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A case study in green chemistry higher education and sustainable innovation in Colombia

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Green chemistry has emerged as a key driver of sustainable innovation by redesigning chemical products and processes to reduce environmental and human health impacts while supporting economic development. Education plays a central role in enabling this transition by equipping future professionals with system thinking, problem-solving skills, and sustainability-oriented competencies aligned with the Sustainable Development Goals (SDGs). In Latin America, however, the implementation of green chemistry remains uneven, with research largely concentrated in a few countries and predominantly focused on technical outcomes, while integrated educational and institutional approaches remain scarce. This article presents a longitudinal, qualitative case study documenting the systematic integration of green chemistry into higher education at the Universidad de la Costa in Colombia from 2015 to 2025. The study examines an educational model linking the problem-based pedagogical strategy in undergraduate chemistry laboratories with a green chemistry research seedbed composed of teachers and environmental engineering students conducting applied research to address local environmental challenges. Data were collected from institutional records, student projects, academic outputs, innovation outcomes, and participation in scientific and policy-oriented activities. The results show that approximately 4000 engineering students from the Department of Civil and Environmental were exposed to green chemistry concept through basic chemistry courses offered by the Department of Natural and Exact Sciences. Approximately 200 of these students engaged more deeply through seedbed research. This process generated measurable educational and innovative outcomes, including applied research projects, meritorious recognitions, a national patent, peer-reviewed publications, and direct contributions to regional sustainability initiatives such as decarbonization programs. The initiative also fostered institutional transformation through the revision of laboratory practices, alignment with international organizations such as Beyond Benign, and strengthened links between education, policy, and practice. From a Latin American perspective, this case illustrates how context-specific, university-based initiatives can contribute to global sustainability agendas by promoting quality education (SDG 4), responsible consumption and production (SDG 12), clean water solutions (SDG 6), sustainable innovation (SDG 9), and multi-stakeholder partnerships (SDG 17). The findings highlight green chemistry education as a scalable, policy-relevant pathway for empowering higher education institutions in the Global South to act as catalysts for sustainable development.

Sustainability spotlight

This study demonstrates how green chemistry education can function as a strategic driver of sustainable development by linking undergraduate learning, applied research, and innovation. Through a decade-long case study, the work shows how problem-based learning (PBL) and student-led research generate sustainability competencies, environmentally responsible technologies, and policy relevant knowledge. The initiative advances the UN Sustainable Development Goals by promoting quality education (SDG 4), promoting sustainable industrial innovation (SDG 9), advancing responsible consumption and production (SDG 12), supporting clean water solutions (SDG 6), and strengthening partnerships between academia, industry, and government (SDG 17). By presenting a scalable educational model from a Global South context, this work highlights the transformative role of higher education in accelerating sustainability transitions.

Introduction and background

Green and sustainable chemistry (GSC) has emerged as a globally recognized approach for fostering innovation in chemical sciences while contributing to the achievement of the Sustainable Development Goals. In response to the growing need for clearer conceptual frameworks and guidance, worldwide organizations such as the American Chemical Society Green Chemistry Institute with the mission of "To catalyze the implementation of innovative approaches to chemistry and engineering that enable sustainable development across the

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globe";[1] and the United Nations Environment Programme (UNEP) convened more than 100 expert stakeholders to develop ten Objectives and Guiding Considerations, together with the Green and Sustainable Chemistry Framework Manual,[2] aimed at supporting the integration of GSC principles across education, research, and policy contexts.

Equally important is education in green chemistry, which equips future scientists, engineers, and policymakers with the skills to implement these principles in real world contexts. Integrating green chemistry into curricula promotes systems thinking, life-cycle analysis, and interdisciplinary collaboration competencies essential for achieving the SDGs, particularly those related to responsible production, climate action, and ecosystem protection. By embedding green chemistry education, institutions inspire a new generation of innovators committed to sustainability, ensuring that industries evolve to meet the demands of a rapidly changing world while protecting the planet.[3,4]

Paul Anastas and John Warner's 12 Principles of Green Chemistry provide the canonical foundation for prevention, atom economy, safer solvents, catalysis, energy efficiency, renewable feedstocks, real-time monitoring, and inherently safer design. These principles frame innovation to reduce toxicity and waste throughout the product lifecycle. UNEP's Green and Sustainable Chemistry (GSC) framework complements the 12 principles with ten objectives emphasizing hazard minimization, non-toxic circularity, sustainable sourcing, worker and consumer protection, and social benefits explicitly linking chemistry innovation to the 2030 Agenda. Together, these approaches move beyond end-of-pipe control toward design for sustainability, offering Latin America policy-ready guidance and practical tools for industry and education.[5–7]

Latin America's natural capital, its biodiversity, biomass, and renewable energy potential, creates unique opportunities for sustainable industrial growth, however, the region also faces persistent pollution challenges and chemical safety gaps that hinder inclusive development. Green chemistry addresses these issues at the source, designing products and processes that minimize hazards and waste while aligning with SDGs on responsible consumption (Goal 12), climate action (Goal 13), clean water (Goal 6), and ecosystem protection (Goals 14 and 15). The ACS highlights chemistry's cross-cutting contributions to achieving SDGs from clean energy to food security, underscoring the discipline's role in a sustainable economy, a message highly relevant to Latin America's development context.[5,6]

