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Tackling sustainability challenges in Latin America and Caribbean from the chemical engineering perspective: A literature review in the last 25 years

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ABSTRACT

Although in Latin America there is the presence of many developing countries, the chemical industry is highly competitive in today's globalized world, due to its availability of natural resources and raw materials. The production of highly profitable chemicals, high value-added metals, petroleum and its derivatives, cosmetics, perfumes and pharmaceutical products have placed Latin America as an interesting option for the global chemical industry in the 21st century. However, given the inefficiency of various processes and the growing production of various industrial areas, the daily production of 430,000 tons of waste materials is recorded in the region. In recent years, in Latin America there has been a growing interest in increasing energy efficiency and reducing waste. An example of such a situation is the development in relevant research areas that are reflected in energy, environmental, economic and inherent security aspects; in short, applications of chemical engineering. In a context of growing population, Latin America's chemical and petrochemical industries are well positioned for significant growth, if the logistical and political challenges characteristic of the geographic area can be addressed. The upcoming challenges associated with achieving sustainable operations in conjunction with the dynamics of global trade are key issues that the industry must face, in addition to the particularities of each country in this diverse, multicultural and dynamic part of the world. Consolidation through increased merger and acquisition activity and an increasingly blurred line between logistics service providers and distributors are notable trends across the value chain that suggest competition is intensifying in Latin America. The purpose of this document is to provide a summary of the current status of the application of sustainability tools in chemical processes in research in Latin America and to forecast what additional beneficial contributions might be on the horizon. We present here a brief literature review of the actions that are already being carried out, in Latin America, in the pertinent topics in sustainability where Chemical Engineering is involved, in the last 25 years.

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1. Introduction

With no more than 15% of the total land area of the planet, Latin America and the Caribbean has a land area of just over 2 billion hectares. This region of the world has the largest number of ecoregions in the world and the greatest variety of natural species. The value of natural terrestrial ecosystems goes far beyond their economic value (CEPAL, 2019). The services they provide are essential for the survival of humanity: they stabilize the atmosphere and the climate; they regulate mesoclimatic humidity and the water cycle; they are a source of wildlife, timber resources and pharmaceuticals, as well as having many other uses, and these are increasingly valuable in industrial terms. Unfortunately, an adequate sense of the value of natural environmental services has not spread to all citizens or governments of Latin America and the Caribbean, nor has it made them aware of the urgent need to take action to stop and reverse the serious impact that society has on natural ecosystems. The lack of planning in technology, in the use of natural resources and adequate policies to ensure their preservation have led to a severe deterioration of the environment in the region, which has been reflected in soil degradation, loss of biodiversity, changes in river beds due to sedimentation, reduction in the availability of fresh water and reduction in the quality of its waters due to contamination and sedimentation. This area of the world has the privilege of being one of the regions with the greatest abundance of natural resources on the planet. Therefore, the highest priority in the action agenda must be given to the conservation, sustainable use and restoration of the natural resources of the region (CEPAL, 2019).

In the same line, in Latin America and the Caribbean, the problem of pollution seems to be taking a worrying turn for the worse, as a result of population and economic growth and the accentuation of certain production and consumption patterns. The main causes of atmospheric pollution in the region are (CEPAL, 2019):

a) industrial activities;
b) the quantity and quality of fuels consumed,
c) the inadequacy of controls on vehicle emissions
d) the growth in vehicle numbers, accelerated by the growing practice of importing used vehicles;
e) human settlements and the high density of urban areas;
f) the use of pesticides in rural communities;
g) particle emissions produced by soil erosion and the burning of
h) agro-industrial mass
i) inefficient energy use and
j) in some cities, unfavourable climate conditions,
k) the burning of fuel in homes located in poor outlying areas.

Records of the main pollutants in the region show a rising tendency over the decade. Between 1990 and 1999, emissions of suspended particles rose by 22%, of nitrogen oxides, by 41%, of hydrocarbons by 6.2%, of sulphur dioxide by 45%, of carbon dioxide by 37% and of carbon monoxide by 28% and these trends have grown exponentially in the two first decades of the 21st century. Lead emissions are still a major problem. Batteries, while paint, and certain foods are important sources of exposure. Finally emissions from vehicles that run on leaded petrol, still widespread in most of the region's countries, is other the main cause (CEPAL; 2019).

