antibacterial agent), leather tanning, textile dyeing, and pharmaceutical and rubber production (Figure 2-11). The Asia-Pacific region dominates the market, holding over 51% share in 2023 (Imarc, 2024).

The global formic acid market is dominated by a handful of major producers, primarily based in Europe and Asia. BASF SE (Germany) leads with the world's largest production facility, holding a significant market share. Feicheng Acid Chemicals (China) and Eastman Chemical Company (USA/Finland) also play key roles, each with capacities exceeding 100,000 metric tons annually. Other notable producers include Perstorp AB (Sweden), GNFC (India), and Shandong Yuanping Chemicals (China). Together, these companies supply most of the global demand across sectors such as agriculture, leather, textiles, and chemicals, with China and Europe as the main production hubs.

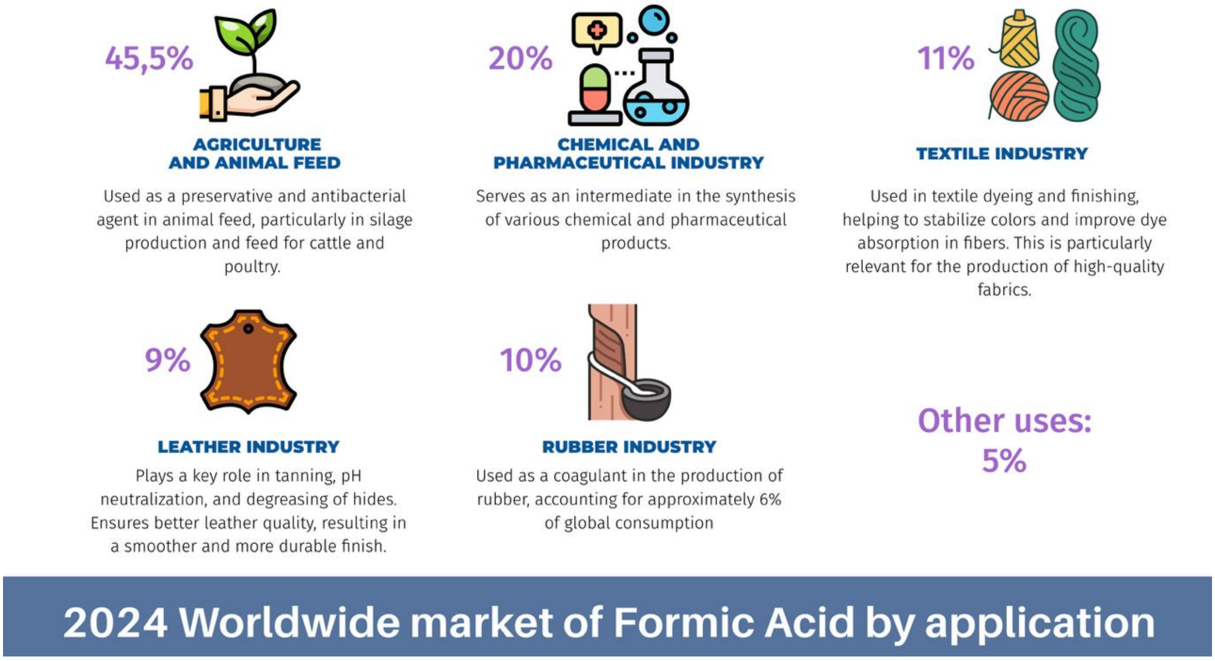

Figure 2-11. Main industrial uses of formic acid worldwide.(Maximize Market Research, 2025) (Virtue Market Research, 2023)

In Colombia, formic acid is a vital chemical input across multiple industries, particularly agriculture, leather processing, and textiles. **The country does not produce formic acid domestically and relies entirely on imports to meet its industrial demand**. According to the World Bank's World Integrated Trade Solution (WITS), Colombia imported approximately USD 4.21 million of formic acid in 2022 (World Integrated Trade Solutions, 2022a) Figure 2-11. **Most of these imports originated from China (USD 2.90 million), followed by the United States (USD 732,000) and Germany (USD 536,000). Smaller contributions came from Panama (USD 37,000) and Belgium (USD 6,000), with China alone accounting for nearly 69% of the total value.**

Complementary data from Veritrade indicates that Colombia recorded approximately USD 9.2 million in formic acid imports over the last five years, involving 66 registered importers and 561 import transactions (Veritrade, 2024). These figures reinforce the country’s dependency on foreign supply to serve key industrial sectors.

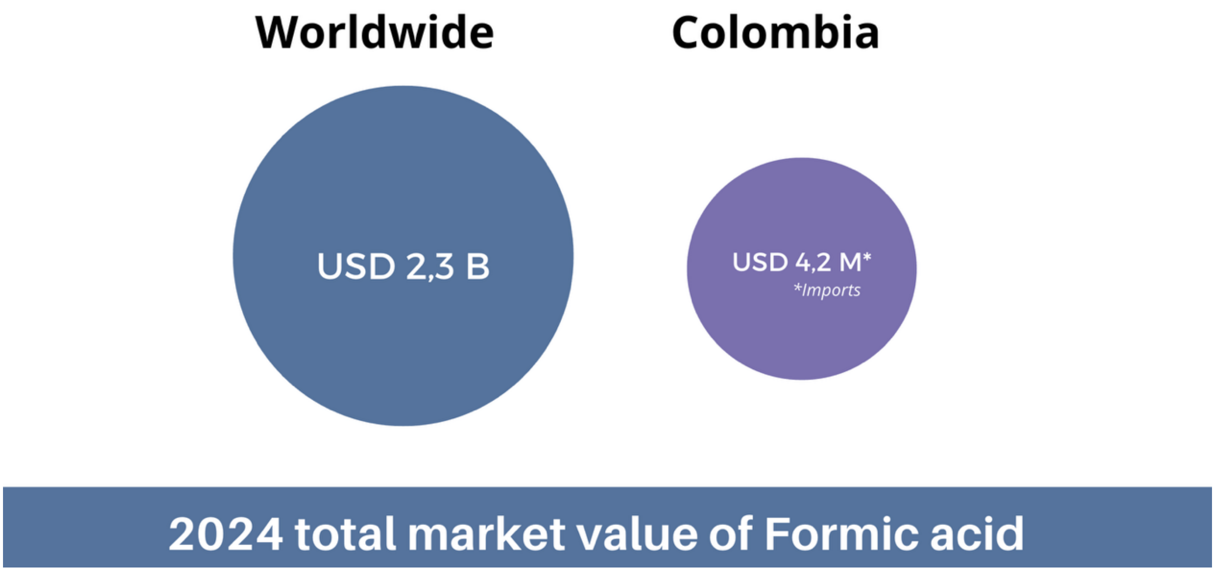

Figure 2-12. 2024 Total market for formic acid, Worldwide vs Colombia. (Procedence research, 2024) (World Integrated Trade Solutions, 2022a)

In terms of pricing, the retail cost of formic acid in Colombia varies by concentration and packaging. For example, an **85% concentrated 1 kilogram unit is priced at USD 12** (Mercadolibre, 2025). Larger formats, such as 35-kilogram drums, are offered by local chemical suppliers, though prices for bulk purchases are typically quoted directly to buyers and not publicly listed (Disproquímica, 2025).

Although Colombia's National Administrative Department of Statistics (DANE), through its Agricultural Prices Information System (SIPSA), reports wholesale input prices for various agricultural goods, it currently does not publish pricing data for formic acid. This heavy reliance on imports and the absence of domestic production highlights an opportunity for Colombia to explore local, sustainable production pathways.

Despite the global trend toward increased use of formic acid in agriculture, Colombia has yet to adopt this application at significant volumes. However, it represents a promising opportunity for introducing more sustainable, high-purity chemical alternatives (above 90% concentration). **Currently, the greatest volume-driven demand for formic acid in Colombia is concentrated in the textile and leather industries, which present the most immediate market potential for CO_2-derived alternatives.**

Formic acid in the textile industry

In terms of volume, the global textile chemicals market was valued at approximately USD 27.1 billion in 2023 and is projected to reach USD 41.7 billion by 2033, growing at a compound annual growth rate (CAGR) of 4.4% (Maximize Market Research, 2025). This growth is driven by increasing demand for functional and sustainable textiles, as well as technological advancements in textile manufacturing processes. **While specific data on global formic acid consumption within the textile industry is limited, available information indicates that formic acid plays a significant role in textile processing. In 2009, approximately 9% of global formic acid consumption was attributed to textile dyeing and finishing processes.** In terms of overall chemical usage, studies have shown that textile processing is chemically intensive. For instance, **research focusing on textile factories in Bangladesh reported an average chemical consumption of 449 grams per kilogram of textile produced, with total annual chemical usage ranging from 954 to 4,525 tons per factory** (Uddin et al., 2023). While this data is region-specific, it underscores the substantial chemical inputs required in textile manufacturing processes.

The textile and apparel industry in Colombia is a key pillar of the national economy. In 2022, the sector generated revenues of approximately COP 14.34 trillion, **accounting for 9.4% of the country's industrial GDP** (Portafolio, 2023). It directly employs over 600,000 people, making it one of the largest sources of manufacturing employment in Colombia (ProColombia, 2023).

The industry includes around 6,500 companies, with a strong presence in cities such as Medellín and Bogotá, which serve as key hubs for production and export. In 2023, leading companies in the sector reported revenues of COP 13.03 trillion, reflecting a slight decline from the previous year due to raw material price volatility and global market challenges (La Nota Económica, 2023).

The Colombian textile industry is highly dependent on a wide array of chemical inputs throughout its production chain (Figure 2-13). Synthetic fibers are produced from thermoplastic polymers, derived from petrochemical synthesis, using solvents, acids, esters, and petroleum-based derivatives. These materials undergo processes like melting, extrusion, and precipitation to form fibers. In the case of natural and artificial fibers, chemical treatments using hydroxides, alcohols, and dyes are essential for stain removal, bleaching, and degreasing. In the fiber spinning stage, detergents and surfactants play a critical role in preparing yarns for color fixation. **During weaving and finishing,**

chemicals such as sodium sulfate, mordant salts, and glycerin are applied to ensure uniform dye distribution, color retention, softness, and dimensional stability of fabrics. Formic acid is integrated into these stages as a pH regulator and neutralizing agent, supporting dye fixation, stripping, and fabric finishing. In the final garment-making phase, additional chemical additives and inks are used for printing and textile surface treatments. These processes illustrate the heavy reliance on synthetic chemicals, creating an opportunity for more sustainable alternatives like CO_2-derived formic acid, aligned with circular economy goals.

Figure 2-13. Simplified textile industry value chain. Based on (Portafolio, 2023)

Formic acid in the leather industry

In the leather industry, formic acid plays a fundamental role across several key processing stages, particularly in tanning, pH adjustment, and degreasing (Figure 2-14). It is widely used in both chrome and vegetable tanning methods to control acidity, improve leather quality, and ensure cleaner effluent streams. **Globally, the leather chemicals market was valued at approximately USD 7.5 billion in 2023 and is projected to grow to USD 10.1 billion by 2030,** driven by demand for premium leather goods, sustainable production methods, and performance-enhancing chemical formulations (Fortune Business Insights, 2025). While formic acid-specific consumption data for leather is limited, it is recognized as one of the most used acids in hide processing, particularly for acidification before chrome tanning and for neutralizing agents post-tanning (Camachem, 2025).

Figure 2-14. Simplified leather industry value chain. Based on (United Nations Industrial Development Organization, 2019)

In Colombia, the leather and footwear industry is economically significant, especially in regions such as Bogotá, Bucaramanga, and Medellín. The sector comprises over 6,000 registered companies, generating more than 100,000 direct and indirect jobs (Acicam, 2023). Although traditionally reliant on imported chemical inputs, Colombian tanneries increasingly seek to comply with environmental regulations by adopting cleaner alternatives and more efficient chemical dosing. **Formic acid stands out as a candidate for substitution of harsher acids like sulfuric acid due to its milder environmental footprint and compatibility with high-efficiency tanning systems**.

Hydrogen Peroxide

The global hydrogen peroxide market was valued at approximately USD 3.48 billion in 2024 and is projected to reach around USD 4.70 billion by 2030, growing at a CAGR of 5.1% (Fortune Business Insights, 2024; MarketsandMarkets, 2024). **Its primary applications include pulp and paper bleaching (USD 9.5B market segment), textile processing (USD 6B), water treatment (USD 4.2B), and healthcare and disinfectants (USD 3.1B),** among others such as electronics and

mining. The Asia-Pacific region currently dominates global consumption, accounting for more than 55% of total demand (IMARC Group, 2024).
Major global producers include Solvay S.A. (Belgium), Evonik Industries AG (Germany), Arkema S.A. (France), and Kemira Oyj (Finland)—each holding significant shares in the market with large-scale production facilities exceeding hundreds of kilotons annually. These companies supply hydrogen peroxide primarily in concentrations ranging from 35% to 70%, tailored to industrial applications with stringent purity requirements.

In Colombia, hydrogen peroxide is a widely used chemical across industrial sectors, particularly in pulp and paper, textiles, and water treatment. According to import records from Veritrade (2024) and DANE, Colombia imported an estimated USD 9.1 million in hydrogen peroxide during the last five years (Figure 2-15**)**, with imports originating mainly from the United States, Germany, Brazil, and Mexico. Concentrations typically range from 35% to 50% for industrial grade uses.