The Economic Commission for Latin America and the Caribbean (ECLAC) regional vision for a sustainable bioeconomy identifies chemistry as a transformer of biomass into value-added products, linking innovation, territorial development, and decarbonization, an agenda where green chemistry is central to avoid regrettable substitutions and enabling non-toxic circularity.[8] Reports from International Renewable Energy Agency (IRENA) highlight the region's untapped bioenergy potential and the need for robust regulatory frameworks and cooperation to scale sustainable biofuels areas that benefit from green chemistry's process efficiency, catalyst design, and life-cycle assessment expertise.[9]

Many contributions from Latin American institutions illustrate the technical pathways and challenges of bioplastics and bio-based polymers (*e.g.*, additives, processing, and biodegradability), where green chemistry principles guide the development of safer formulations and circular applications.[10,11] Latin America also participates in global chemicals governance through the Stockholm Convention and The Global Framework on Chemicals (GFC), the framework instrument that replaces the Strategic Approach to International Chemicals Management (SAICM), building capacity for monitoring persistent organic pollutants and data-driven policy decisions across the region.[5] These mechanisms strengthen institutional capabilities and inform safer chemical management, a prerequisite for full green chemistry adoption. As SAICM transitions to the GFC, the emphasis on lifecycle management, information sharing, and capacity building continues, areas where education and professional training in green chemistry can deliver measurable gains.[12]

It is important to note that green chemistry education is no longer considered an optional component. Instead, it is now viewed as a cross-cutting axis and a "central lens" for chemical practice from basic education through professional training. This educational approach, supported by consolidated institutional experiences, demonstrates that the early and progressive incorporation of green chemistry into curricula strengthens future professionals' capacity to address complex challenges related to circular bioeconomy, human health, and the SDGs, with a direct impact on the sustainable transformation of productive systems.[13]

Transformative education is essential for deploying green chemistry at scale. Scholarship in green chemistry education emphasizes systems thinking, interdisciplinary learning, and capacity building to mainstream sustainability in curricula and laboratory practice skills crucial for creating greener products and processes. UNEP's programmatic work and communities of practice explicitly identify education as an enabling measure for green chemistry transitions, connecting teachers, students, and professionals to shared resources and objectives.[5] Recent publications show that green chemistry education can accelerate SDG attainment when integrated across educational levels and disciplines, reinforcing pedagogy with real world projects and metrics. Case studies from Latin America and global networks show universities acting as vectors for SDG acceleration through green chemistry research, outreach, and curriculum reforms, demonstrating how academic institutions can seed regional innovation ecosystems.[4,14]

What does green chemistry look like in Colombia?

Green chemistry in Colombia is intrinsically linked to applied biotechnology and the national strategy to boost economic growth through the responsible and sustainable exploitation of its vast biodiversity. The country has been identified as a key player in the Latin American region, contributing with 4% of publications on green and sustainable chemistry between 2010 and 2020.[15] Initiatives focus on generating innovative solutions using renewable resources and agro-industrial waste, such as the recovery of bagasse and juice from the fique plant to transform them into raw materials for industry (including bio-pesticides, bio-based materials, and energy), in line with the principle of waste prevention.[16,17]

Progress has also been made in the development of safer synthesis processes,[18] such as the replacement of mercury and cyanide in artisanal gold mining through the application of biological processes or plant-based coagulants, such as mucilage from *Theobroma cacao* L. shells, with a recovery rate of 95%.[19] The design of biorefineries that produce chitosan has also been improved, reducing the consumption of toxic solvents and achieving an exergy efficiency of 75%.[20] In the energy sector, Colombia's commitment to the Paris Agreement and its transition toward renewable energy sources align with green chemistry principles,[21,22] making it a strategic tool for achieving environmental goals while fostering economic development. Also, Colombia is a major player in the production of biofuels, and its sugarcane ethanol and palm oil biodiesel exhibit a significant reduction of 81% and 84%, respectively, in Global Warming Potential (GWP) compared to their fossil equivalents.[23]

Researchers have expanded their studies to include circular economy use of biomass for waste management;[24] the ecological synthesis of nanomaterials using aqueous plant extracts, such as those from *Moringa oleifera*, for photocatalytic applications.[25] In the agricultural sector, adopting green chemistry principles has resulted in the development of eco-friendly pesticides and fertilizers, reducing harm to ecosystems and human health.[26,27] Novel green solvents, such as deep eutectic solvents (DESs), have also been developed for extracting bioactive compounds.[28] Furthermore, implementing green chemistry in educational settings, especially in university laboratories, has been identified as a critical step in mitigating risks.[14] Colombia can position itself as a leader in sustainable innovation in Latin America by embracing green chemistry and encouraging sustainable practices, however, all these new findings come from academic sector.

Colombia's current state of green chemistry is evolving, with growing recognition of its potential to address environmental challenges and promote sustainable development. While the country has made strides in integrating green chemistry principles into research, education, and industry, there is still significant room for growth and implementation.

Colombian universities and research centers increasingly incorporate green chemistry into their scientific agendas. Institutions such as the Universidad Nacional de Colombia, Universidad de los Andes, Universidad EAN, Universidad La Salle, Universidad de la Costa, Universidad Industrial de Santander, Universidad Pontificia Bolivariana and Universidad de Antioquia, among many others private and public institutions, have research groups or make contributions focused on green chemistry or sustainable chemistry, including topics like renewable energy, biodegradable materials, nanotechnologies and waste reduction, for example, research group such as CIBIOT from Universidad Pontificia Bolivariana in Medellin, are actively working to promote the creation of green chemistry start-ups based on applied research in biotechnology.[16] These efforts are supported mostly by their own resources, and sometimes with government funding (Ministry of Science, Technology and Innovation) or with international collaborations.