In the case of industrial pollution, during the 1990 s industrial output increased substantially in absolute terms, led by the export sector. The composition of gross domestic product (GDP) changed in the same way as exports, although to a much lesser degree. Meanwhile, a small group of countries managed to reorient their exports on the basis of sectors using more advanced technology, such as.

motor vehicle, electronics and other types of machinery, which are less polluting than traditional exports such as chemicals and hydrocarbon. The effect of technological change on industrial pollution needs to be researched in greater depth. Acording to CEPAL (2020) in Latin America and the Caribbean, CO_2 emissions were 34% higher in 1999 than in 1980, with most of the increase coming since 1994 (in fact, in 1994 total CO_2 emissions were just 18% higher than in 1980, but between 1994 and 1999 they rose steadily by about 2.5% a year).

The trend of emissions per unit of output in relation to per capita GDP does not show a definied or clear direction. The behavior of this indicator is associated with energy consumption structures (sources and sectors) and with changes in the region's production structures during the 2000 s. Latin America, with 8.5% of the world's population, now accounts for 5.4% of world greenhouse gas emissions (CEPAL, 2019). The largest share of emissions in the region is produced by Mexico, with 356 million tons a year. The emissions of Mexico and Brazil account for 53% of the regional total. Although the two countries between them have roughly the same population as the United States, their combined emissions add up to barely 12% of that industrialized country's total. Two thirds of the region's emissions come from the burning of liquid fuels (oil and derivatives), while coal accounts for less than 8%. Emissions per unit of output are fairly small: 0.41 kg of CO_2/US$/GDP at purchasing power parity, as against a world average of 0.67. As regards the relationship between emissions and the total primary energy supply, the region produces 2.1 tons of CO_2 per ton of oil equivalent. This indicator is below the world average because of the substantial role of renewable sources, particularly water, in the regional energy structure (CEPAL, 2020).

Also, Latin America and the Caribbean is the region of the world that, on average, has the greatest availability of water resources. Although it has only a little over 15% of the land area and 8.5% of the population of the world, the region has about one-third of the total world supply of renewable water resources. South America alone has nearly 30% of total world runoff, calculated at 42,650 km^3. The potential water availability per km^2 in South America is double of the world average and is unparalleled in any other region. According CEPAL (2020), Brazil alone has nearly 40% of the region's water resources. In Latin America and the Caribbean, only Haiti, Peru and Barbados suffer from water stress, although there are various areas of other countries which are in this situation (for example, northwest and northeast Mexico, areas of the Pacific coast of South and Central America, extensive areas of Patagonia and some areas of Andean altiplan). Whereas in other regions of the world the population perceives water shortage to be the main limitation on their development processes and has generated a special culture in this respect, in the case of Latin America and the Caribbean there is only an incipient awareness of the need for rational management of water resources because of their relative scarcity. As far as the sustainability of development

is concerned, it is not only the absolute level of availability of water per inhabitant that is important but also, and above all, the rate of change of that indicator, which is going down markedly in most of the countries of the region. The chemicals industry in Latin America is so diverse and large that generalizations about its water use efficiency cannot easily be made (CEPAL, 2019). However, data do not show that the chemicals industry being historically one of the largest industrial consumers of water. In the chemicals industry is for cooling the most prevalent use of water. Many chemical reactions generate heat, and the reaction equipments must then be cooled so that the temperature is controlled at the desired limit and the reaction does not get out of control (CEPAL, 2019). Typically in cooling towers, this heat is dissipated before water is returned to the plant for subsequent reuse and several applications. After an extended period of increase, water cooling demands are now declining. Even though the Latin American chemicals industry's production is still growing, its water use per unit of production has shown a steadily decreasing trend over the last 40 years, which is a relevant data for sustainability purposes. Increased water recycling and production efficiency, and the substitution of air in place of water during certain cooling processes, have all been cited as explanations for the decrease in per unit water use in certain cooling processes, benefiting the sustainability of the region.