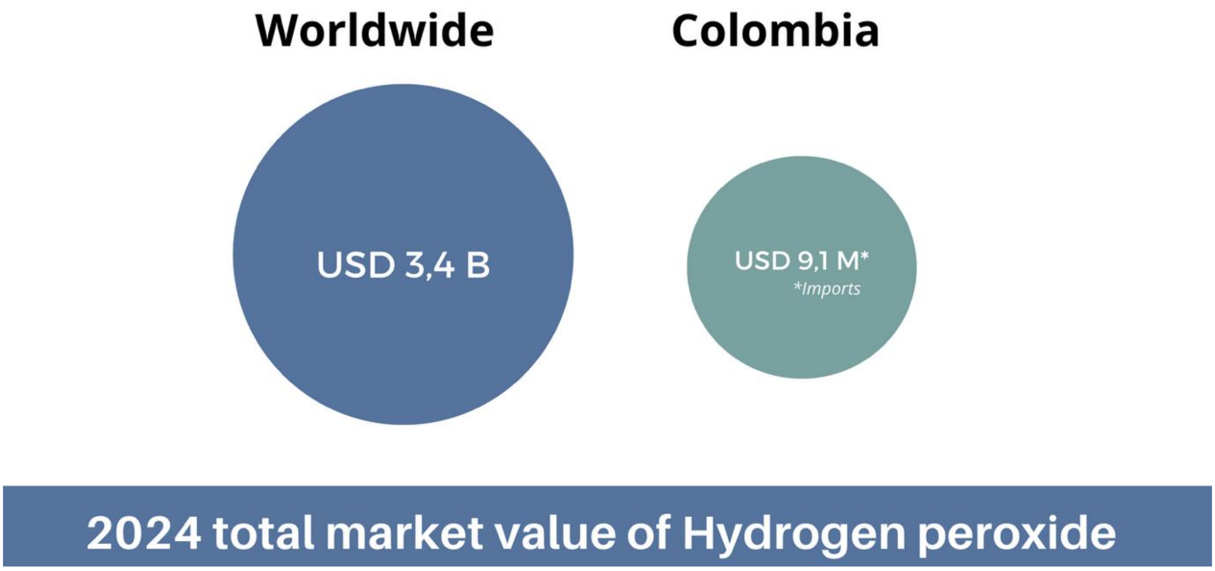

Figure 2-15. 2024 Total market for Hydrogen peroxide, Worldwide vs Colombia.

Retail prices vary depending on concentration and format. For instance, a 35% concentration, 1-liter bottle is available online for approximately USD 6–8 (MercadoLibre, 2025). Large industrial users typically source hydrogen peroxide in drums or IBC tanks through local distributors such as Disproquímica, Novaqua, DQI and Oxiquim.

Despite its widespread use, **Colombia does not produce hydrogen peroxide domestically and depends entirely on imports. This creates an opportunity for**

sustainable, CO_2-based production methods like those proposed by the WaterProof project, particularly considering the compound's role in environmental remediation and disinfection. Its compatibility with water treatment and its relatively high degradation rate into oxygen and water make hydrogen peroxide a key chemical for circular, low-emission industrial models.

Hydrogen Peroxide in Pulp and paper

The pulp and paper value chain comprises four main stages (Figure 2-16): pulp production, bleaching, paper manufacturing, and product conversion (FAO, 2024). It begins with the extraction of cellulose fibers from wood or fibrous materials through mechanical or chemical pulping methods such as kraft or sulfite processes. **One of the most critical steps is the bleaching stage, where hydrogen peroxide (H_2O_2) plays a key role. Used especially in mechanical pulp (e.g., TMP and CTMP), hydrogen peroxide enhances brightness while preserving fiber integrity and reducing the formation of toxic by-products like organochlorines.** It is also applied in deinking during paper recycling and in wastewater treatment, helping meet stricter environmental discharge standards. Compared to traditional chlorine-based agents, hydrogen peroxide is biodegradable, non-toxic, and leaves minimal residues, making it a preferred option for sustainable pulp and paper production. The final stages involve drying, finishing, and converting paper into products like tissue, office paper, and packaging. As environmental regulations tighten globally, the demand for clean bleaching agents like H_2O_2 is expected to grow, reinforcing its strategic role within this industrial chain.

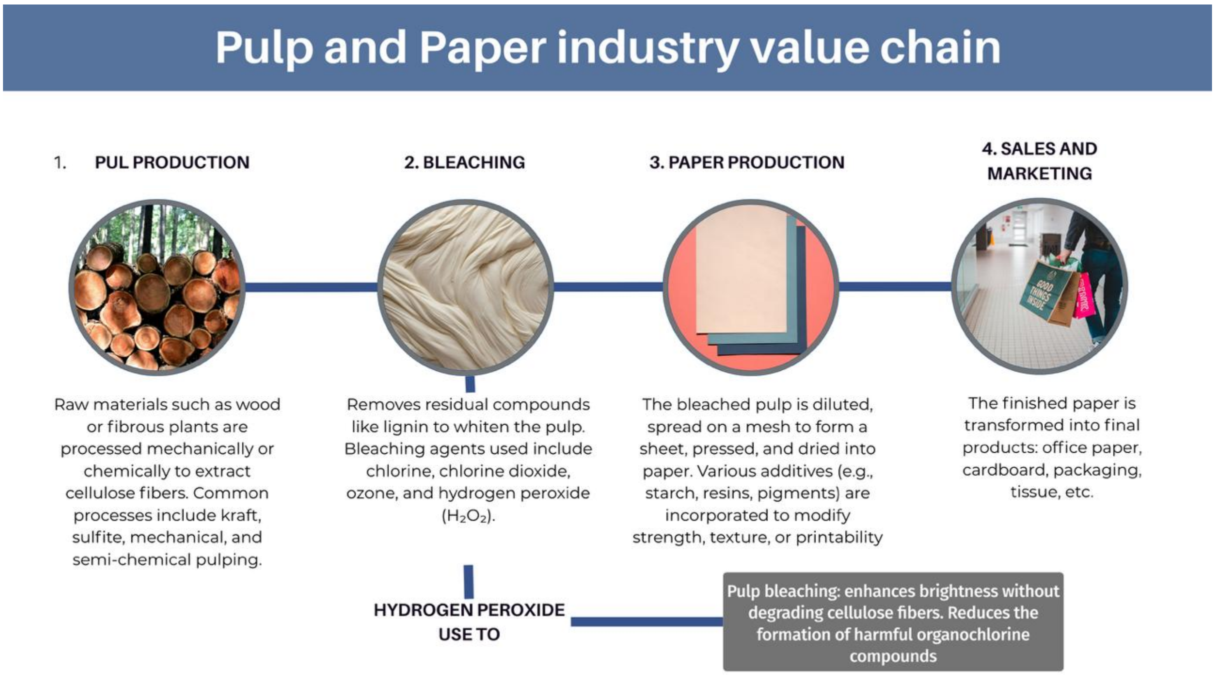

Figure 2-16. Simplified pulp and paper industry value chain. Based on (FAO, 2024)

The pulp and paper industry plays a strategic role in the manufacturing sector in Colombia, particularly in regions like Antioquia, Cundinamarca, and Valle del Cauca. **The industry includes more than 200 companies dedicated to pulp production, paper manufacturing, and tissue conversion, generating over 9,000 direct jobs and contributing significantly to packaging, hygiene, and education sectors** (Cámara de la Industria de la pulpa, 2020). The sector accounts for approximately 4.6% of Colombia's industrial GDP and exports primarily to Ecuador, Peru, and Central America. Globally, Colombia represents about 0.3% of total paper and cardboard production and 0.1% of global pulp output, while its share in Latin America reaches 6% for paper and 13% for pulp production. While the sector still relies heavily on imported bleaching agents, there is growing interest in cleaner alternatives aligned with circular economy goals. **Hydrogen peroxide is increasingly used to replace chlorine-based compounds in bleaching processes due to its lower environmental impact and compatibility with closed-loop water systems**. This shift not only improves compliance with wastewater standards but also enhances product quality, positioning hydrogen peroxide as a key input for more sustainable pulp and paper production in Colombia.

Hydrogen Peroxide in Water treatment

The wastewater treatment value chain consists of several key stages, including preliminary treatment, primary sedimentation, biological treatment, disinfection, and sludge management (Figure 2-17**). Hydrogen peroxide (H_2O_2) plays a critical role in the disinfection and advanced oxidation processes (AOPs) phases,** where it is used to degrade persistent organic pollutants, reduce pathogens, and eliminate micropollutants such as pharmaceuticals and pesticides (Kumar & Kanmani, 2022). When combined with UV or iron catalysts (Fenton reactions), H_2O_2 generates hydroxyl radicals that effectively break down complex contaminants. Its use offers several advantages over traditional chlorine-based disinfectants: it is environmentally friendly, decomposes into water and oxygen, and avoids the formation of chlorinated by-products that are harmful to aquatic life and human health.

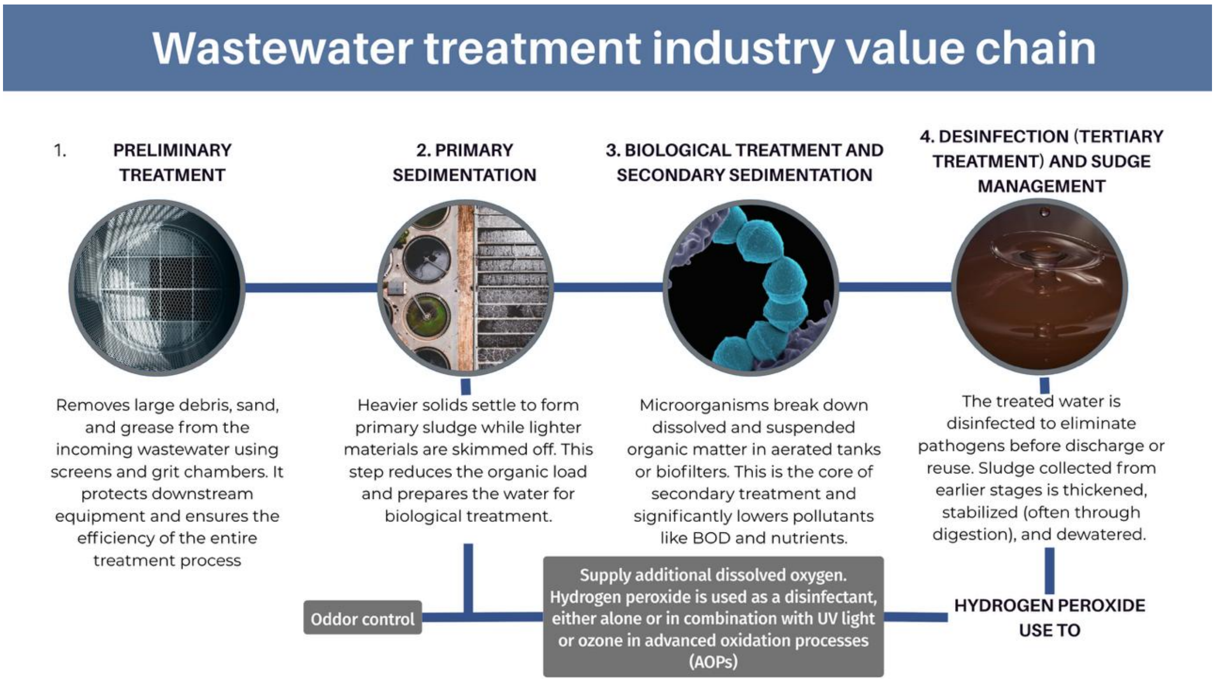

Figure 2-17 : Simplified Wastewater industry value chain. Based on (Zhou et al., 2025)

In Colombia, water treatment plants operated by entities such as Grupo EPM and Acuavalle have begun exploring cleaner alternatives for water disinfection and odor control in the sludge dehydration, including hydrogen peroxide, particularly in pilot-scale implementations and advanced reuse systems. While chlorine remains the predominant disinfectant, hydrogen peroxide is gaining attention due to its compatibility with closed-loop water systems and its ability to degrade emerging contaminants without generating harmful by-products. However, **the application of hydrogen peroxide in municipal wastewater treatment remains limited, as tertiary treatment processes, where H_2O_2 is most effective, are not widely implemented across the country**. These positions drinking water treatment, especially the disinfection stage, as the primary entry point for broader adoption of hydrogen peroxide in Colombia's water sector, either as a complement to or replacement for chlorine.

Acidic Deep Eutectic Solvents (ADES)

The global market for Acidic Deep Eutectic Solvents (ADES), though still emerging, is gaining traction as a promising green alternative to traditional industrial solvents. In 2024, the ADES market was valued at approximately USD 123.6 million and is projected to reach USD 806.2 million by 2034, with an impressive compound annual growth rate (CAGR) of 22.9% (Prophecy Market Insights, 2024). ADES are formed by mixing a hydrogen bond donor (HBD) and a hydrogen bond acceptor (HBA), often incorporating organic acids such as formic acid, resulting in a non-toxic, biodegradable, and thermally stable solvent. **Their applications span across chemical synthesis, metals recovery, biomass processing, pharmaceutical formulation, and catalysis** (Figure 2 9). They are also gaining relevance in carbon dioxide capture, precious metal recovery from electronic waste, and cleaner separation processes, aligning well with circular economy goals.

Globally, research institutions and chemical innovators like Proionic GmbH (Austria) and Ionic Liquids Technologies GmbH (Germany) are leading efforts in commercialization. Meanwhile, multiple EU Horizon-funded projects are exploring industrial-scale applications of ADES in metallurgy, pharma, and green chemistry, driving innovation and regulatory acceptance.

In Colombia, the use of ADES remains mostly confined to academic and pilot-scale initiatives. **There are no large-scale industrial producers or importers of ADES currently reported**. However, growing local interest in biobased inputs and low-toxicity solvents, particularly in sectors like mining, agriculture, and water treatment, creates fertile ground for early adoption.

For instance, ADES made from CO_2-derived formic acid, as envisioned by the WaterProof project, could be used in precious metal recovery from sewage sludge and incineration ash, a relevant application for Colombia's urban waste management systems. Additionally, ADES could provide a sustainable alternative to traditional extractants used in leather tanning and chemical manufacturing, where environmental compliance is increasingly critical.