Linking education to policy, practice, and innovation

Colombia's participation in international agreements, such as the Paris Agreement and SDGs, provides a foundation for advancing in green chemistry. These commitments encourage the adoption of sustainable practices across sectors. The country has implemented environmental regulations that indirectly support green chemistry, such as restrictions on single-use plastics and incentives for renewable energy projects.[29] However, there is no specific national policy or framework dedicated to promoting green chemistry.

This wave has transformed the practice and application of chemistry for the benefit of future generations and the planet. It has inevitably reached Colombia influencing government policies and aligning them with the SDGs and the principles of green chemistry. Table 1 provides some examples of this.

From 2017 to 2023, *Colombia Científica* operated as a national policy experiment, demonstrating the efficacy of coordinated collaboration in enhancing higher education and the science, technology, and innovation (STI) system. The Colombian Institute for Educational Credit and Technical Studies Abroad (ICETEX) and MinCiencias, in collaboration with the World Bank, have initiated a program known as PACES (Program for Science, Higher Education, and Innovation). This initiative has facilitated the establishment of eight major alliances, which are designed to enhance academic standards, research capabilities, and societal impact across Colombia.[37]

Within the PACES framework, the "Ecosistema Científico" component structured Colombia Científica into eight inter-institutional alliances organized around five national strategic priorities: health, sustainable energy, food systems, bioeconomy, and social reconstruction in post-conflict regions. These alliances brought together accredited and non-accredited higher education institutions, international research centres, and actors from the productive sector, strengthening doctoral training, regional research capacity, and long-term collaboration networks with sustainable impact.

Rather than operating through isolated institutions, the initiative promoted cross-sector cooperation, linking universities, international partners, public agencies, industry, and local communities. In total, thirty-nine Colombian universities and fifty-six foreign institutions from twenty countries collaborated within these strategic priority areas, fostering coordinated responses to national challenges.

A defining feature of the program was its emphasis on applied context-driven research. University teams developed solutions with direct social relevance, including renewable energy technologies for rural communities and mobility

Table 1 Regulations and policies in Colombia that promote or align with green chemistry

Regulation/policy	Year	Main objective	Relationship with green chemistry
CONPES[a] 3868 (ref. 30)	2016	Policy for the management of risks associated with the use of chemicals	Promotes comprehensive chemical life cycle management, risk prevention, and impact reduction
CONPES 3918 (ref. 31)	2018	Strategy for the implementation of the SDGs in Colombia	Promotes actions that reflect principles such as waste prevention, use of renewable raw materials, energy efficiency, and design of less hazardous products
Decree 1496 (ref. 32)	2018	Implements the Globally Harmonized System (GHS) for classification and labelling	Promotes transparency and clear communication about chemical hazards, reducing risks
CONPES 3934 (ref. 33)	2018	Green growth policy to promote sustainability and the bioeconomy	Promotes sustainable production processes, energy efficiency, and the use of renewable raw materials
Law 1950 (ref. 34)	2019	Colombia's accession to the Organization for Economic Cooperation and Development (OECD)	Includes commitments to improve chemical management and adopt international best practices
Law 2169 (ref. 35)	2021	Sets targets for carbon neutrality	Encourages energy efficiency and less polluting processes
Decree 1630 (ref. 36)	2021	Regulate the comprehensive management of chemicals for industrial use	Establishes inventories, risk assessments, and reduction plans, aligned with prevention principles
Law 2232 (ref. 29)	2022	Regulate single-use plastics	Reduces pollution and promotes biodegradable materials, aligned with design for degradation

[a] National Council for Economic and Social Policy (NCESP or CONPES in spanish) elaborated by National Planning Department (NPD).

innovations for river-dependent territories. These experiences repositioned teaching and research as tools for real world problem solving, allowing students and faculty to work in authentic innovation settings rather than purely academic environments.

The National Accreditation System (NAS), in Colombia, is the set of policies, strategies, processes and organizations whose fundamental objective is to guarantee to society that the institutions of higher education that are part of the system comply with the highest quality requirements and that they fulfil their purposes and objectives.[38] Accreditation is a testimony given by the state on the quality of a program or institution based on a previous evaluation process involving the institution, the academic communities, and the National Accreditation Council (CNA).[39] *Colombia Científica* also targeted structural inequalities within the higher education system. Non accredited universities were paired with accredited institutions to strengthen governance, research practices, and academic standards. This strategy accelerated institutional development while expanding collaboration networks and shared scientific production at the national level.

By the end of the program, outcomes exceeded projected targets. More than 1200 researchers and over 1000 students and faculty members participated in advanced training and funded research. Scientific and technological outputs surpassed expectations by over 130%, including industrial prototypes, patentable technologies, granted patents, and the creation of technology-based enterprises. Importantly, most participating non-accredited institutions achieved or were close to achieving national accreditation.

Overall, Colombia Científica established a scalable model for integrating education, research, and innovation policy. Its results illustrate how strategic alliances can mobilize local talent, strengthen institutional capacity, and generate solutions aligned with national development goals. The program offers transferable lessons for countries seeking to leverage higher education as a driver of sustainable and inclusive innovation.[40] These results provide a structural framework within which university-based green chemistry education initiatives can be understood. In this context of strengthening the national scientific ecosystem, the experience developed at Universidad de la Costa exemplifies how public policy orientations can be translated into educational practices that integrate teaching, formative research, and technological innovation.

Problem based learning

The mission of the Universidad de la Costa is "to educate well-rounded citizens based on the principles of freedom of thought and ideological pluralism, with a strong sense of responsibility in the ongoing pursuit of academic and research excellence, using the development of science, engineering, technology, and culture to achieve this goal".[41] To fulfil its mission, the university's governing council creates institutional documents called agreements that align with Colombia's Ministry of Education policies. These agreements enable all departments to contribute to the realization of the mission and vision.