Latin America faces another challenge due to its abundance of lignocellulosic waste from agricultural activity: the water footprint (WF) in the production of bioenergy. When compared to other forms of energy, the WF of bioenergy is large. In general, it is more efficient to use total biomass, including leaves and stems, to generate electricity than produce biofuel. For most crops, the WF of bioelectricity is about a factor of 2 smaller than the WF of biodiesel or bioethanol. This difference is caused by the crop fraction that can be used. For electricity, total biomass can be used; for biodiesel or bioethanol, only the oil fraction or starch of the yield can be used. In general, the WF of bioethanol is smaller than that of biodiesel. According to CEPAL (2020), the WF of bioenergy shows large variation, depending on 3 factors: (i) the climate at the location of production, (ii) the crop used, and (iii) the agricultural practice (Fig. 1).

Building on the Millennium Development Goals, the United Nations (UN) Sustainable Development Goals (SDGs) are the cornerstone of the 2030 Agenda for Sustainable Development, billed by the UN as "An Agenda of unprecedented scope and significance." The seventeen ambitious goals, which are intended to be reached by 2030, are conceived as integrated, indivisible, and as balancing the economic, social and environmental dimensions of sustainable development. The seventeen SDGs are organized around five core pillars:

i) "Planet: protecting the environment while ensuring sustainable use and management of natural resources.
ii) People: ending poverty and hunger and ensuring that all human beings can lead fulfilling lives in a healthy and dignified environment.
iii) Prosperity: ensuring environmentally sustainable economic growth, mutual prosperity, and decent work for all.
iv) Partnership: strengthening global solidarity to address inequalities within and between countries, by focusing on the needs of the most vulnerable.
v) Peace: building societies that are peaceful, just and inclusive, and in which human rights and gender equality are respected".

In the particular case of Chemical Engineering, two of the SDG's are mainly addressed: 6 and 12. The Research Topic addressed to SDG 6, from a Chemical Engineering perspective, focuses on waste water treatment technologies, drinking water production and supply. In the case of the Research Topic addressed to SDG 12, it focuses on alternatives to reuse waste and transform it into raw materials or energy resources. Overall, it appears that chemical engineers have the ability to contribute towards sustainability not only by coming up with processes to use resources more efficiently or reducing harmful waste, but primarily by making these processes economically favorable.

In summary, Latin America and the Caribbean are particularly vulnerable to industrial growth, climate change, poor management of hydraulic resources, burning of fossil fuels, contamination of hydraulic and terrestrial resources, high energy waste, which compromise the sustainability of development in many parts of the region. In this sense, research in the area of waste treatment, environmental impact, carbon dioxide capture, energy-saving, and many more issues related to sustainability and circular economy are areas of relevance and current affairs in Latin America. Sustainability offers a viable path for achieving "green" goals across the chemical industry in the Latin American region. There is the potential to develop industrial technologies that could provide goods, services, and products in a way that does not reduce the supply chain of resources, harm the environment and human health, or limit the opportunities and choices for future generations (basic principles of sustainability). Even though sustainability has already started to make a significant impact on the (bio)chemical industry, there are substantial additional benefits that can be derived.

Although most efforts have been oriented towards the development of scientific-technological alternatives for the promotion of sustainable development, in Latin America there are also incipient efforts to encourage sustainability from the educational framework. One example is the work carried out by Rivas et al. (2020a, 2020b). Their work presented the current state of the art, key discussion points, and guidelines for improved Process Iintensification (PI) teaching (remembering that PI is one of the tools of Chemical Engineering that contributes to sustainability), as determined by a group of PI experts with industrial or academic backgrounds, pedagogy experts and government representatives, who met in June 2019 at the Lorentz Center (Leiden, The Netherlands) with the goal of uniting efforts on PI education and producing guidelines. In the first part of the series, they look at the industrial and societal demands for an educational strategy within the context of PI. As a preface to Part 2, which gives practical examples that will aid in educating on Process Intensification, the vocabulary and background information on PI, as well as information on educational application in business and academia, is offered.

Another example of efforts from chemical engineering in the educational sector is the work presented by Hernandez et al. (2021). They mentioned that The resolution of path dependencies and the associated carbon lock-in is critical to Mexico's long-term energy transition. This practical teaching guide proposes using a case-illustration typology to identify and explore how carbon lock-in policies affect Mexico's

Fig. 1 – Natural resources in Latin America and the Caribbean.

sustainable energy transition. When tangible actions are defined by the students and educators, this methodology is an unique endeavor that tries to implement the case study in classrooms with the objective of encouraging conversations and solution-oriented approaches. This approach transforms the case study into a "live" case study that leads to actionable recommendations. The applied teaching guide helps educators, most of whom are researchers, to consider how Mexico's case study could be taught, not only to help students comprehend the issues, but also to give educators/researchers the ability to effectively distribute knowledge. The carbon lock-in in Mexico is caused by oil and oil-fired power plants, which are expensive to create but very inexpensive to operate. To sum up, this case study reveals potential entry points for Mexico's shift to sustainable energy—resources that can encourage clean energy use despite carbon lock-in.