Green chemicals market

Finally, the broader global shift toward green industrial chemistry reinforces the market potential for CO_2-derived alternatives like formic acid, hydrogen peroxide, and ADES. The sustainable chemicals market was valued at over USD 90 billion in 2023 and is projected to surpass USD 160 billion by 2032, growing at a CAGR above 6.5% (Fortune Business Insights, 2025). This trend is creating new demand across industries such as textiles, agriculture, construction, and personal care, where bio-based and low-impact chemical inputs are increasingly prioritized. **In Colombia, although the green chemicals industry is still emerging, national strategies like the Circular Economy Roadmap (ENEC) and innovation programs led by Minciencias are laying the groundwork for adoption.**

Key gaps and opportunities

Table 2-7 outlines the main economic gaps and opportunities identified for the WaterProof project

Table 2-7. Main Gaps and Opportunities- Economic

Gaps	Opportunities
Lack of CO_2 Utilization Incentives: Despite national efforts to tax emissions and promote climate neutrality, Colombia lacks targeted fiscal incentives or carbon credit mechanisms specifically for CO_2 utilization (CCU)—making it difficult for emitters to economically justify adopting technologies like WaterProof.	**Import Substitution with Green Alternatives:** WaterProof offers a sustainable domestic alternative to imported formic acid (≈ USD 4.2M/year) and hydrogen peroxide—potentially lowering costs and carbon footprints across multiple sectors.
Low Domestic Production of High-Purity Chemicals: Colombia is entirely import-dependent for key compounds such as formic acid (the price of formic acid from China or other producers is more competitive). This reliance creates supply risks and pricing volatility but also highlights the absence of infrastructure for local production of green chemicals.	**Rising Global Demand for Green Chemicals:** The global green chemicals market (> USD 90B) and growing adoption of eco-labels and circular procurement create an entry point for CO_2-based ingredients, especially in export-oriented industries like textiles and processed leather goods.
Weak Industrial Demand for Sustainable Inputs: While the textile and leather industries show volume-based potential, there is still low awareness and limited demand for bio-based or CO_2-derived alternatives, particularly in agriculture—one of the fastest-growing application areas globally	**First-Mover Advantage in Latin America:** Colombia has no current CCU manufacturing capacity, so WaterProof could position itself as a regional pioneer—serving domestic markets and exporting to Latin America.
Fragmented Carbon Markets and Low CO_2 Prices: Colombia's current carbon tax is modest (≈ USD 5/tCO_2) and voluntary carbon market mechanisms are still developing, reducing the economic returns from	

avoided emissions and limiting investor confidence in CCU business models.	

Demand-side expert interviews

To validate contextual gaps and explore the feasibility of adopting WaterProof in Medellín's textile sector, an interview was conducted with **professionals from Grupo Crystal's sustainability and environmental management teams**. **Grupo Crystal, one of Colombia's leading textile companies, has set ambitious climate goals, including a 30% emissions reduction target by 2030 (Scope 3), and operates processes that involve dyeing and finishing, key stages with intensive chemical use and high emissions (Grupo Crystal, 2024)**. The interview provided critical insights into both the potential and limitations of implementing CCU-derived chemical products within this industry.

Key insights from the interview include:

• **Growing but fragmented climate ambition**: Crystal's strategy focuses on emissions reduction across Scopes 1, 2, and 3. While Scope 2 emissions are already mitigated through renewable energy use, Scope 1 reductions are being addressed through biomass and technological upgrades. However, Scope 3 emissions, particularly those linked to raw materials like imported cotton, remain hard to control.

• **Sustainable chemical use driven by exports**: Crystal actively works to substitute hazardous chemicals due to strict requirements from international clients (e.g., Lululemon, Lacoste), not because of national regulation. Certification schemes like GOTS (Global Organic Textile Standard) (Global Standard gemeinnützige GmbH, 2023) and GRS (Global Recycled Standard) (Textile Exchange, 2014) and compliance with ZDHC (Zero Discharge of Hazardous Chemicals) (ZDHC Foundation, 2020) and MRSL (Manufacturing Restricted Substances List) (ZDHC, 2022) lists are key drivers for adopting greener chemistry.

• **Dyeing and finishing operations still relevant in Colombia**: Despite a broader trend toward importing pre-processed textiles, Crystal maintains full dyeing and finishing capacity in its Marinilla plant. Several regional suppliers such as Tintatex also operate in Medellín, confirming local demand for chemical inputs like formic acid and hydrogen peroxide.

• **Wastewater and sludge limitations**: Crystal has upgraded its wastewater treatment to comply with chloride discharge standards under Resolution 0631. However, reverse osmosis pilots failed due to cost and technical constraints. The sludge produced is currently not suitable for reuse due to specific chemical compositions, closing the door for valorization unless innovative solutions are found.

• **Pilot and cost-driven adoption logic**: Crystal is open to piloting new sustainable products—including CCU-derived acids and solvents, but only if performance, cost-efficiency, and certification benefits are demonstrated. Internal evaluation committees and customer value are critical in the decision-making process.

> *"We are always open to testing new things, but if the product is more expensive, it must come with a bigger benefit, such as compliance, market recognition, or a certified added value."*
>
> *— Professionals, Grupo Crystal*

This interview underscores the strategic role of the textile sector as a potential demand-side adopter of WaterProof outputs, especially formic acid and hydrogen peroxide. While regulatory incentives remain weak in Colombia, export-driven compliance pressures offer a window of opportunity for high-purity, sustainable chemical alternatives derived from CO_2.

2.2.5 Environmental basic: what about impact?

Life Cycle Assessment (LCA) studies across steel, chemical, and cement sectors reveal that while CCU can significantly reduce net CO_2 emissions, capturing up to 90% of CO_2 from industrial flue gases, its overall environmental benefit is highly sensitive to the capture route, energy source, and the end-use of the captured carbon (Garcia-Garcia et al., 2021). For instance, activated carbon-based Temperature Swing Adsorption TSA systems paired with methanol production consistently show lower global warming potentials and reduced toxicity risks compared to alternatives like MEA-based capture or mineralization of steel slag. At the same time, the environmental trade-offs, such as increased freshwater ecotoxicity or energy input requirements, underscore the importance of aligning CCU adoption with broader green chemistry standards and certification schemes. Some environmental benefits of CCU technologies are mentioned in the Figure 2-18.

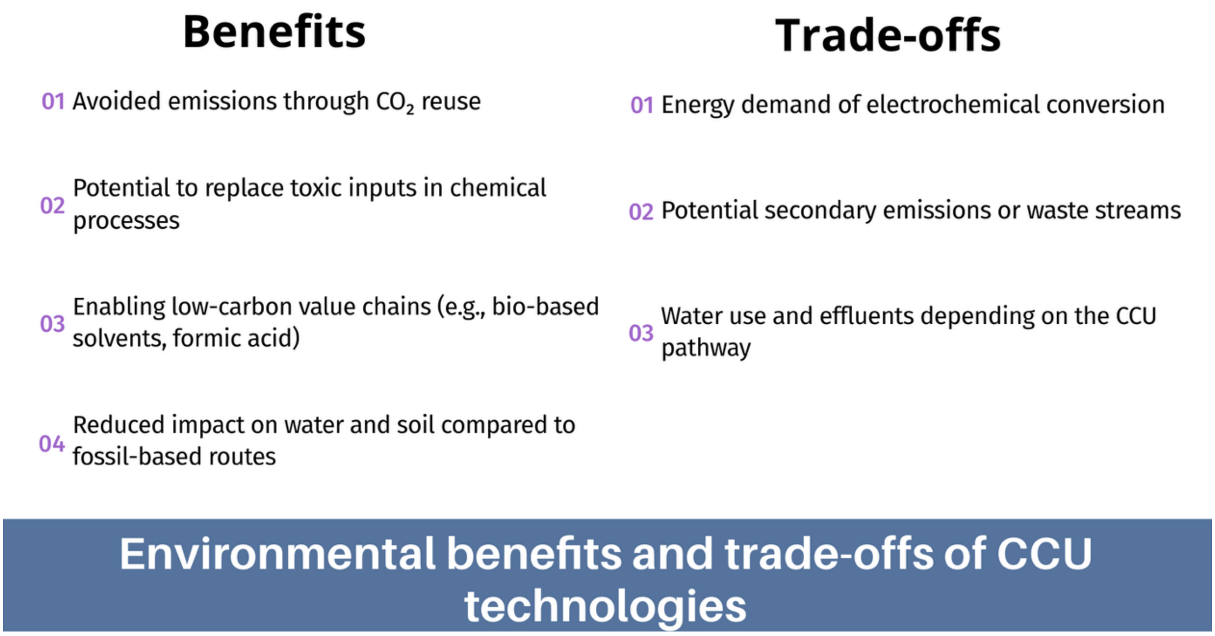

Figure 2-18. Environmental benefits and trade-offs of CCU technologies

Assessing the environmental performance of CCU technologies requires a comprehensive, life-cycle approach. This means moving beyond CO_2 capture alone and evaluating environmental impacts from raw material extraction to product end-of-life. **Internationally recognized frameworks such as ISO 14040/44 for LCA, OECD sustainability indicators, and emerging methodologies like Environmental Life Cycle Costing (ELCA) provide the foundation for this analysis**.

presents a consolidated overview of key environmental impact categories and indicators relevant to CCU, particularly for applications like WaterProof, which integrates electrochemical conversion of CO_2 into green chemical ingredients.

Table 2-8. Key environmental impact categories and indicators- WaterProof

Impact Category	Key Indicators	Relevant to WaterProof?
Climate change	kg CO_2eq avoided per ton of product; Scope 1–2–3 emissions; GWP100 (IPCC)	Captured vs. emitted CO_2 across value chain
Energy consumption	Total kWh per functional unit; % from low-carbon sources; energy penalty factor	Renewable electricity is critical
Water use	m^3 per kg of product; intensity by process stage	Particularly relevant in solvent production
Ecotoxicity	Emissions of hazardous compounds to air/water/soil (e.g., amines, solvents)	Impact varies by capture technology
Human toxicity	Compliance with MRSL/ZDHC; use of carcinogenic or endocrine-disrupting substances	Relevant for integration in textiles, leather, paper
Resource efficiency	kg of raw materials replaced by CO_2-derived inputs; circularity index	Closed-loop chemical chains
Fossil fuel displacement	Avoided fossil-based feedstocks in fuels, solvents, polymers	Central to CCU's added value
Acidification & eutrophication	Emissions of SO_x/NO_x or nutrient loads from processes	Requires monitoring depending on pathway
Land use	Area requirements for infrastructure or bio-based CCU (e.g., microalgae)	Limited in WaterProof, but relevant for some routes
CO_2 leakage risk	Potential CO_2 loss during capture, transport, or storage	More critical in CCS, but must be monitored
Energy penalty	Efficiency loss vs. baseline (MJ per kg of product)	Benchmarking vs. fossil-based alternatives
Social impact factors	Stakeholder wellbeing, job creation, community health, public perception	To be addressed in complementary analysis
Policy alignment	Eligibility under national/regional carbon pricing or eco-labeling schemes	GRS, GOTS, EPDs, ZDHC are key standards

For the WaterProof technology, specific attention must be paid to energy source, chemical purity, and compliance with hazardous substance restrictions, especially in downstream applications like textiles, paper, and leather.

In Colombia, and particularly in Medellín, industries such as textiles, leather, cement, and pulp and paper are not only historically significant but also central to regional employment and export capacity. **Medellín alone concentrates one of the largest textile and clothing production chains in the country and is also home to important players in the leather and cement sector**. These industries face increasing regulatory and market pressure to reduce their environmental footprint, particularly in terms of chemical safety, emissions, and traceability. For CCU-based technologies like WaterProof, which offer alternatives to fossil-derived surfactants and solvents, aligning with sector-specific environmental certifications is critical. These frameworks not only define environmental compliance; they also serve as entry points to global value chains and environmentally preferred procurement systems.

Table 2-9. Sustainable frameworks for exporting products. Textile and leather industries.

Sector	Key Standards / Schemes	Relevance to WaterProof
Textiles	GOTS (Global Organic Textile Standard), GRS (Global Recycled Standard), ZDHC, OEKO-TEX	Pressure to eliminate toxic chemicals and demonstrate traceability; opportunities for bio-based surfactants and solvents
Leather	Leather Working Group (LWG), ZDHC MRSL, ISO 17075 (chrome VI), Blue Angel (Germany)	Opportunities to replace solvent-based cleaners and toxic auxiliaries with CCU-derived alternatives
Cement	ISO 14001, Environmental Product Declarations (EPDs), EU ETS (emissions trading scheme)	CCU can reduce Scope 1 emissions via mineralization or on-site utilization; pilots can support EPD documentation
Paper	FSC, PEFC, EU Ecolabel, ISO 14001	Cleaners and process water treatment using CCU-derived green chemistry; alignment with circular procurement criteria

Some of the most interesting international certifications for each industry that represent the greatest opportunities in the WaterProof context are analyzed below.

<u>Textile Sector: GOTS & ZDHC</u>

GOTS (Global Standard gemeinnützige GmbH, 2023) sets strict criteria for ecological and social compliance along the entire textile supply chain. It restricts the use of substances such as:

- Azo dyes
- Chlorinated solvents
- Heavy metals (e.g., lead, chromium, mercury)
- Nonylphenol ethoxylates (NPEs)
- Synthetic surfactants and quaternary ammonium compounds

WaterProof's technology/product offers the potential to replace hazardous detergents with green alternatives made from formic acid and to replace synthetic solvents, meeting ZDHC MRSL requirements (ZDHC, 2022). These substances are biodegradable, low in toxicity, and free from endocrine-disrupting compounds, offering compatibility with both GOTS and ZDHC gateway platforms, facilitating access to certified supply chains.