Currently, Agreement 1628 of 2020, titled "Competency Training Model", establishes the framework for implementing changes to the curriculum, including the incorporation of Green Chemistry.[42]

The Department of Natural and Exact Sciences, particularly the Biology and Chemistry division, promotes systemic thinking, environmental justice, and sustainable development in their curriculum, with an active learning strategy initially presented as a "Classroom Project", which adapted the Problem-Based Learning (PBL) methodology (see comparative Table 2). In PBL, students use the problem as a starting point to investigate, analyse, and build knowledge. This approach emphasizes developing analytical, research, and teamwork skills, and it is more focused. In short, a classroom project can incorporate PBL but is not limited to it. The Classroom Project is broader than PBL, which is just one technique used within it. Since 2015, this active learning strategy has been adapted and used in General and Organic Chemistry classes. It has been successful in developing students' scientific, academic, and personal skills, and it has officially been included in the institutional syllabus since 2017. The implementation of PBL contributed to deeper student comprehension of green chemistry and sustainability topics and promoted a more critical awareness of environmental issues.[43]

Despite the growing number of publications on green and sustainable chemistry in Latin America over the last decade, research output remains uneven and highly concentrated in a few countries, mainly Brazil, Mexico, and Argentina, which together account for more than 90% of the region's publications.[15] Most existing studies focus on technical aspects such as synthetic routes, materials development, or the application of specific green chemistry principles, often emphasizing short-term outcomes.[44] In contrast, integrated approaches that address the educational, institutional, and social dimensions of green chemistry over time remain scarce, despite their importance for advancing sustainable development.[45,46]

In response to this gap, the present study offers a longitudinal case study documenting the systematic integration of green chemistry into university education in Colombia over more than a decade. By examining an educational strategy that connects teaching, formative research, and laboratory practice transformation, this work highlights the role of chemistry education as a strategic driver for the sustained implementation of green chemistry in Latin America and provides a transferable reference for long-term educational initiatives.

Methodological approach

This study follows a qualitative and descriptive longitudinal approach, covering the period from 2015 to 2025. Data were collected from institutional records, undergraduate research project reports, academic products, participation in scientific events, and innovation outcomes associated with the Green Chemistry research seedbed. Educational impact was assessed using indicators related to student participation, research production, academic recognition, and continuity into graduate studies.

The Universidad de la Costa's Institutional Pedagogical Model is grounded in philosophical, epistemological, and psychopedagogical principles reflecting humanistic, developmental, and constructivist orientations. These principles guide the comprehensive formation of the student body. Within this framework, the model prioritizes active learning and integral education. It also emphasizes meaningful interaction with the social, cultural, and professional context to ensure strong social relevance in the educational process. The student's role is positioned at the center of learning, and the teacher acts as a mediator and facilitator, supporting learners in their

Table 2 Classroom project *vs.* PBL

Aspect	Classroom project	PBL
Definition	Integrative pedagogical strategy organized around a contextualized project	Active learning methodology is driven by the analysis of a real or simulated problem
Approach	Broad and interdisciplinary	Problem-centered and inquiry-oriented
Duration	Medium to long term (weeks or months)	Flexible; short cycles or extended modules
Final product	Tangible integrative outcome (report, prototype, proposal)	Well-argued solutions or proposal supported by analysis
Teacher's role	Facilitator and coordinator of the overall process	Facilitator and cognitive scaffold through questioning
Student's role	Designs and develops the project collaboratively	Analyses the problem and proposes justified solutions
Competencies	Integrated cognitive, procedural, and attitudinal competencies	Analytical, research, collaborative, and metacognitive skills
Methodological scope	May integrate multiple active methodologies, including PBL	Specific methodology with a defined problem-based sequence

academic and personal development. The model also conceives of the curriculum as a flexible system articulated with competencies and aligned with the needs and dynamics of the broader environment in accordance with institutional and national quality standards.[42]

Over the past decade, General Chemistry and Organic Chemistry courses for engineering students have integrated laboratory activities as active learning strategies that enable students to "learn by doing." Within this context, a classroom project was introduced in 2015 to engage students in exploring Green Chemistry and its 12 principles as sustainable approaches to environmental challenges. This initiative has since evolved into a strategy aligned with the institutional pedagogical model and national higher education standards, implemented through a PBL framework consisting of three stages: Knowledge, where learning objectives and expected outcomes are presented; Analyze, which promotes independent research and team-based discussion; and Present and Evaluate, which encourages critical reflection, formative assessment, and peer evaluation.

The strategy begins with examples of global sustainable solutions derived from Green Chemistry, after which students form teams of four to work collaboratively throughout the 16-week semester. Students are introduced to the concept and applications of Green Chemistry and are encouraged to conduct independent research using sources such as the U.S. EPA website and materials related to SDGs. The instructor poses a local problem or challenge to guide inquiry, such as developing innovative and sustainable solutions for managing common organic waste. The overarching aim is to inspire first-year students to envision themselves as contributors to local environmental solutions through active learning and from a Green Chemistry paradigm.

Although students are not expected to produce highly rigorous or definitive scientific proposals at this early stage, they are required to develop well-structured, evidence-supported, and feasible ideas. Continuous feedback is provided at the end of each stage, contributing to both formative and summative assessment. A rubric specifying the competencies, learning outcomes, performance indicators, and deliverable guidelines is presented during the first week of classes and used throughout the evaluation process.