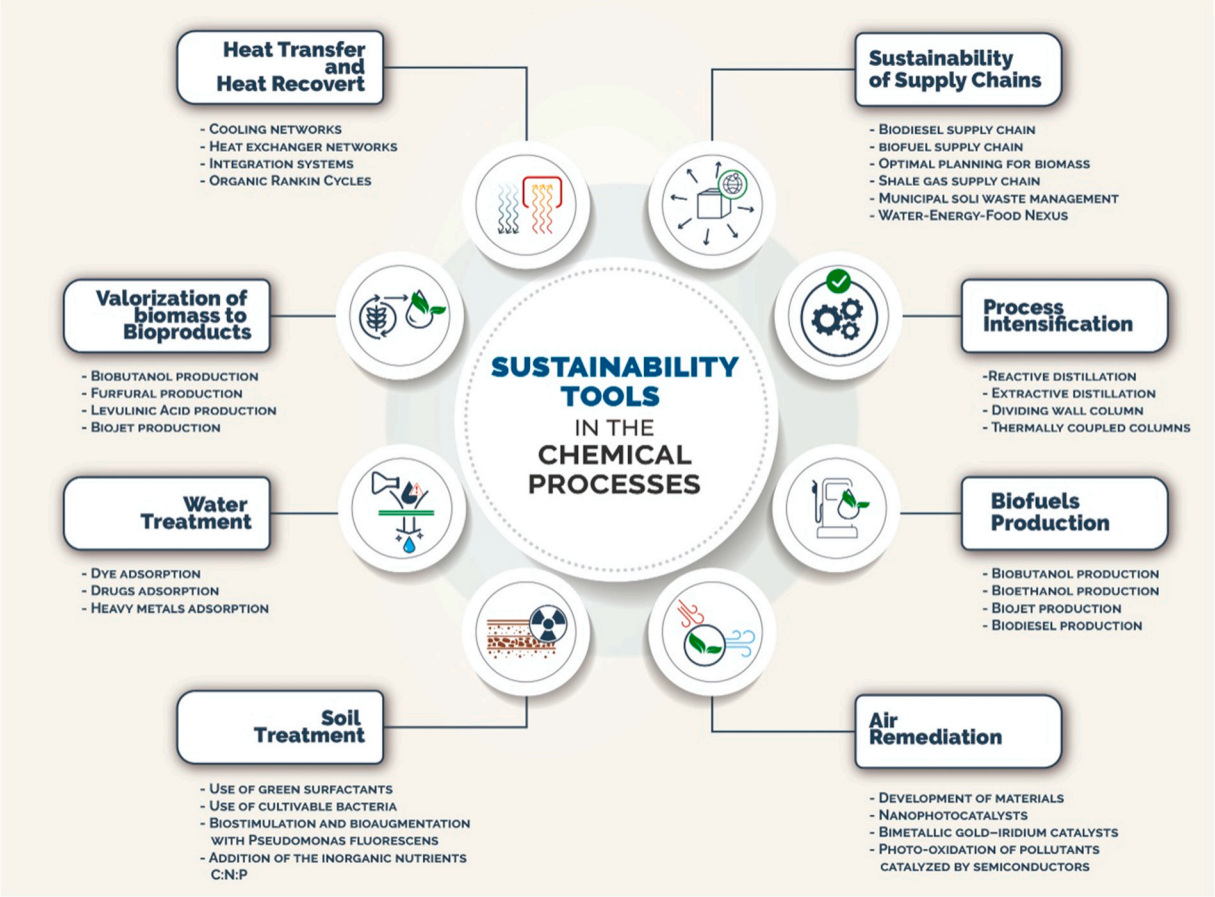

Fig. 2 – Sustainability tools in the chemical processes in research in Latin America region.