<u>Leather Sector: LWG & ISO 17075</u>

The Leather Working Group (LWG) (Leather Working Group, 2024) evaluates tanneries on energy and water use, waste, and chemical management. Critical substances restricted include:

- Solvent-based degreasers
- Chrome VI (monitored via ISO 17075)
- Formaldehyde
- Phthalates and azo dyes

WaterProof's CCU platform can contribute with biodegradable cleaning agents made from formic acid, for the degreasing and soaking stages in leather processing. These ingredients reduce reliance on VOC-emitting solvents and help tanneries improve scores under the LWG protocol.

<u>Cement Sector: ISO 14001 & EPDs</u>

Cement producers in Colombia, such as Grupo Argos, are increasingly adopting ISO 14001 (ISO, 2021) and generating Environmental Product Declarations (EPDs) to quantify lifecycle emissions. These documents rely heavily on:

- CO_2 emissions (Scope 1)
- Energy consumption
- Clinker substitution or CO_2 mineralization evidence

By integrating WaterProof electrochemical CO_2 conversion modules at the plant level, cement companies could utilize captured CO_2 on-site, either as precursors for industrial chemicals or through indirect incorporation into admixtures. These interventions support Scope 1 mitigation while generating traceable LCA data for EPD reporting, enhancing climate credibility and eligibility in green building procurement.

<u>Paper Sector: EU Ecolabel & FSC</u>

In the paper and pulp sector, certifications like EU Ecolabel (Donatello et al., 2019) and FSC Chain of Custody (Forest Stewardship Council, 2017) emphasize:

- Elimination of harmful process chemicals (e.g., chlorine, NPEs, EDTA)
- Effluent toxicity
- Biodegradability of additives
- Sustainable sourcing and production

Wastewater treatment sector:

WaterProof technologies can supply green cleaning agents made form formic acid and dispersants that substitute traditional bleach-stabilizing or pitch control chemicals (like Hydrogen peroxide). These CCU-based ingredients are free of alkylphenols and persistent compounds, supporting compliance with EU Ecolabel's toxicity and biodegradability criteria. Additionally, their traceable origin (CO_2-based) adds value to corporate sustainability disclosures under FSC-aligned standards.

Key Gaps and Opportunities

The Table 2-10 highlights the main environmental gaps and opportunities relevant to the WaterProof project

Table 2-10. Main Gaps and Opportunities- Environmental

Gaps	Opportunities
Lack of localized LCA data on electrochemical CO_2 conversion systems in Colombia.	**WaterProof pilots can generate first-of-its-kind environmental performance benchmark**s for CCU in urban and industrial contexts.
High energy demand and potential environmental trade-offs of electrochemical conversion not yet quantified.	**ISO 14040/44-based LCA and alignment with international reporting tools (e.g., GHG Protocol, EPDs) can help mainstream CCU in regulatory frameworks.**
Weak connection between CCU technologies and existing industrial environmental certifications (e.g., ISO 14001, EPDs).	**Integration of low-carbon energy sources (solar, hydro) into CCU systems can mitigate energy penalties** and enhance net environmental gains.
Environmental risks from side streams (e.g., effluents, by-products) remain poorly characterized.	WaterProof can enable industries (e.g., cement, paper) to strengthen environmental disclosures and **reduce Scope 1 emissions through CO_2 valorization.**
Limited integration of CCU in circular procurement or climate financing mechanisms.	**CCU-based products or materials could be positioned under circular economy or climate innovation frameworks** to attract funding and adoption
The textile and leather sector are strong in Colombia, but **few brands export significant volumes to markets with stringent environmental regulations**.	**Growing positioning of Colombian brands in international markets,** which requires compliance with regulatory standards that involve replacing polluting chemicals.

To validate contextual gaps and explore the feasibility of adopting WaterProof in Colombia's academic and sustainability innovation ecosystem, an interview was conducted a sustainable expert, professor and researcher at EAFIT University. Who has worked on sustainable technologies, including water treatment using microalgae and evaluating environmental performance. Her insights provided a critical academic and technical perspective on the barriers and requirements for scaling CCU (technologies such as WaterProof.

Key insights from the interview include:

- **TRL skepticism and technological uncertainty:** Adriana emphasized that electrochemical CCU technologies, remain at a low technology readiness level (TRL). She expressed strong skepticism about their current feasibility, noting that catalytic processes of this kind involve materials that are easily degraded, depend on scarce transition metals, and pose major technical challenges. From her perspective, until the technology proves scalable and cost-efficient, market discussions are premature.
- **Legislation as a future driver**, **but not a current enabler**: While Adriana acknowledged that emission reduction is a growing concern, she emphasized that regulatory enforcement is currently insufficient to create a viable CCU market in Colombia. Although some industries (construction, food, cement) are beginning to assess future obligations due to emerging international standards or financing mechanisms (e.g., green credit lines), most companies remain passive, waiting for mandatory policies before investing
- **Market acceptance depends on cost and performance, not origin**: according to Adriana, end-users will not resist adopting CO_2-derived products**,** especially if they are competitively priced. She noted that sectors like cosmetics or specialty chemicals could even benefit from marketing "biobased" or "sustainable" inputs. However, the economic viability and performance parity are key.
- **Certifications and impact assessments are secondary concerns**, once the product exists: when asked about the relevance of certifications for CO_2-derived chemicals, Adriana noted that ISO-based environmental product declarations (EPD) already exist to compare products on a life-cycle basis. However, she believes this becomes relevant only once a technology is proven, scaled, and producing at meaningful volumes. Until then, these discussions are speculative.
- **Critical supply risks and sustainability trade-offs**: she also pointed out emerging environmental risks from the inputs required by electrochemical CCU

systems, including rare materials for electrodes and high electricity demands. Unless these challenges are addressed using renewable energy and circular material strategies, WaterProof's sustainability promise may be undermined**.**

"If they invent it and scale it up, there will be a market. But that's still a long way off"

-Sustainability expert, EAFIT

2.3 Replicability assessment

2.3.1 Potential benefits, challenges, and actions for replicability

The replicability of the WaterProof technology across Colombia and Latin America hinges on a combination of favorable structural conditions and persistent institutional, economic, and market barriers. The following analysis summarizes the key qualitative insights derived from the implementation context and findings from previous sections.

1. High potential but low institutional readiness for CO_2 utilization

- **Benefit**: Colombia has ambitious climate goals, a robust national carbon tax framework, and growing interest in circular economy models—all of which create fertile ground for CCU deployment. Public-private networks for innovation (e.g., Ruta N, Minciencias, private utilities) are actively exploring sustainable technologies.
- **Challenge**: There is no dedicated regulatory framework for electrochemical CO_2 conversion or for the commercialization of CO_2-derived products such as formic acid or ADES. Existing regulatory instruments still prioritize CO_2 uses in **Enhanced Oil Recovery (EOR)**, **Sustainable Aviation Fuels (SAF)**, and **Green Hydrogen**.
- **Action**: Develop a roadmap for CCU-specific regulation, starting with pilot project exemptions, recognition of formic acid as a green product, and MRV (Monitoring, Reporting and Verification) protocols aligned with carbon market requirements.

2. The main bottleneck is economic, not technical

- **Benefit**: The country has high-emission facilities like Argos and EPM, skilled talent in electrochemistry and engineering, and an openness to sustainability-driven innovation.
- **Challenge**: **The low domestic carbon price (~USD 5/tCO_2), absence of direct incentives for CO_2 utilization, and limited access to blended finance mechanisms** make it difficult to justify early-stage investment in technologies like WaterProof. This contrasts with the EU, where carbon prices exceed USD 80/tCO_2, enabling viable CCU business models.
- **Action**: **Design economic incentives**, such as green tax credits, public procurement quotas for CO_2-based chemicals, and eligibility for climate innovation funds (e.g., GCF, CAF, EU Horizon programs).

<u>3. Local production of key chemicals presents a strategic opportunity</u>

- **Benefit**: Colombia depends entirely on imports of formic acid (~USD 4.2M in 2022) (World Integrated Trade Solutions, 2022) and hydrogen peroxide (~USD 9M over five years) (Chemanalyst, 2024). These are products directly aligned with WaterProof's outputs.
- **Challenge**: ADES (deep eutectic solvents) remain largely unknown to most industrial actors in Colombia, with no current market or certification pathways.
- **Action**: Prioritize the production and market insertion of **formic acid and its derivatives**, as well as hydrogen peroxide, to meet clear existing demand and contribute to import substitution. Treat ADES as a **secondary opportunity**, requiring **market development efforts**, pilot co-design with target industries, and collaboration with R&D actors to validate their applications over time.

<u>4. Focus on the right industries—and stages</u>

- **Benefit**: The **textile, leather, and pulp & paper sectors**, especially in Medellín, are well positioned to absorb CCU-derived inputs due to their large environmental footprint and proximity to CO_2 sources. Additionally, **export-oriented companies** in these sectors are increasingly required to comply with **stringent environmental certifications** such as **GOTS, GRS, ZDHC, and LWG**, making them natural early adopters of sustainable chemical alternatives.
- **Challenge**: These sectors in Colombia are mostly concentrated in **downstream activities** like garment or leather goods manufacturing. Chemical-intensive upstream processes (dyeing, tanning) are often outsourced or dependent on imports, limiting domestic demand for sustainable chemical inputs.

- **Action**: Promote the development of **high-value, sustainable chemical alternatives** derived from WaterProof that can replace the most used or most problematic inputs, particularly those flagged in ZDHC MRSL and similar frameworks. Simultaneously, support **industrial reconversion and local upstream processing** to build domestic demand and create new value chains around clean chemistry.

5. Pilot projects are critical to build confidence and open the market

- **Benefit**: Facilities like **Aguas Claras WWTP (EPM)** and **Argos cement plants** offer real-world testing grounds to demonstrate the viability of WaterProof under local conditions.
- **Challenge**: Early adopters face technological, reputational, and financial risk in implementing a non-traditional carbon technology. The absence of a mature CCU ecosystem compounds this reluctance.
- **Action**: Deploy containerized pilot units through **public-private partnerships**, backed by international cooperation. Ensure that these pilots generate measurable environmental metrics (e.g., CO_2 avoided), align with LCA standards, and are eligible for **carbon credits** or green labeling schemes.

2.3.2 Gap assessment: identifying key issues, benefits, and recommendations for closing gaps

To assess the replicability potential of the WaterProof technology, a structured methodology was applied to identify, prioritize, and classify the key gaps that could affect deployment and scaling in Colombia. This methodology combined two complementary tools: the **Multi-Criteria Gap Matrix with Priority Index (**Table 2-11**)** and the **Vester Matrix for influence–dependency analysis (**Table 2-12**)**.

<u>Step 1: Multi-Criteria Gap Matrix and Priority Index</u>

First, a long list of gaps was identified across five sustainability dimensions: environmental, economic, technological, social, and institutional/policy. Each gap was evaluated against three weighted criteria:

- **Impact (Weight = 3):** How much the gap affects the feasibility or effectiveness of the technology.
- **Feasibility of Closing (Weight = 2):** How easy or difficult it would be to address the gap with current capacities and resources.
- **Evidence Level (Weight = 1):** How well-documented and supported the gap is in the literature, stakeholder interviews, or case studies.

Each criterion was scored from 1 (low) to 3 (high), and a weighted **Priority Index** was calculated for each gap. This allowed a comparative ranking of over 25 gaps and helped shortlist a set of **12 high-priority gaps** for further analysis (highlighted).

Table 2-11. Gaps priority index

Dimension	Gap Description	Impact	Feasibility	Evidence	Priority Index	Weighted Priority Index
Environmental	Lack of localized LCA data for electrochemical CCU	3	3	2	8	17
Economic	Low Domestic Production of High-Purity Chemicals	3	3	2	8	16
Technological	Insufficient pilot-scale infrastructure	3	2	2	7	16
Economic	Lack of CO_2 Utilization Incentives	3	2	2	7	16

Social	Employment vulnerability in traditional sectors	3	2	2	7	15
Environmental	High energy demand and unquantified trade-offs	3	2	2	7	15
Environmental	Limited exports from sectors under green compliance	3	2	2	7	15
Policy	Lack of specific CCUS regulation	3	2	2	7	14
Social	Industrial pollution affecting urban communities	3	2	2	7	15
Economic	Fragmented Carbon Markets and Low CO_2 Prices	3	2	2	7	15
Social	Limited incorporation of social indicators in assessments	2	3	3	8	14
Technological	Lack of CO_2 purity characterization	3	2	2	7	16
Environmental	Environmental risks from side streams not characterized	3	2	1	6	14
Technological	Absence of gas pretreatment systems	3	2	1	6	14
Policy	Generic regulation of CCU-derived products	3	2	1	6	14
Technological	Limited technical experience in CCU	2	3	2	7	14
Social	Weak community participation in tech deployment	2	3	2	7	14
Technological	Shortage of specialized training	2	3	2	7	14
Social	Low public awareness of CCU and green chemistry	2	3	2	7	14
Social	Lack of training in social sustainability for technical roles	2	3	2	7	14
Policy	Limited focus on CCU in Colombia's 2030 Agenda	2	3	2	7	14
Policy	Low prioritization of industrial CCUS innovation	2	3	2	7	14
Environmental	Weak link to environmental certifications	2	3	2	7	14
Environmental	Limited integration of CCU in procurement/finance	2	3	2	7	15
Economic	Weak Industrial Demand for Sustainable Inputs	2	2	2	6	12
Policy	Dependence on political continuity	2	2	1	5	11

Step 2: Influence–Dependency Classification Using the Vester Matrix

The 12 most relevant gaps were then analyzed using the Vester Matrix (Figure 2-19**),** a systems thinking tool used to assess the dynamic relationships between elements in complex environments. In this step:

Each gap was assigned a code (e.g., B1, B2…) and entered a **cross-influence matrix**.