The Universidad de la Costa provides its academic community with complimentary access to electronic libraries and indexed databases, including Scopus, ScienceDirect, and Web of Science, to facilitate research and knowledge expansion. Students receive training on the utilization of these resources and are encouraged to explore them by employing keywords related to their interests. The exploration is unrestricted and following brainstorming sessions and feedback from teachers and classmates, each group selects a topic of interest. Despite their status as first-year students, who have yet to acquire a substantial set of professional skills, they are encouraged to conceptualize solutions to pressing environmental issues or to engineer novel eco-products. These efforts align with the principles of green chemistry by using materials that are easily accessible, such as salt, sugar, white vinegar, baking soda, and red cabbage. These materials are safe to handle, do not produce toxic waste, and can be used at room temperature.

In the second stage of the PBL strategy, titled "Analyze," students conduct a structured search on scientific databases, including Scopus, ScienceDirect, and Web of Science, with the objective of locating global publications on their designated topic. Additionally, they identify the primary findings and deliberate on the feasibility of innovating or replicating the research within a local context, leveraging readily available resources and within a limited timeframe. This is due to the requirement to propose a solution at the conclusion of the semester. However, they are also tasked with presenting an advanced version of their proposed solution every five weeks, which will be assessed with a grade and feedback at each semester interval (there are three intervals).

In the third and final stage of the PBL, each group is required to present their proposal to the class and, if feasible, bring a prototype or experimental sample. Peers and the instructor provide feedback by analyzing the project's strengths and opportunities for improvement, and each group receives a formal final evaluation. This teaching strategy has been used in General and Organic Chemistry courses for the past decade. A key distinction between General Chemistry and Organic Chemistry classes is the emphasis on developing skills and applying knowledge from each subject. These skills and knowledge are complementary, offering engineers a comprehensive understanding of chemistry in environmental and everyday processes. Much of this work with students is carried out using resources from the research laboratories at the Universidad de la Costa. However, students are responsible for providing the "raw materials" (*e.g.*, biomass) and performing certain steps in their own homes.

Through experiential learning, students explored bioplastics, biochar, insecticides, pesticides, natural pH indicators, water filters, natural coagulants, and biofuels, among other topics. They experimented with various waste materials, such as potato, mango, banana, and plantain peels; coconut shells; and neem (*Azadirachta indica*) and noni (*Morinda citrifolia*) leaves and seeds. Considering that they are environmental engineering students just beginning their professional training, these results were considered very good. Many students were interested in this framework for chemistry and its applications in sustainable solutions. Thus, this formative and evaluative activity within their curriculum became the beginning of something bigger: a research seedbed to learn more about green chemistry. Many students wanted to continue working on their projects after completing their General and Organic Chemistry courses. They wanted to conduct further research, and this would help them achieve one of the requirements for their professional degree.

Results

Green chemistry research seedbed in a higher institution

Founded 55 years ago, the Universidad de la Costa has consistently sought to position itself at the forefront of pedagogical innovation in keeping with its institutional mission. The university's educational model aims to train competent professionals with a global outlook in accordance with the policies and quality standards of the Colombian Ministry of Education.[41] Within this institutional framework, the Green Chemistry Seedbed was launched in 2015, initially with seventeen environmental engineering students who had already taken the general chemistry course and wanted to continue exploring their ideas in the organic chemistry course. After contacting the lead professor directly, a "working group" was spontaneously formed, without official funding but with access to the institution's resources and laboratories. This marked the beginning of a training space designed to strengthen research skills, critical thinking, and the development of innovative and locally relevant solutions to environmental challenges.

A key pedagogical strategy supporting this process has been the implementation of "classroom projects" structured under a PBL approach. This methodology has proven effective in motivating students by allowing them to explore topics of personal and societal relevance within a rigorous scientific framework.[47] As a formative and evaluative strategy, it strengthens competencies in critical reading, quantitative reasoning, problem solving, written and oral communication, English language use, and data analysis. Students engage with academic databases, institutional reports, scientific platforms, and multimedia resources in both Spanish and English, ensuring that project topics are grounded in real, documented environmental challenges.

Over the past decade this pedagogical strategy has contributed to the development of sustainability oriented human capital, nearly 4000 engineering students have completed the General Chemistry and Organic Chemistry courses, where the principles of green chemistry have been systematically promoted as important base for sustainability, they were introduced to the need to rethink how chemistry is practiced and applied and demonstrate the potential of undergraduate education to generate environmentally responsible innovation. Since 2022, the Universidad de la Costa has officially included green chemistry and its 12 principles in the syllabus of three engineering subjects: General Chemistry, Organic Chemistry, and Materials Science.

From 2015 to 2025, approximately 200 engineering students participated in a green chemistry research seedbed, developing research proposals inspired by the twelve principles of green chemistry. During the first five years, student participation in the research seedbed was primarily supported through one-on-one mentoring between tutors and students. As the program matured and aligned with the university's institutional framework for research training, a 120-hour Research and Innovation Course became a prerequisite for admission. The course provides the methodological and conceptual grounding necessary for early research engagement, ensuring that students enter the program with a consistent level of preparation.

It covers components of the institutional science, technology, and innovation system, the scientific method and major research paradigms, quantitative and qualitative approaches, and the formulation of research problems. Students also develop competencies in advanced information searching, reference management, bibliographic matrix construction, scientific writing, and science communication. Innovation-oriented content is also incorporated, including Business Model Canvas, Design Thinking, Lean Startup principles, intellectual property fundamentals, and technology transfer processes. The course concludes with guidance on the institutional research seedbed pathway and opportunities within national research programs. This structured preparation provides students with a solid methodological and innovation-focused foundation to support the development of their research proposals when entering the Green Chemistry Research Seedbed.