The present literature review provide a summary of the current state of the application of sustainability tools in the chemical processes in research in Latin America and forecast what additional beneficial contributions might be in the horizon in the last 25 years. For the preparation of this review article, a search was conducted using scientific databases (scopus) using as keywords the name of the various sections of this article and sustainability. The search was general and limited to the Latin American region. More than 100 papers published in journals and books chapters from the year 1997–2022 have been included in the annotated bibliography. Designed to be a blueprint for a more sustainable future, the 17 Sustainable Development Goals of the United Nations were set and agreed by world leaders in 2015. They address global challenges around inequality, poverty and climate change, and comprise 169 targets for governments, businesses and organizations to strive towards. Were set and agreed by world leaders in 2015. They address global challenges around inequality, poverty and climate change, and comprise 169 targets for governments, businesses and organizations to strive towards. Based on the 17 goals, we divide the different sustainability issues to review for Latin America and the Caribbean into 8 areas as shown in Fig. 2.

2. Heat transfer and heat recovery systems

Industrial operations account for around 26% of Latin America's total energy consumption and are characterized by a variety of energy losses, including heat streams that are ejected into the environment as exhaust gases or effluents at varied temperatures. The energy generated in industrial processes that is not put to practical use, lost, wasted, or dumped into the environment is referred to as industrial waste heat. Reducing or recovering such energy flows can surely help to improve environmental performance while also lowering overall manufacturing costs. As a result, recovering and reusing as much wasted heat as feasible is desirable. Heat transfer is used in almost every process in modern engineering. It plays a crucial role in improving the efficiency of energy conversion systems from this perspective. Furthermore, heat recovery is widely regarded as the most effective way to achieve long-term energy management. Waste heat can be recovered using a variety of technologies in a variety of applications (CEPAL, 2020). This section will discuss new developments in heat transfer technologies and heat recovery systems for sustainable development. While great effort is put into thermal recovery systems, there is always a need to develop and showcase new ideas in this vast industry.

With regard to the research conducted in this area, a search in scopus and refining by country and date yielded the results shown in Fig. 3.

Fig. 3 shows that Latin America has no country in the top 10 of research conducted in this area. Research in this area is led by China, the United States, the United Kingdom and India, with a long distance with the Latin America countries.

The efforts made in Latin America include, for example, Rivera-Ortega et al. (1999). Which offer a method for thermal integration of electrically powered heat pumping systems between intermediate stages in distillation columns based on the notion of column grand composite curve. A four-way trade-off between energy, capital, temperature lift, and