For each pair of gaps, the degree of influence (from 0 = none to 3 = strong) was estimated, based on expert judgment and logical relationships between barriers.

The **Influence Index** (sum of influence a gap exerts) and the **Dependency Index** (sum of influence a gap receives) were calculated for each element.

This produced a quadrant-based classification:

- **Critical (High Influence / High Dependency):** These gaps are both causes and consequences in the system, requiring careful coordination.
- **Active (High Influence / Low Dependency):** These are key leverage points; addressing them can unlock broader change.
- **Passive (Low Influence / High Dependency):** These are mostly effects; they improve when upstream gaps are solved.
- **Indifferent (Low Influence / Low Dependency):** These have limited system-wide relevance and lower urgency.

Table 2-12. Results of Vester matrix

Code	Gap	Influence	Dependence	Quadrant
B1	Lack of localized LCA data for electrochemical CCU	14	11	ACTIVE
B5	Limited technical experience in CCU	16	8	ACTIVE
B11	High energy demand and unquantified trade-offs	13	11	ACTIVE
B3	Low Domestic Production of High-Purity Chemicals	15	20	CRITICAL
B4	Lack of CO_2 Utilization Incentives	15	17	CRITICAL
B6	Lack of specific CCUS regulation	15	13	CRITICAL
B7	Weak link to environmental certifications	16	14	CRITICAL
B9	Insufficient pilot-scale infrastructure	12	12	CRITICAL
B2	Limited incorporation of social indicators in assessments	8	3	INDIFFERENT
B10	Low public awareness of CCU and green chemistry	7	9	INDIFFERENT
B12	Lack of CO_2 purity characterization	4	9	INDIFFERENT
B8	Limited integration of CCU in procurement/finance	5	13	PASSIVE

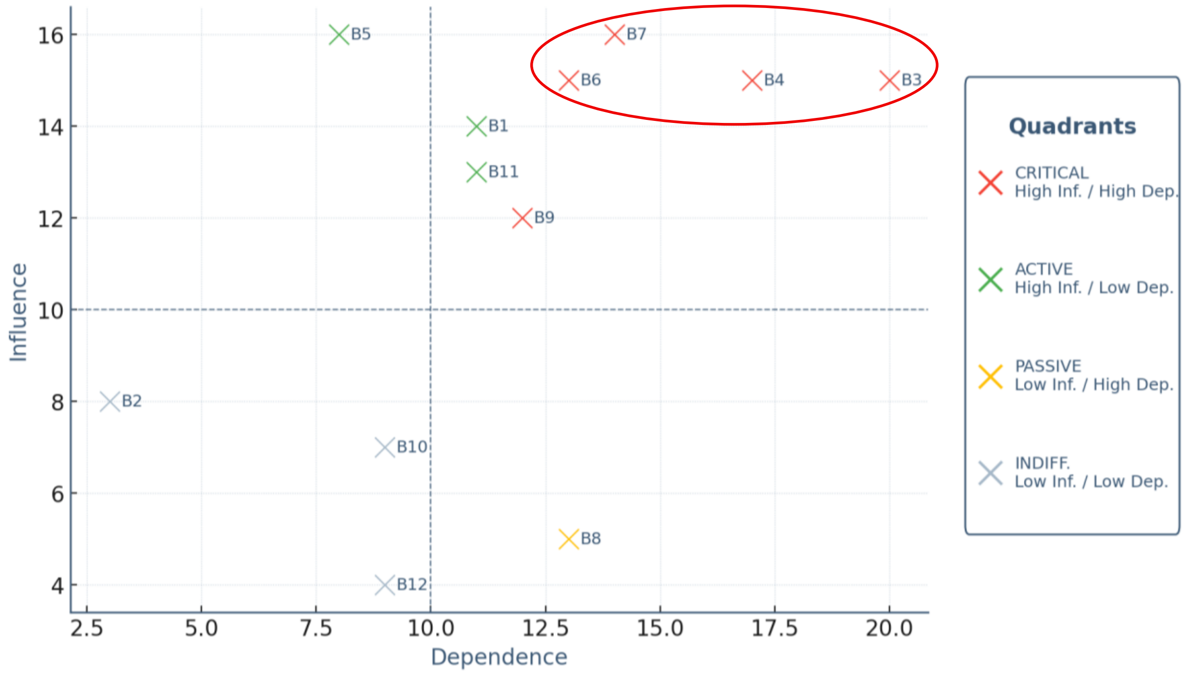

Figure 2-19. Vester matrix

Critical gaps are deeply embedded in the system; both affecting and being affected by other variables. It is risky to ignore and require coordinated, multi-stakeholder strategies (Figure 2-19). Recommended actions include:

- Design targeted incentive mechanisms (e.g. tax credits, carbon credit multipliers) for CO_2-based chemicals.
- Fund demonstration projects and pilot platforms to build operational experience.
- Integrate CCU technologies into green procurement and circular economy frameworks.
- Conduct environmental trade-off assessments (e.g. LCA, water-energy analysis) to validate net benefit.

Regarding **Active gaps, these are high-leverage gaps. Solving them can trigger positive effects across the system.** Some actions to consider:

- Standardize and publish national-level LCA baselines for CCU products.
- Align WaterProof with national industrial strategies for import substitution and export certifications.
- Establish a fast-track regulatory pathway for CO_2-derived products under circular economy law.

Finally, **the passive gap is mostly an effect of other gaps (e.g., lack of pilots or regulatory clarity). It will improve as upstream gaps are addressed.** Align WaterProof pilot outcomes with ISO 14001, EPD, and sectoral certifications (e.g. ZDHC, LWG) to facilitate market entry and green labeling.

The gaps classified as indifferent, including the limited incorporation of social indicators in assessments, low public awareness of CCU and green chemistry, and lack of CO_2 purity characterization, currently exhibit both low influence on the broader system and low dependency on other factors. While these gaps are not immediate leverage points, they should not be dismissed. Instead, **they represent latent enablers that could become more relevant as the CCU ecosystem matures.** Notably, their classification highlights that, **although social dimensions are important, the core challenge for adoption lies primarily in market dynamics**. **The success of WaterProof and similar technologies will depend on driving penetration within key industrial sectors and securing demand for CO_2-derived products**. As these products are integrated into existing supply chains, particularly in export-oriented industries with strict sustainability requirements, **consumer and societal awareness will naturally increase**. In this sense, **social acceptance is likely to follow industrial uptake, not precede it**. Therefore, while social gaps should be addressed gradually (e.g., by integrating performance metrics and awareness campaigns), the immediate focus should remain on enabling market access and industry-driven adoption.

3 Sustainability assessment for inception of the technologies

This chapter introduces a multidimensional sustainability assessment of the WaterProof technologies, examining their potential implementation in Colombia. The analysis integrates environmental, economic, technological, and social dimensions, applying Life Cycle Thinking (LCT) to identify key opportunities and challenges at the early stage of deployment. This framework provides the foundation to evaluate trade-offs, prioritize actions, and align technological development with national decarbonization and circular economy strategies

3.1 What indicators define sustainability for these technologies?

Economic:

As shown in Table 3-1, **the economic analysis of WaterProof's formic acid production compares production costs with market prices for two capacity scenarios**. Derivable D4.3. Intermediate techno-economic and market analysis estimates operational costs at €0.59/kg (€590/t) for the Volta electrochemical route, excluding CAPEX. International trade databases (ITC, 2025) (United Nations, 2025) place the average market price at ~USD 3.25/kg (≈€3.00/kg), indicating strong potential margins.
Engineering data (Deliverable D2.2. **Engineering design (PFD, preliminary layout, P&ID, HAZOP**) show the TRL-6 demonstrator produces 2.5 t/year, while expert input suggests a minimum viable commercial plant at 5,000 t/year, scalable by 10X or more depending on CO_2, renewable energy, and market demand.
OPEX is ~€1,475/year at pre-commercial scale and €2.95M/year at commercial scale. Using industry multipliers for electrochemical plants (IEA, 2023b) CAPEX is estimated at €7k–€15k for the demonstrator and €9M–€15M for the commercial unit.
WaterProof shows competitive margins at both scales, but full-scale deployment hinges on market uptake and access to CO_2 and renewable energy infrastructure.

Table 3-1. Key parameters and indicators for sustainability analysis- Economic dimension

Data	What it's used for	Value	Source
Estimated cost per kg of formic acid produced by WaterProof	To compare against market prices and estimate margins	€0.59/kg	D4.3 Intermediate Techno-Economic and Market Analysis (Volta route cost)
Global average price of formic acid (€/kg)	To calculate import substitution savings	€0.8/kg	(Business Analytic IQ, 2025)
Approximate substitution volume (kg/year) - Precommercial scale	To estimate potential revenue and ROI	2,500 kg/year	D2.2 Engineering Design – Mass Balance (UO-3, 2.5 t/year formic acid)
Approximate substitution volume (kg/year) - Minimum commercial scale	To estimate potential revenue and ROI	5,000,000 kg/year	Expert consultation – minimum commercial scale
Estimated annual OPEX - Precommercial scale (€)	To estimate operational costs at pilot scale	€1,475/year	Calculated from €590/t and 2.5 t/year capacity
Estimated annual OPEX - Minimum commercial scale (€)	To estimate operational costs at commercial scale	€2,950,000/year	Calculated from €590/t and 5,000 t/year capacity
Estimated CAPEX range - Precommercial scale (€)	To estimate investment needs for pilot	€7,000 – €15,000	Estimated from OPEX × multiplier (5–10×) for pilot plants
Estimated CAPEX range - Minimum commercial scale (€)	To estimate investment needs for commercial plant	€9,000,000 – €15,000,000	Estimated from OPEX × multiplier (3–5×) for commercial plants

Table 3-2 **summarizes the estimated economic performance of WaterProof under two operational scenarios: pre-commercial scale (demonstrator capacity) and minimum commercial scale (5,000 t/year of formic acid).** The metrics include production volumes, operational costs (OPEX), estimated capital expenditures (CAPEX), revenue potential based on international market prices, and resulting ROI and payback times.

Table 3-2. Economic feasibility Analysis for WaterProof

Parameter	Pre-commercial scale	Minimum commercial scale
Production capacity (t/year)	2.5	5,000
OPEX (€)	1,475	2,950,000
CAPEX (€)	7,000 – 15,000	9,000,000 – 15,000,000
Market price (€/kg)	0.80	0.80
Annual revenue (€)	2,000	4,000,000
Annual profit (€)	525	1,050,000
ROI (%)	3,50% – 7,50%	7,00% – 11,67%
Payback (years)	13,33 – 28,57	8,57 – 14,29

At pre-commercial scale, the low OPEX and small CAPEX now result in a modest ROI (3.5–7.5%) and a long payback period (13.3–28.6 years). Absolute revenues remain very low, making this scale economically unattractive without subsidies or complementary income streams, and mainly suitable for technical demonstration and market validation.

At minimum commercial scale, annual revenues reach approximately €4M, with OPEX growing proportionally. ROI drops significantly to 7.0–11.7%, and payback extends to 8.6–14.3 years. While still positive, these figures indicate that commercial deployment would require either higher market prices, cost reductions, or additional value streams to achieve strong attractiveness.

Colombian Formic Acid Market and Implications for WaterProof

Colombia's total formic acid consumption is ~1,300 t/year (Business Analytic IQ, 2025)**, almost entirely imported. With a conservative average import price of ~USD 1.50/kg (≈€1.38/kg), based on World Integrated Trade Solutions data showing values between USD 1.5–1.7/kg from Germany or Panama and up to >USD 5/kg from countries such as Belgium or France, the Colombian market shows significant variability depending on the origin** (World Integrated Trade Solutions, 2022b)**.** Main applications include leather tanning, textile dye fixing, agrochemical production, and forage preservation in livestock. WaterProof's estimated production cost (€0.59/kg) is roughly 2.3× lower than the conservative market price, yielding a potential gross margin of ~€0.79/kg before CAPEX, additional OPEX, and logistics.

Given the limited domestic market, even the minimum commercial plant capacity (5,000 t/year) would surpass Colombia's demand by a factor of 3.8, making regional exports or the displacement of imports in neighboring countries essential. At a conservative market price of €1.38/kg (World Integrated Trade Solutions, 2022b), market penetration scenarios range from low (20% share, 260 t/year, ~€358,800/year revenue) to medium (50% share, 650 t/year, ~€897,000/year revenue) and high (100% share, 1,300 t/year, ~€1.794 M/year revenue). The pre-commercial TRL-6 scale (2.5 t/year) would generate only ~€3,450/year, covering less than 0.2% of national demand—suitable for technical and commercial validation but with negligible market impact. For exclusive domestic supply, a plant with around 1,500 t/year capacity would be sufficient, while a 5,000 t/year facility would require an export strategy to prevent idle capacity.

Scaling in Colombia should either match local demand with modular capacity or integrate into a regional export model to sustain high ROI.

Table 3-3. Economic feasibility analysis for WaterProof- Colombian Context

Scenario	Annual Production (t)	Market Price (€/kg)	Annual Revenue (€)	Annual OPEX (€)	Profit (€)	ROI (CAPEX 3–5× OPEX)
Pre-commercial	2.5	1.38	3,450	1,475	1,975	13% – 26.7%
Commercial – 20% local mkt	260	1.38	358,800	153,400	205,400	13.7% – 22.4%
Commercial – 50% local mkt	650	1.38	897,000	383,500	513,500	13.7% – 22.4%
Commercial – 100% local mkt	1,300	1.38	1,794,000	767,000	1,027,000	13.7% – 22.4%

This Colombian case analysis assumes that WaterProof's production costs and critical process inputs remain consistent with the original reference context. This includes the availability and quality of CO_2 emissions required as feedstock, as well as access to electricity in the quantity, quality, and cost necessary to operate the electrochemical system. Significant changes in these parameters could materially impact operating costs, technical feasibility, and projected returns on investment.