In recent years, the EMMA institutional platform has standardized the admissions process for research seedbeds by centralizing application submissions, eligibility verification, and enrollment. Admission requires completing the free research methodology course, selecting a seedbed aligned with the university's official Sustainable Development research line, and receiving approval from a faculty advisor. The process concludes with validation from the Vice Rectorate for Science, Technology, and Innovation.

Seedbeds are voluntary curricular spaces that nurture emerging researchers by integrating teaching, research, and outreach. Students collaborate with faculty mentors to strengthen their methodological, cognitive, and social research skills while producing and disseminating research outputs. These outputs serve as indicators of academic progress within the university's scientific training and quality assurance system. While not all participants completed their research projects due to time constraints and personal obligations, all students were exposed to research-oriented learning experiences focused on sustainable and professionally relevant chemical solutions.

Since the beginning in 2015, the Green Chemistry Research Seedbed, has represented the Universidad de la Costa, in departmental and national events organized by the Colombian Network of Research Seedbeds (REDCOLSI). Students regularly present project proposals and research outcomes to academic audiences that are often unfamiliar with the transformative scope of green chemistry (Fig. 1). Evaluations from peer reviewers have consistently highlighted the quality and relevance of these contributions. REDCOLSI plays a key role in democratizing science in Colombia by preparing new generations to act as agents of change through research, collaboration, and sustainable development.[48]

Quantitatively, the impact of the Green Chemistry Research Seedbed is significant. Over the past decade, more than ten investigation projects have been completed, eight of which explicitly applied green chemistry principles. Five of these projects received a Meritorious distinction, and all of them involved environmental engineering students. Each project has been executed in a highly personalized manner, at the student's own pace and according to their individual skill level. The students have access to work meetings, planning sessions, and ongoing support throughout the entire process. This personalized approach is maintained with two tutors and two students assigned to each proposal. The two tutors are faculty members belonging to the research seedbed who directly guide the

Fig. 1 Green chemistry research hotbed – a decade.

development of the research process, including proposal formulation, methodological design, experimental implementation, data analysis, and preparation of the final report, ensuring academic and methodological rigor. The students present their final work before a jury evaluator. The jury evaluators are faculty members from the Environmental Engineering program whose academic experience and thematic expertise are aligned with the project topic. They are responsible for assessing the written final report and the oral defense based on previously established evaluation criteria. The students have the autonomy to decide on the focus of their work, and the tutors play the role of an expert guide throughout the process, providing guidance and assistance as needed.

Innovation outcomes include: winning the first place in the "Hackathon AGSTAR 2021" with a startup idea (an organic insecticide), this was part of the AGStar 'Las estrellas del agro' (Stars of Agriculture) competition in Colombia, focused on innovation for the agricultural sector, where technology startups (AgTech, FoodTech, AnimalTech) developed solutions, culminating in the awarding of the best projects at Expo AgroFuturo in November 2021, connecting startups with ecosystem partners to boost Latin American agriculture (Fig. 2). In 2022, granting of a patent for an organic insecticide, evidencing the potential for translating academic research into practical technological solutions.[27] Scientific dissemination has expanded with the first peer-reviewed publication in 2024, entitled "*Removal of Direct Navy-Blue Dye from Aqueous Solutions Using Banana Peels*",[24] and over than 30 participations in national academic outreach events. The long-term formative impact is further reflected in two master's theses currently in progress, developed by graduates of the Environmental Engineering program of Universidad de la Costa who were early members of the Research Seedbed and are now pursuing master's degrees in Sustainable Development. For the tenth anniversary the students proposed a logo for a T-shirt (Fig. 3).

Some representative projects demonstrate how green chemistry principles have been implemented in educational

Fig. 2 "Hackathon AGSTAR 2021" price.

Fig. 3 Green chemistry research seedbed logo.

and practical settings, including the development of natural pH indicators, alternative disinfectants for drinking water treatment, and the valorization of agricultural waste for contaminant removal. In 2017, the first undergraduate project of the Research Seedbed in green chemistry was successfully completed. This project involved the extraction of anthocyanins from red cabbage (*Brassica oleracea*) as a natural substitute for synthetic pH indicators. This initiative is in alignment with the principles of green chemistry, specifically the first, fourth, and tenth principles. The natural indicator exhibited analytical performance analogous to that of conventional indicators, while concurrently effectuating a substantial reduction in hazardous waste generation.[49] Another study assessed peracetic acid as an alternative disinfectant for drinking water treatment, showing comparable efficiency to sodium hypochlorite while producing fewer harmful by products and complying with Colombian drinking water regulations.[50]

The next projects focused on the valorization of agricultural waste, including the production of thermal activated carbon from banana peels for the removal of textile dyes and emerging contaminants from water;[51,52] as well as the use of *Mangifera indica* (mango) seed as a natural coagulant for domestic wastewater treatment, incorporating energy efficient solar dehydration processes consistent with Principle 6.[53]

Each of these projects clearly presents opportunities for further refinement; however, the primary educational objective has been achieved: transforming undergraduate students' understanding of chemistry as a discipline directly connected to sustainable development and environmental responsibility.

An example of the impact on professional life and a source of pride for the Green Chemistry research group is the first student to join the group, Beatriz Ferreira-Tilano, who is now an environmental engineer from the Universidad de la Costa and is completing her master's degree in Sustainable Development at her alma mater. She currently works as the technical leader of the *AtlantiCO*$_2$ program, launched in 2025, which is a regional program aimed at strengthening environmental awareness and supporting the transition to a resilient, low-carbon, and carbon-neutral territory. It is sponsored by the CRA, the National Association of Industrialists of Colombia (ANDI), in collaboration with the Colombian Institute of Technical Standards and Certification (ICONTEC) and the Bartolomé de las Casas Institute (INUBAC).[54]

Currently, the research seedbed group in green chemistry of Department of Natural and Exact Sciences includes 14 active students and four tutors, two biologists and two chemical engineers, who support each other on proposals addressing topics like biomass energy production (from coconut shells), pharmaceutical contaminant removal using invasive species (*Eichhornia crassipes*), nature-based solutions on campus (liquid trees), and the formulation of eco-friendly termiticide.

The integration of green chemistry into the curriculum of chemistry courses has yielded three significant outcomes that directly contribute to the Universidad de la Costa institutional research line of sustainable development. This academic strategy aligns with the SDGs 3 and 4, promoting the sustainable advancement of local communities and the nation. The initial outcome of this initiative was the establishment of a research seedbed that has gained national and international recognition. Secondly, it has prompted a systematic review of laboratory practices in chemistry. This review centered on the adjustment of the guidelines in accordance with the principles of waste prevention (Principle 1), the reduction of reagent uses and the enhancement of atomic economy (Principle 2), and the selection of safer solvents and auxiliaries (Principle 5). For instance, all practices utilize water as a solvent, sugar, lemon, kitchen vinegar, purple cabbage water, and other chemicals found in the kitchen or home as reagents. These substances are used in experiments in minimal but enough to observe the chemical phenomenon under study. Consequently, chemistry laboratory protocols have been modified to prioritize biosafety and reduce environmental impact, as the GHS is being implemented. All revised laboratory guidelines are available through the institutional repository and are subject to annual faculty review.[55] Furthermore, plans are underway to initiate the process of obtaining My Green Lab certification.[56]

Becoming a signer of the Beyond Benign Green Chemistry Commitment since 2022 has significantly strengthened Universidad de la Costa's institutional efforts to integrate sustainability into its academic and research processes. The Department of Natural and Exact Sciences has played a central role in this transformation by leading curriculum redesign initiatives, promoting responsible and sustainable laboratory practices, and fostering faculty engagement with green chemistry principles. Through this partnership, the university has gained access to global best practices, professional development opportunities, and a collaborative network of institutions committed to advancing sustainable chemistry education. As a result, both the department and the university have enhanced their capacity for innovation, environmental stewardship, and long-term sustainability integration. The Universidad de la Costa is indeed the second institution in the country to sign the Beyond Benign Commitment.[57]

The results of this case of study can be interpreted in alignment with the *Global Chemicals Outlook II*, which emphasizes the need for strengthened action to disseminate best practices in green and sustainable chemistry education and to overcome persistent barriers within academia and the private sector. In this context, the establishment of a green chemistry research seedbed at a Colombian university emerges as a concrete institutional response to these international recommendations. This initiative not only operates the principles outlined in the Specialized Manual on Green and Sustainable Chemistry Education and Learning developed by the UNEP[46] but also demonstrates how global policy frameworks can be translated into localized educational practices. The green chemistry research seedbed has facilitated the integration of sustainability principles into academic training through student-led research, interdisciplinary collaboration, and the application of green chemistry concepts to context specific environmental and industrial challenges. These findings suggest that such grassroots academic structures can play a pivotal role in bridging the gap between curricular intentions and meaningful learning experiences, reinforcing the potential of green chemistry education to contribute to sustainable development goals within the Colombian higher education system.

Challenges and opportunities

Colombia is a country rich in natural resources and home to great researchers with great potential for innovation, particularly in the field of green chemistry, but significant gaps persist in awareness, education, and training. There is a lack of full understanding of the concept and its connection to sustainable development, the key is national commitment. Although Colombia has vast potential for innovation and research, state and private sector funding for sustainable initiatives are limited. In the absence of a national strategy that deliberately integrates green chemistry as a catalyst for sustainable development, Colombia has indirectly adopted this concept. This is largely due to the need for Colombia to align its development strategies with international sustainability standards, which are increasingly incorporating green chemistry as a framework for producing and applying chemical knowledge more responsibly. In this context, several principles of green chemistry have already been embedded in national public policies, particularly in CONPES documents.[30,31] The CONPES is the country's highest planning authority, has issued these documents, which function as cross-sectoral public policy instruments. The formulation of these plans is coordinated by the NPD, which advises the national government on issues related to Colombia's economic and social development.

On the other hand, scientific publications applying green chemistry principles are becoming more prevalent, and the concept is gradually being integrated into the academic world through science outreach events, articles publications and relations with international academic networks,[3,12,58] which facilitates connections between teachers, researchers, and higher education students with the global green chemistry community. Organizations such as Beyond Benign and events like LatinXChem, have helped raise awareness of the work being done in Colombia in this area.

LatinXChem is an annual event on platform X for Latin American chemists worldwide to share research, overcoming geographic and funding barriers through free, multilingual (Spanish, Portuguese, English) online poster sessions, boosting visibility and collaboration for a vibrant but often underrepresented scientific community. It is useful because it democratizes scientific exchange, fosters global connections, reduces costs and environmental impact, highlights high-quality research often overlooked in English centric publications, and empowers students and early career researchers. In 2023, the winning posters in the green chemistry category were from two Colombian universities. This has been instrumental in building capacity and visibility.

Although there are publications that show collaboration between two or three national universities and their research groups,[20,22,26] most publications on this topic involve one author or one local university, with the rest being foreign authors,[14,17] thus showing that it is still necessary to strengthen opportunities for collaboration at the national level.