Social

Social impacts, key figures, and relevance were analyzed for WaterProof inception technology are included in Table 3-4.

Table 3-4. Social Impact Summary for WaterProof in Colombia

Impact Area	Key Figures	Relevance
Employment Creation	5,000 t/year = 20 direct jobs 1,500 t/year = ~6 direct jobs	Skilled positions in chemical engineering, operations, maintenance, environmental monitoring
Sectoral Linkages	Textiles: 600,000+ jobs Leather: ~2,680 MSMEs	Potential to integrate CCU processes, improve environmental performance, and create green jobs
Community Benefits	17% report frequent water contamination; 7.4% constant	CCU could reduce industrial pollutants, improve health outcomes, enhance social license

- Employment Impact: **Based on sector benchmarks and project data, a full commercial-scale WaterProof plant of 5,000 t/year could generate approximately 20 direct jobs in technical and operational roles such as chemical engineering, process operations, maintenance, and environmental monitoring** (IEA, 2023)(ProColombia, 2023). **Adjusting proportionally to Colombia's optimal domestic market scale of ~1,500 t/year, this would represent around 6 direct jobs, with additional indirect employment expected in supply chains, logistics, and CO_2 feedstock sourcing**. These numbers align with job-intensity estimates for chemical processing facilities in emerging economies, where smaller plants maintain proportionally leaner workforces but still provide high-quality, skilled positions.

- Sectoral Integration and Value Chains: WaterProof deployment could strengthen local capacity by linking to high-employment sectors. The Colombian textile industry employs over 600,000 people (ProColombia, 2023), representing about 30% of Medellín's regional GDP, while the leather sector includes roughly 2,680 MSMEs (Acicam, 2023). Integrating CCU-enabled processes for formic acid production into these value chains could improve environmental performance, enhance working conditions, and create opportunities for labor requalification toward green manufacturing.

- Community and Environmental Wellbeing: Reducing industrial emissions via CCU could have direct positive effects on community health and quality of life. In the DANE Environmental Quality Survey (DANE, 2023), 17% of households reported frequent water contamination and 7.4% constant contamination, often linked to industrial activity. By lowering pollutant loads, CCU plants could reduce public health burdens and enhance local environmental quality, reinforcing social license to operate.

- Alignment with National Climate Policy: Colombia's carbon market achievements—over 231 million tons of CO_2 reduced and $4.5 billion generated—demonstrate an institutional and societal framework that is favorable for low-carbon innovation (El País, 2025). CCU technologies can complement this ecosystem, particularly if coupled with transparent communication, local training programs, and equitable benefit-sharing with communities near industrial hubs.

Although CCUS is gaining traction in Colombian policy, electrochemical CO_2 conversion technologies, central to WaterProof, are absent from current strategic planning. Early-stage CCU projects continue to prioritize Enhanced Oil Recovery (EOR), risking the reinforcement of fossil fuel pathways and delaying institutional support for cleaner alternatives. This policy gap could limit access to incentives, slow down workforce training in green industries, and reduce the social co-benefits that CCU could deliver.

Technological

Table 3-5 summarizes some of the key technical parameters of the WaterProof project, covering aspects such as production capacity, energy requirements, CO_2 purity specifications, and pilot site location. These elements are essential for assessing the technological feasibility, scalability, and operational conditions of the system

Table 3-5. WaterProof Technology Data Table

Data	What it's used for	Value	Source/Assumption
Confirmed TRL of WaterProof	To evaluate technological maturity	TRL 6 (pre-commercial demonstrator)	Project technical documentation
Pilot site location	To contextualize local integration and logistics	HVC waste Incineration plant	Project documentation (WaterProof)
Type of facility	To assess operational conditions and feedstock availability	Wastewater treatment facility with integrated CO_2 capture	Project documentation
Specialized technical personnel required	To link with training and workforce development needs	Yes – chemical engineers, electrochemistry specialists, maintenance technicians	Industry norms for electrochemical plants
Annual production capacity – Pilot scale	To calculate resource needs and scaling	2.5 t/year HCOOH	D2.2 Engineering Design – Mass Balance UO-3
Annual production capacity – Minimum commercial scale	To estimate scale-up and market potential	5,000 t/year HCOOH	Expert consultation on commercial scale
Energy requirements – Pilot scale	To assess electricity demand and infrastructure	≈ 6.25–7.5 MWh/year	Calculated from specific energy use (2.5–3 MWh/t) × production

Energy requirements – Commercial scale	To assess electricity demand and infrastructure	≈ 12,500–15,000 MWh/year (12.5–15 GWh/year)	Scaled from pilot energy intensity
CO_2 purity required	To determine feedstock requirements and pre-treatment needs	≥ 99% vol. CO_2 with minimal SOx, NOx, H_2S	D2.1 Engineering Specifications – CO_2 feed requirements

For the technological assessment in the Colombian context, Cementos Argos, specifically its Cartagena production plant, is proposed as the model site. This facility is one of the largest and most modern cement plants in the country, with an estimated capacity of 2.3–2.5 million tonnes of clinker per year, making it a major single-point CO_2 emitter with concentrated and continuous flue gas streams ideal for CCU integration. **Argos has a strong track record in climate action, with a net-zero target for 2050, intermediate goals for 2030, and active investment in CCU-related R&D, such as its microalgae-based CO_2 capture project at the same site**. The combination of scale, existing CO_2 valorization infrastructure, technical readiness, and strategic alignment with national decarbonization goals positions the Cartagena plant as an optimal reference for assessing the feasibility of deploying the WaterProof technology in Colombia. below presents the key technical parameters for assessing the feasibility of implementing a WaterProof pilot at Argos' Cartagena plant. Most of these values have been assumed or extrapolated from scientific and industrial literature due to the lack of direct, site-specific data from the company.

Table 3-6. Sustainability Technology Assessment Variables -Colombian Context

Parameter	Value / Range	Description	Status / Reference
Plant capacity (cement production)	~2.3–2.5 million t clinker/year	Public industrial and press reports on Argos Cartagena facility	Industry newshttps://www.argos.co/colombia/plantas-y-puertos (Global Cement and Concrete Association, 2023; La República, 2014)
CO_2 concentration in flue gas	20–25 vol% (typical for cement kilns)	Literature: cement kiln exhaust gas composition; no exact value reported for Cartagena	(IEA, 2018)
CO_2 flow rate	~2.0–2.3 $MtCO_2$-eq/year (gross emissions)	Estimated using emission factors (0.85–0.9 t CO_2/t clinker) and plant capacity	Calculated from capacity and (Global Cement and Concrete Association, 2023)

Flue gas temperature	140–200 °C (pre-stack, before conditioning)	Literature for similar dry-process cement kilns	(European Cement Research Academy, 2016)
Flue gas pressure	Slightly above atmospheric (~1.02–1.05 bar)	Literature for cement plant exhaust ducts	(European Cement Research Academy, 2016)
CO_2 purity before capture	Raw flue gas purity ~20–25%; after typical amine capture ~95–99%	Literature; no Argos-specific data	(CEMBUREAU, 2025)
Electricity consumption – baseline plant	~90–120 kWh/t cement	Literature for modern dry-process plants	(CEMBUREAU, 2025)
Electricity consumption – microalgae CCU project	~1–2 MWh/tCO_2-eq captured (including pumps, mixing, lighting if used)	Comparable pilot-scale literature; no Argos-specific public data	(Miranda et al., 2021b)
Integration point for WaterProof	Flue gas duct from kiln preheater	Based on CCU integration best practices for cement plants	Technical assumption

For the preliminary technological sustainability assessment of implementing WaterProof at Cementos Argos' Cartagena cement plant, the analysis is based on literature-derived estimates rather than site-specific measurements, as direct company data on CO_2 purity, flow rate, temperature, and pressure are not currently available (Table 3-6**).** Cement plant flue gases are typically ~20–25% CO_2 with significant N_2, O_2, and minor contaminants (SOx, NOx, particulates), requiring a dedicated gas purification step to achieve the ≥99% CO_2 purity necessary for efficient electrochemical conversion. **Experimental work using real flue gas from the Cartagena kiln** (Miranda et al., 2021b) **confirms that cement-derived CO_2 can be processed effectively in biological capture systems, supporting its compatibility with downstream CCU processes.** For the WaterProof route, pre-treatment, potentially via amine scrubbing or membrane separation, could add €40–70/tCO_2 to OPEX, consistent with the lower bound of mature post-combustion capture systems (US$ 50–150/tCO_2) (M. Li et al., 2022). This cost could be reduced if existing infrastructure or low-grade waste heat recovery from kilns is leveraged.

Scaling from the pilot reference (2.5 t/year HCOOH), the Cartagena facility's flue gas output could theoretically sustain full commercial WaterProof production (5,000 t/year) if market demand justified it; for the Colombian-relevant scale of

~1,500 t/year, the process would require ~2,050 t/year of purified CO_2 and consume ~2.1–2.5 GWh/year of electricity. **Co-location with Argos' existing CCUS infrastructure, such as the microalgae capture plant, could enable shared CO_2 capture, compression, and handling systems, reducing CAPEX and operational redundancy**. However, electricity tariffs and the added cost of gas purification will be decisive factors for economic viability. Previous CCU work at Argos with microalgae, while technically successful, remains far more costly (US$ 700–1,600/tCO_2) and is thus not a direct cost proxy, but it does demonstrate Argos' operational readiness and commitment to CO_2 valorization. **A refined mass balance, energy integration study, and techno-economic assessment will require direct process data from Argos**.

For Argos case, scaling from the pilot reference (2.5 t/year HCOOH), the Cartagena facility's flue gas output could theoretically sustain full commercial WaterProof production (5,000 t/year) if market demand justified it.

Market

For the Colombian market (Table 3-7), the potential deployment of the WaterProof technology is framed by a growing demand for sustainable, bio-based chemical inputs and the absence of local formic acid production. **Current demand is fully met through imports, primarily from Germany and Panama, at prices ranging from €1.5/kg for bulk volumes to over €4/kg for premium grades.** With an estimated total addressable market (TAM) of 1,300 tonnes/year and a serviceable available market (SAM) of around 1,000 tonnes/year concentrated in textile, leather, agrochemical, and food sectors, the opportunity space for CCU-derived formic acid is significant.

Sustainability standards in textiles (e.g., GOTS, GRS, ZDHC, OEKO-TEX) and leather (e.g., LWG, ZDHC MRSL, ISO 17075, Blue Angel) are fostering the shift to safer, traceable, and renewable inputs, while similar frameworks in cement and paper support low-carbon and circular chemistry adoption. These drivers align with consumer trends: over 70% of Colombians support clean technologies even at higher costs (DANE ECV, 2023), reinforcing market receptiveness to CCU-based products.

For a more detailed market analysis, it would be advisable to take a specific company in the textile or leather sector as a case study on the demand side for formic acid, enabling precise mapping of procurement volumes, sustainability requirements, and potential substitution pathways.

Table 3-7. Market Dimension Data- Colombian scenario

Variable / Data	Purpose	Value / Estimate for Colombia	Source / Notes
Total Addressable Market (TAM) – total formic acid consumption (t/year)	Determine maximum market size	~1,300 t/year	(Business Analytic IQ, 2025)
Serviceable Available Market (SAM) – sectors of interest (textile, leather, agrochemicals, food)	Define relevant market	~1,000 t/year (≈77% of TAM)	(Business Analytic IQ, 2025)
Serviceable Obtainable Market (SOM) – reachable considering capacity & competition	Estimate achievable share	Scenarios: 20% (260 t/year), 50% (650 t/year), 100% (1,300 t/year)	Based on demand & production scenarios used in economic analysis
Import volumes by country of origin	Identify current suppliers and substitution potential	Main: Germany, Panama (1.5–1.7 USD/kg); Belgium, France (>5 USD/kg)	(Business Analytic IQ, 2025)
Average and range of import prices	Price positioning & margin calculation	1.5 €/kg (conservative); up to >4 €/kg for premium imports	(Business Analytic IQ, 2025)
Growth rate (CAGR)	Evaluate demand trends	~3–4% CAGR in Latin America	(Maximize Market Research, 2025)
Competitors (local/regional)	Map offer & advantages	No local formic acid production in Colombia; imports dominate	Industry intelligence
Substitute products	Identify substitution risk	Acetic acid, citric acid (depending on application)	Industry reports, technical datasheets
Regulatory drivers	Identify demand push/pull	Textiles: GOTS, GRS, ZDHC, OEKO-TEX – drive elimination of toxic chemicals, traceability, opportunity for bio-based solvents and surfactants. Leather: LWG, ZDHC MRSL, ISO 17075 (chrome VI), Blue Angel – replace solvent-based cleaners and auxiliaries. Cement: ISO 14001, EPDs, EU ETS – CCU supports Scope 1 reduction, EPD documentation. Paper: FSC, PEFC, EU Ecolabel, ISO 14001 – green chemistry for cleaners and water treatment.	(Global Standard gemeinnützige GmbH, 2023)
Customer willingness to pay for low carbon	Assess sustainability premium potential	>70% of Colombians support clean tech even at higher cost	(DANE, 2023)

Barriers to entry	Evaluate entry requirements	Import tariffs (~5% for some HS codes), REACH/technical certifications for exports	(pwc, 2025)

For successful replication of WaterProof in Colombia, the economic case must be built on co-location with existing CO_2 sources to cut CAPEX/OPEX, the technology adapted to local gas quality and energy costs, early community engagement ensured to secure a social license, and initial sales targeted to high-compliance sectors (e.g., textiles, leather) where sustainability premiums can offset higher production costs. For a future business case in Colombia, it is recommended to use an Argos cement plant, such as the one in Cartagena, as the emissions source, and a high-export textile group like Crystal on the demand side. Under current Colombian conditions, the technology would be most sustainable at a 1,500 t/year commercial scale, requiring ~2,050 t/year of purified CO_2 and ~2.1–2.5 GWh/year of electricity—levels that balance local demand with manageable operational costs and export potential, with an estimated ROI of 14–16% and payback period of 6–7 years.