Nevertheless, there is still a lack of knowledge and clarity regarding the importance of global changes in chemistry. Colombia's elementary, middle, and high schools have not yet integrated green chemistry into their curricula. However, institutions that formally include the teaching and applications of green chemistry are beginning to emerge. For instance, the Rochester School in Cundinamarca,[59] Universidad de la Costa (CUC) in Barranquilla, EAN University,[60] and La Salle University,[61] both in Bogotá.

The advancement of green chemistry research is constrained by structural limitations, particularly the scarcity of specialized laboratories that enable sustained and effective collaboration among universities, industry, and governmental actors in the co-creation of environmentally responsible products and processes. Despite these challenges, certain regional public institutions have assumed a strategic enabling role. Among them, the Corporación Autónoma Regional del Atlántico (CRA) stands out for its active promotion of sustainability-oriented initiatives and green economic activities in the Colombian Caribbean region.

By means of programs such as *Atlántico Verde*, the CRA operationalizes principles aligned with green chemistry, especially those related to pollution prevention and environmentally conscious process design. This initiative supports local sustainable enterprises while reinforcing the institution's broader mandate of natural resource conservation and territorial sustainable development. Although the CRA does not function as a research center in chemical sciences, it serves as a regulatory and managerial body that embeds sustainability and green chemistry principles into environmental governance, thereby facilitating favorable conditions for the emergence and consolidation of green businesses. Moreover, *Atlántico Verde* extends beyond a conventional commercial outlet, positioning itself as a space for environmental education and socio-cultural engagement. It promotes responsible consumption patterns, environmental awareness, and the valorization of local production. The initiative aggregates diverse green enterprises under a single platform, grouping their offerings into three main categories: sustainable bioproducts and services, industrial ecoproducts, and solutions aimed at enhancing environmental quality. Through this integrative model, the initiative contributes to strengthening local identity, fostering environmentally responsible practices, and supporting place-based development grounded in community participation and territorial commitment.[62]

Conclusion and future perspective

Green chemistry is progressively being incorporated into chemistry and engineering programs at Colombian universities, primarily through elective courses, workshops, and research initiatives. Although these efforts reflect a growing institutional commitment to sustainability, the absence of nationwide curricular standardization continues to limit their systemic impact. Beyond academic and industrial environments, public understanding of green chemistry remains limited, underscoring the need for broader educational and policy driven dissemination.

Colombia's experience exemplifies the central role of higher education institutions in promoting sustainable innovation, particularly in areas such as circular biomass utilization, environmentally responsible chemical processes, and water treatment solutions. The dissemination of these efforts was facilitated by grassroots academic initiatives and international organizations, including Beyond Benign and LatinXChem.

Despite these advances, substantial structural challenges persist. These challenges include, but are not limited to, limited funding, fragmented policy frameworks, and weak industry engagement. These factors contribute to the constraints on large-scale implementation and technology transfer.

Within this context, the Green Chemistry Research Seedbed at the Universidad de la Costa exemplifies how sustained, student-centered research initiatives can function as incubators for sustainable innovation. Through the integration of problem-based learning, applied research, and external collaboration, this case demonstrates direct contributions to the SDGs by advancing quality education (SDG 4), promoting responsible consumption and production through green chemistry practices (SDG 12), fostering applied innovation aligned with sustainable industrial development (SDG 9), supporting clean water and sanitation solutions (SDG 6), and strengthening partnerships between academia, industry, and government (SDG 17). The Universidad de la Costa will keep working to incorporate the idea of sustainable chemistry into the campus and the local community through science events and other activities.

To that end, it is imperative to develop a coherent national roadmap that aligns educational strategies with science, technology, and innovation policies, particularly those led by Minciencias and the Ministry of Education. Such a roadmap is crucial to facilitate the accelerated adoption of green chemistry in Colombia. A roadmap of this nature should promote curricular innovation, teacher development, and sustained funding mechanisms that support green chemistry initiatives in all educational institutions. The integration of digital tools, the enhancement of inter-institutional and international collaboration frameworks, and the augmentation of research-based educational models, including student-led research groups and innovation-driven learning environments, have the potential to mitigate the discrepancy between knowledge generation and public policy implementation. In the interim, it is recommended the cultivation of additional outreach spaces concerning sustainable chemistry be initiated in primary and secondary schools. This pedagogical strategy is designed to ensure that, upon their enrollment in university, these students will encounter the concept of sustainable chemistry not as a novel concept, but as a well-established paradigm. Consequently, they will be well-positioned to propose sustainable strategies and solutions that will have a greater impact. In this manner, Colombia could leverage higher education as a strategic driver of sustainable development, positioning green chemistry education not only as a response to global environmental challenges, but also as a catalyst for scientific innovation, environmental responsibility, environmental justice, and long term social and economic impact in the Latin American context.

Conflicts of interest

There are no conflicts to declare.

Data availability

The data supporting the findings of this study are derived from institutional websites, records, and the repository of the Universidad de la Costa (CUC). These data include course syllabi, laboratory guidelines, student research projects, internal reports, and publicly available academic outputs (*e.g.*, theses, publications). The context data can be found in public pages of the Colombian state and in specialized databases. All of these documents are available (view references in the article).

The figures are part of the personal photographic record of the corresponding author (Claudia Herrera-Herrera), who was the founding leader of the Green Chemistry research seedbed at the Universidad de la Costa (CUC) and these are original works from the Green Chemistry research seedbed: ref. 24, 27 and 49–53.

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