3.2 Evaluating the impact: Life Cycle Thinking (LCT)

Colombia's National Interconnected System (SIN) is predominantly powered by hydropower (65–75%), resulting in a historically low grid carbon intensity (~0.11 kg CO_2/kWh, XM 2024). This is well below the 0.25 kg CO_2e/kWh benchmark for climate-competitive electrochemical CO_2 utilization.

Life Cycle Thinking-LCT is an approach that evaluates the potential environmental impacts of a product or technology across all stages of its life cycle (Paulillo et al., 2021), from raw material extraction to end-of-life, rather than only during operation.

For electrochemical carbon capture and utilization (e-CCU) projects, such as WaterProof, **LCT is crucial because the climate benefits of converting CO_2 into products like formic acid depend strongly on the source of energy, process efficiency, and the overall system integration.**

GWP (Global Warming Potential, 100-year horizon) measures the total climate impact expressed as kg CO_2-equivalent per functional unit (e.g., per kg of formic acid). In e-CCU systems, GWP is highly sensitive to the carbon intensity of electricity and process efficiency. In Table 3-8 “Medium → Low” indicates that the impact category improves by one level when renewable or low-carbon electricity is used.

Table 3-8. Qualitative Life Cycle Impact Matrix

Life Cycle Stage	GWP	Water Use	Ecotoxicity	Energy Consumption	Description
CO_2 Capture	Medium → Low*	Low–Medium	Low–Medium	Medium	Impact depends on capture route and pretreatment; in integrated LCAs, capture contributes less than conversion but is not negligible (Paulillo et al., 2021)
Electrochemical Conversion → Formic acid	Medium → Low*	Medium	Low–Medium	High	Absolute hotspot: cell operation and product separation dominate; climate benefit only appears with low-carbon electricity
Use of Product Formic acid	Low	Low	Low–Medium	Low	Use rarely dominates total impact; local risks from acidity manageable via neutralization or best practices.
End of Life Formic acid	Low	Low	Low	—	Readily biodegradable (OECD); low persistence and bioaccumulation potential (ECHA Europe, 2024)

Important key points for Colombia are:

Electricity carbon intensity as the decisive factor

- **Global LCAs show that e-CCU technologies only outperform fossil-based production when the electricity carbon intensity is ≤0.25 kg CO_2e/kWh** (Paulillo et al., 2021).
- Colombia’s National Interconnected System (SIN) has historically maintained a low carbon intensity (~0.11 kg CO_2/kWh)(XM, 2023) due to hydropower dominance, which positions it favorably for competitive GWP. However, **seasonal variability (e.g., El Niño) can increase emissions intensity** (Blazer et al., 2024; Yamaguchi et al., 2025)**, so mitigation strategies like renewable PPAs are recommended.** Upcoming renewable integration projects (solar and wind in La

Guajira and the Caribbean Coast) present cost-effective opportunities for traceable, low-carbon power supply.

Main environmental hotspots – conversion and separation

- **The electrochemical conversion stage and product separation/ concentration are the largest contributors to energy use and environmental impact,** with separation alone accounting for 30–85% of process energy (Blazer et al., 2024; Yamaguchi et al., 2025).
- In Colombia, efficiency improvements should focus on high faradaic efficiency, low cell voltage, and achieving ≥20 wt% formic acid in the crude stream to reduce downstream energy burdens (ECHA Europe, 2024).

Use and End-of-Life Impacts are Manageable

- **The use phase of formic acid in sectors like textiles, leather, and chemicals does not significantly dominate life cycle impacts.**
- Main risk: potential local water acidification, which can be mitigated via neutralization and best operational practices.
- End-of-life: Formic acid is readily biodegradable with low persistence and bioaccumulation potential (ECHA Europe, 2024), offering environmental advantages for Colombia's water systems.

Life Cycle Thinking: Strategic Implications for WaterProof in Medellín

1. **Climate Competitiveness:** With Colombia's electricity mix, electrochemical formic acid production can achieve a lower GWP than fossil-based routes if efficiency and product concentration targets are met.
2. **Water & Ecotoxicity:** Using CO_2 from local biogenic or industrial sources poses no major systemic risks; focus should be on effluent treatment and avoiding harmful additives during separation/purification.
3. **Priority Actions:**

- Secure a Renewable Power Purchase Agreement (PPA) or SIN low-carbon certification.
- Optimize cell design for higher concentration output and reduced ohmic loss.
- Recover and reuse heat in separation processes to cut energy demand.

Table 3-9. GWP100 Benchmark analysis for formic acid routes

Technology / Route	GWP (kg CO_2e/kg HCOOH)	Description	Source
Conventional fossil methyl formate route	4.3 – 4.7	High due to fossil methanol feedstock and fossil-based process heat.	(Paulillo et al., 2021)
Renewable methanol methyl formate route	1.8 – 2.2	Significant reduction from renewable methanol, but still high energy demand for distillation.	(Paulillo et al., 2021)
Direct CO_2 hydrogenation (H_2 from electrolysis)	0.5 – 0.8 (renewable H_2) / 1.5 – 2.0 (grid H_2)	Highly dependent on hydrogen source carbon intensity; renewable H_2 routes are among the lowest-GWP options.	(Blazer et al., 2024; Yamaguchi et al., 2025)
WaterProof electrochemical CO_2 reduction (VOLTA)	0.3 – 0.5 (Colombian SIN avg. ~0.164 kg CO_2/kWh) / up to 1.2 with fossil-heavy grids	Uses local biogenic/industrial CO_2 and low-carbon electricity; performance highly sensitive to electricity mix.	Paulillo et al., 2021; XM 2020; IEA 2024

3.3 Scenario projection

This prospective analysis applies a scenario planning framework to explore possible futures for implementing the WaterProof technology in Colombia by 2035, using the cement industry as the primary CO_2 source and the textile and leather sectors as the main off-takers for the resulting formic acid. The 2035 horizon aligns with Colombia's long-term climate and energy strategies, such as the *Estrategia 2050- E2050* (Gobierno de Colombia, 2021) and the *Política Nacional de Cambio Climático*- PNCC (Minambiente, 2017), allowing enough time for both regulatory evolution and industrial adoption to take place. This timeframe also captures the potential transition of the technology from pilot phase to commercial scale, enabling the evaluation of structural drivers, regulatory shifts, and market transformations that could influence WaterProof's deployment trajectory.

The two key uncertainty axes were derived directly from the gap analysis presented in the previous chapter, which identified:

- On the policy side: *lack of CO_2 utilization incentives* and *lack of specific CCUS regulations*.
- On the industrial side: *low domestic production and consumption of green chemicals*.

These factors translate into the following axes for scenario development:

- **Policy support level**: ranging from strong governmental incentives, regulatory clarity, and integration into national decarbonization strategies, to slow or fragmented policy implementation.
- **Industrial adoption rate**: from rapid uptake driven by export-oriented demand and corporate climate commitments, to slow adoption limited by financial, technical, or market barriers.

WaterProof's 2035 outlook hinges on policy momentum and market readiness. Early action on renewable energy, cement–textile partnerships, and export compliance can secure its role in Colombia's green industrial transition, across any future scenario.

Table 3-10 presents the drivers and constraints for the scenario development:

Table 3-10. Drivers and constraints for scenario development

Dimension	Drivers (factors increasing adoption likelihood)	Constraints (factors limiting adoption likelihood)
Industrial Adoption	• Concentrated, Stationary CO_2 Streams: Cement plants (e.g., Argos Cartagena, Rioclaro) emit high-volume, continuous CO_2 streams, making capture logistically simpler than diffuse sources (Minambiente, 2024a). • Cement Sector Climate Commitments: Argos and other majors have corporate net-zero pledges, explicitly targeting process CO_2 reductions (Argos, 2023). • Proven Industrial Off-takers: Textile and leather industries in Colombia have prior experience adopting greener chemicals, motivated by export compliance (European Comission, 2023). • Export-Oriented Demand: Exporting manufacturers are under pressure to decarbonize supply chains to access EU and US markets.	• Product–Source Mismatch: Cement plants do not directly use formic acid, requiring partnerships and supply chain integration with textile/leather off-takers. • High CAPEX Competition: Cement decarbonization budgets are also allocated to clinker substitution and alternative fuels, potentially delaying CCU investment. • SME Capacity Gap: In textile/leather, smaller firms may lack capacity to integrate new chemicals without technical assistance or financing. • Formic Acid Import Dependence: Colombia imported ~USD 2.24M of formic acid in 2021 (mainly from China/Germany), reflecting no local high-purity production (World Integrated Trade Solutions, 2022)
Policy Support Level	• Hard-to-Abate Sector Priority: Cement is named as a strategic decarbonization target in ECDBC and E2050, making it eligible for CCUS incentives under Law 2099/2021.	• Implementation Lag: CCUS decree is still in draft; PNCTE crediting for utilization is not yet operational. • Lack of Product-Chain Regulation: No explicit policy link between CCU outputs (e.g., formic acid)

	• PNCC & Law 1931/2018: Provide the MRV (Monitoring, Reporting & Verification) system and PNCTE (National Program for GHG Emissions Reduction) that could integrate CCU crediting (Minenergía, 2022). • Draft CCUS Decree: Establishes licensing and regulatory sandboxes for CCUS, facilitating cement plant integration (Minenergía, 2022). • Carbon Pricing Opportunity: Carbon tax coverage of fossil fuel use in cement production could be complemented by crediting avoided process emissions via CCU.	and downstream industry adoption incentives. • Policy–Industry Misalignment: Coordination between Minambiente, Minenergíaa, and industrial ministries on CCU integration is still weak.

The resulting four quadrants (Figure 3-1): Green Acceleration, Regulatory Drag, Tech-led Niche, and Slow Lock-in, capture different combinations of these factors. Each scenario highlights distinct opportunities, risks, and required actions for stakeholders.

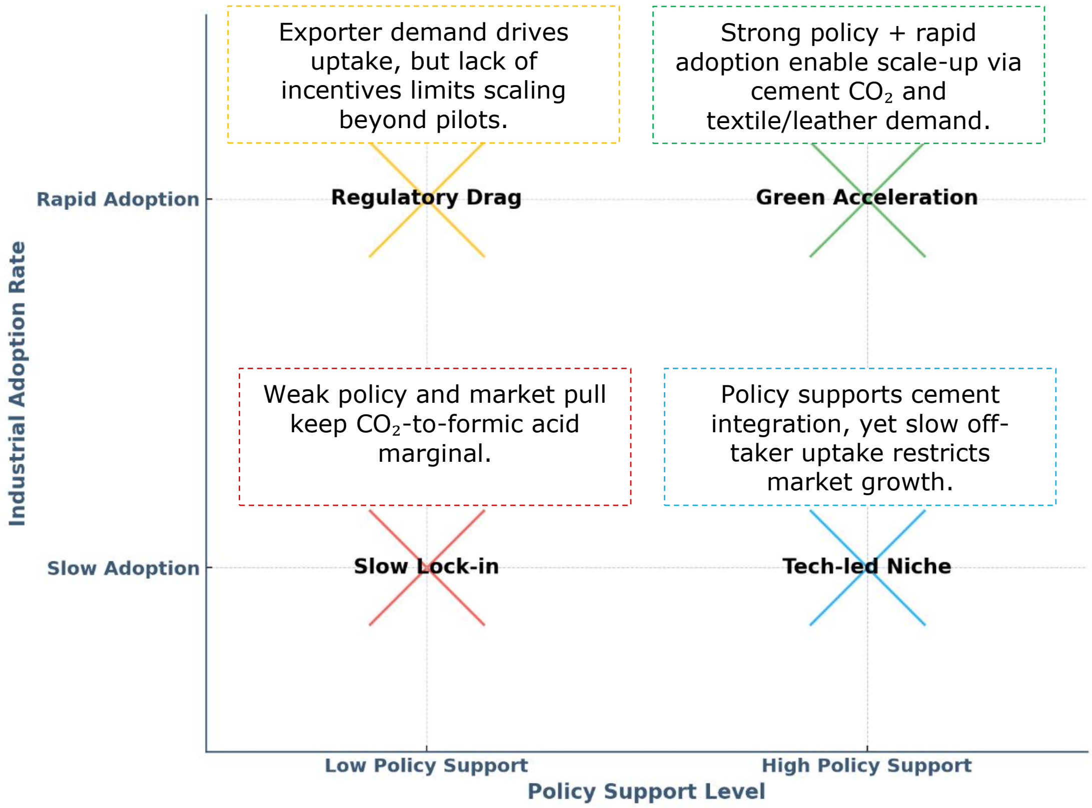

Figure 3-1. Scenario Matrix – WaterProof (Cement CO_2 Source + Textile/Leather Off-take)

Overall, the scenario analysis (Figure 3-2) shows that WaterProof's successful deployment in Colombia by 2035 will depend on the intersection of strong institutional support and a steady increase in industrial adoption of green chemicals.

Scenarios such as Green Acceleration highlight the transformative potential when robust CO_2 utilization incentives, clear CCUS regulations, and proactive industrial engagement align, unlocking both climate and economic benefits. Conversely, outcomes like Regulatory Drag or Tech-led Niche underscore the risks of slow policy implementation or limited market readiness, which could restrict WaterProof to niche applications or delay scale-up. Across all futures, early actions, such as securing renewable energy supply, forging cement–textile/leather supply chain partnerships, and positioning formic acid as a compliance enabler for export markets, emerge as no-regret strategies to enhance resilience and competitiveness regardless of the policy or market pathway.

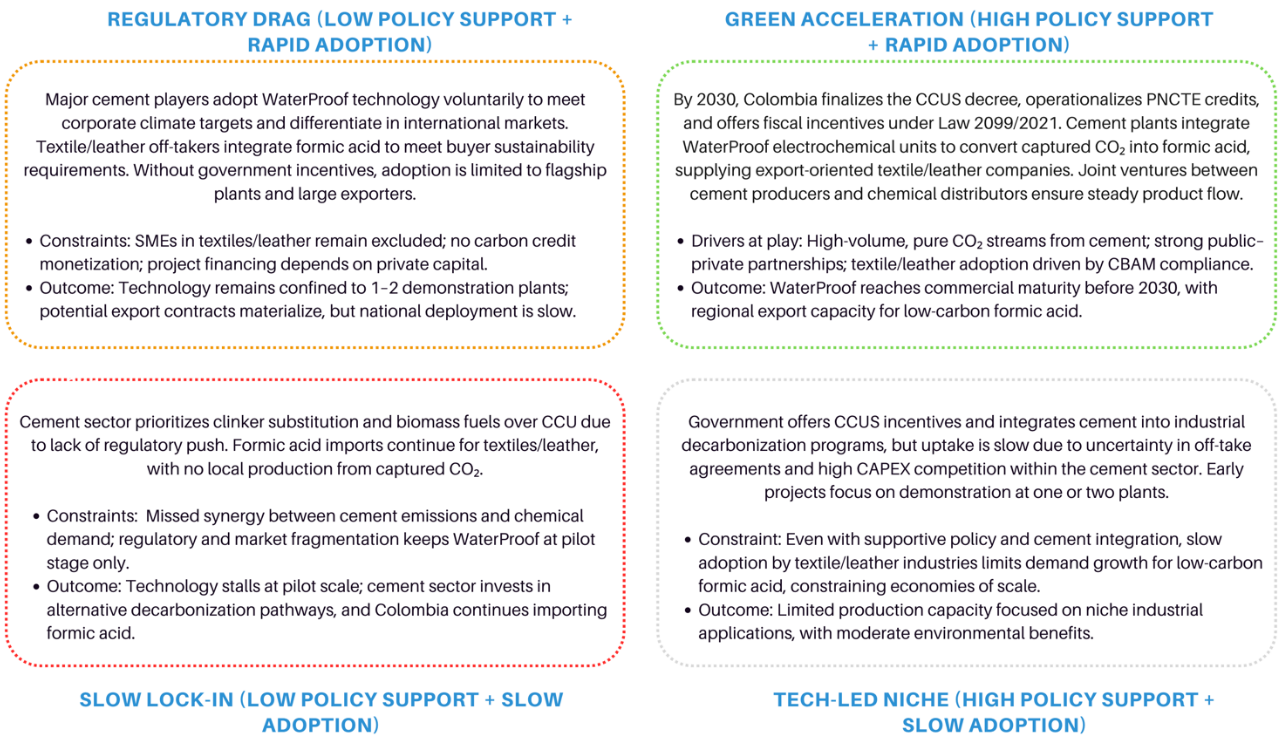

Figure 3-2. Scenario narratives- WaterProof in Colombia. SME: small and medium enterprises. PNCTE: National program of tradable greenhouse gas emission quotas (Minambiente, 2018) . CBAM: Carbon Border Adjustment Mechanism (European Comission, 2023).

4 Future outlook: lessons and opportunities

4.1 Achievements:

- Baseline Analysis: Comprehensive mapping of stakeholders, industrial emitters, and infrastructure in Medellín, with detailed profiling of CO_2 sources such as wastewater treatment plants, landfills, and cement plants.
- Gap Analysis: Identification and prioritization of regulatory, technical, market, and social gaps for CCU deployment in Colombia, applying the Vester matrix to classify gaps into active, critical, passive, and indifferent categories.
- Preliminary Sustainability Assessment: Application of Life Cycle Thinking (LCT) to WaterProof technology, providing a qualitative evaluation of Global Warming Potential (GWP), water use, ecotoxicity, and energy demand, benchmarked against global electrochemical CCU literature.
- Prospective Scenario Development: Creation of 2035 scenario narratives based on two key uncertainty axes – policy support level and industrial adoption rate – integrating the cement industry as the primary CO_2 source and textile/leather sectors as off-takers for formic acid.
- Stakeholder Engagement: Execution of targeted interviews and consumer perception surveys in Colombia to assess awareness, interest, and potential barriers to CCU product adoption.

4.2 Key findings:

- CO_2 Source & Off-taker Synergy: The combination of Colombia's cement industry (as a concentrated, stationary CO_2 source) with the textile/leather sector (as an export-driven off-taker for green chemicals like formic acid) presents a technically and market-feasible replication pathway.
- Policy Readiness Gaps: While national frameworks such as the ECDBC, Law 1931/2018, and Law 2099/2021 recognise CCUS potential, there is still no operational crediting mechanism for CO_2 utilisation and no direct policy linkage to downstream adoption incentives.
- Industrial Adoption Barriers: The textile and leather industries show readiness among large exporters due to CBAM/REACH compliance pressure, but SMEs face capacity and financing gaps for integrating new green chemicals.

- Life Cycle Thinking Insights: Colombia's low-carbon electricity mix (0.11 kg CO_2/kWh) provides a competitive GWP baseline for electrochemical formic acid production, provided that high process efficiency and product concentration are achieved.
- Scenario Planning to 2035: The analysis identifies two critical uncertainty axes—level of public policy support and rate of industrial adoption—deriving from the Vester matrix gap analysis. Four scenarios ("Green Acceleration," "Tech-led Niche," "Slow Lock-in," "Regulatory Drag") map potential futures, with recommendations for adaptive strategies in each.

4.3 Integration with Other Work Packages:

The outputs of WP4 feed directly into

- WP2 (Techno-economic Analysis): Providing contextualized assumptions for process efficiency, energy sourcing, and market dynamics in Colombia.
- WP3 (Market Assessment): Offering sector-specific adoption insights from Colombian textile and leather industries.
- WP4.5.3 (Business Case and Strategy for a Business Unit in Medellín): Delivering the strategic foundation and scenario-based feasibility inputs for a case built around Argos Cartagena cement plant as CO_2 source and textile sector as product off-taker.

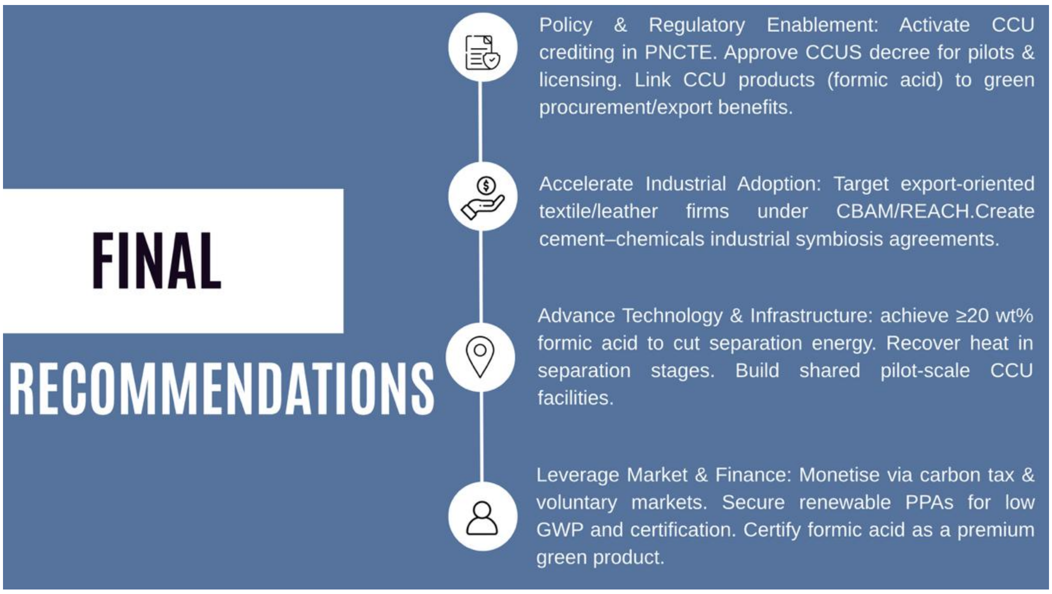

Figure 4-1. Final **Environmental Quality Survey** recommendations

5 List of abbreviations

Abbreviation	Description
ADES	Acidic Deep Eutectic Solvents
AOPs	advanced oxidation processes
BECCS	Bioenergy with Carbon Capture and Storage
CBAM	Carbon Border Adjustment Mechanism
CAGR	Compound Annual Growth Rate
CCU	Carbon Capture and Utilization
CCUS	Carbon Capture, Utilization and Storage
CO_2	Carbon Dioxide
DANE	Colombia's National Administrative Department of Statistics
ECDBC	Estrategia Colombiana de Desarrollo Bajo en Carbono (Colombian Strategy for Climate-Resilient Low-Carbon Development)
ECV	(ECV), over 70% of Colombians
EDTA	Ethylenediaminetetraacetic acid
ENEC	Circular Economy Roadmap
ELCA	Environmental Life Cycle Costing
EOR	Enhaced Oil Recovery
EPDs	Environmental Product Declarations
E2050	Estrategia de Largo Plazo de Bajas Emisiones de GEI a 2050 (Colombia’s 2050 Long-Term Strategy for Low Emissions)
ETS	Emissions trading system
FA	Formic acid
FSC	Forest Stewardship Council
GHG	Greenhouse Gases
GRS	Global Recycled Standard
GOTS	Global Recycled Standard
GWP	Global Warming Potential
HTL	Hydrothermal liquefaction
H_2S	Hydrogen Sulfide
IPCC	Intergovernmental Panel on Climate Change
LCA	Life Cycle Assessment
LCT	Life Cycle Thinking
LWG	Leather Working Group
MRSL	Manufacturing Restricted Substance List
MRV	Monitoring, Reporting, and Verification
NGOs	Non-Governmental Organization
NPEs	Nonylphenol ethoxylates
NOx	Nitrogen oxides
SOx	Sulfur oxides
PFAS	Per- and Polyfluoroalkyl Substances
PNCC	Política Nacional de Cambio Climático (National Climate Change Policy)
PNCTE	Programa Nacional de Cupos Transables de Emisión (National Program for Tradable Emission Quotas)
PPAs	Power Purchase Agreements
REACH	Registration, Evaluation, Authorisation and Restriction of Chemicals (EU regulation)
RENARE	National Emissions Reduction Registry
SAF	Sustainable Aviation Fuels
SBTi	Science-Based Targets initiative

SIN	Sistema Interconectado Nacional (National Interconnected Power System, Colombia)
SLCA	Social Life Cycle Assessment
SMEs	Small and Medium-sized Enterprise
SAM	Serviceable Available Market
SIN	National Interconnected System
SOM	Serviceable Obtainable Market
TRL	Technology Readiness Level
TSA	Temperature Swing Adsorption
UNFCCC	United Nations Framework Convention on Climate Change
VCMs	voluntary carbon markets
WP	Work Package
WITS	World Bank's World Integrated Trade Solution
WWTP	Wastewater treatment plant
ZDHC	Zero Discharge of Hazardous Chemicals

6 Anexxes

7 References

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Annex A

WaterProof colour codes and format templates

Dark blue
CMYK: 100/70/0/40
RGB: 0/53/112
HEX: #003570

Yellow
CMYK: 0/35/100/0
RGB: 249/176/0
HEX: #f9b000

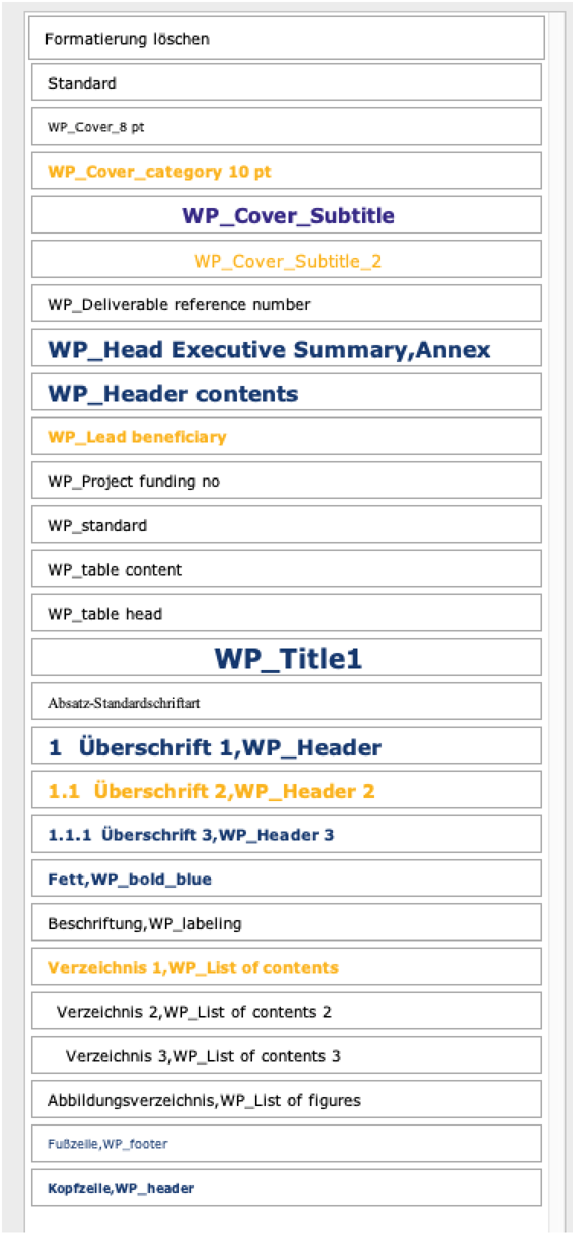

Figure 7-1: Important format templates