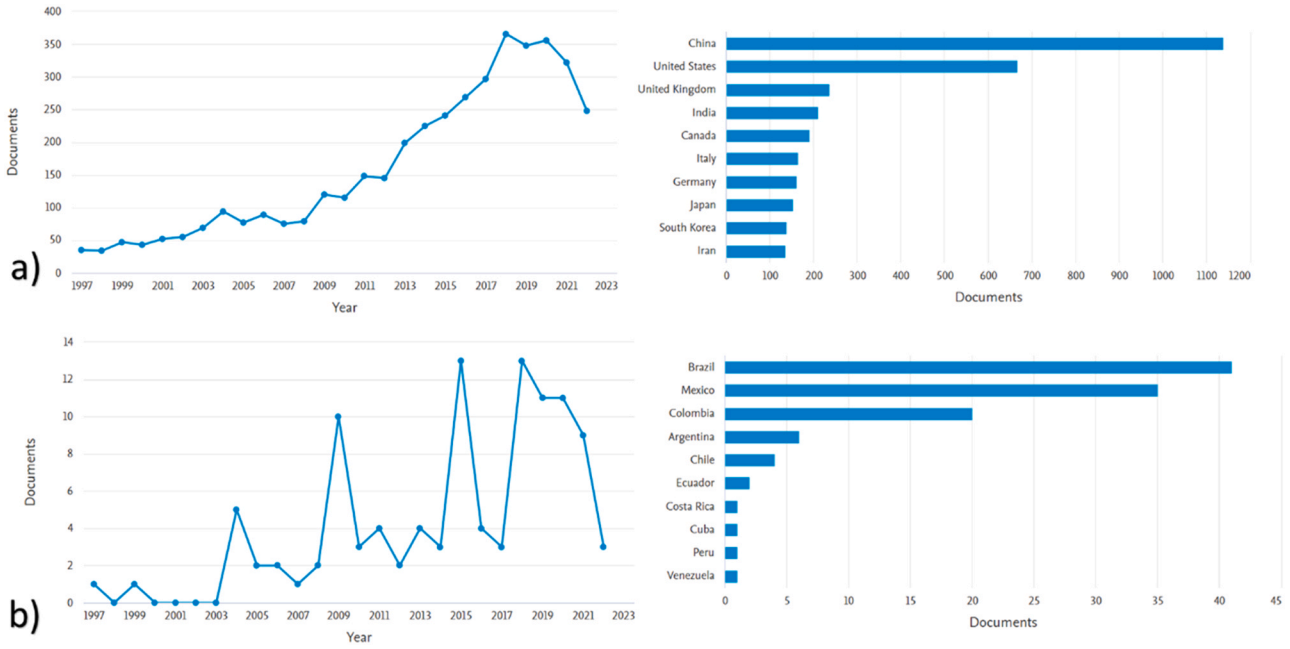

Fig. 3 – Research conducted in Heat Transfer and Heat Recovery Systems, a) International, b) LatinAmerica.

electricity to fuel cost ratio is discussed as part of an optimization approach.

Picón-Nuñez et al. (2002) present the use of steady-state simulations for de-bottlenecking heat recovery networks in a paper. When process streams vary operating conditions such as flow rate and supply temperature, a heat exchanger network intended for fixed circumstances can be de-bottlenecked. A network is said to be flexible if it can function properly in normal and abnormal conditions. Heat recovery network de-bottlenecking can be considered a special case of design for increased flexibility. A single-phase network of heat exchangers simulation model is presented.

Ponce-Ortega et al. (2009) proposed a model that incorporates the synthesis and detailed design aspects of cooling networks at the same time. The model is built on a mixed-integer nonlinear program that is transformed from a generalized disjunctive programming formulation. The goal is to reduce the overall yearly cost, which includes the cost of cold utility consumption, the cost of capital for coolers and pumps, and the cost of pumping. The model employs a stagewise superstructure that allows for series and parallel cooler configurations, as well as cold utility bypass, mixing, and splitting. The model also includes several constraints in order to adhere to specific design guidelines. In addition to the best cooling network topology, the solution includes information on each cooler unit's mechanical design features and thermal-hydraulic variables.

Ponce-Ortega et al. (2010) tackle the synthesis problem of optimal heat exchanger networks employing different utilities. Based on a stagewise superstructure that incorporates all possible matches between hot and cold streams in each stage, a mixed-integer nonlinear programming model is built. Exchanges of process streams with utilities are allowed in each stage of the superstructure, unlike previous MINLP formulations, to find the optimal position of hot and cold utilities. A disjunctive programming approach is used to assess the best combination of multiple types of available utilities. The model can handle isothermal and non-isothermal process streams, as well as forbidden, needed, and restricted matches.

Procedures for the design of systems in which water and energy consumption account for a major part of the running cost are outlined in the study by Polley et al. (2010). Several characteristics distinguish good process design, the most important of which are efficient raw material utilization, cheap capital cost, and good operability. It is demonstrated that the water conservation and heat recovery issues can be separated, and that the water conservation solutions should be implemented first. It is then demonstrated that without having to construct any heat recovery network, the number of heaters and heat recovery units necessary for the system, the amount and kind of hot utility required for the plant, and the complexity of the heat recovery network can all be determined. Before beginning the design of the heat recovery network, the engineer might choose the better water saving alternative.

Lira-Barragán et al. (2013) proposed a new method for energy integration in absorption refrigeration systems. It enables heat transfer between hot and cool process streams, as well as the integration of excess process heat and external utilities such as solar energy, fossil fuels, and biofuels. The social impact is quantified by the number of jobs generated by the project throughout its full life cycle, and an optimization formulation is designed to satisfy the combined objectives of concurrently decreasing total annualized cost and greenhouse gas emissions. The tax credit earned by reducing greenhouse gas emissions when cleaner technologies are adopted is accounted for by the economic function.

A strategy for simultaneously resolving the problem of optimal integration of regenerative organic Rankine cycles (ORCs) with overall processes is provided in the work by Hipólito-Valencia et al. (2013). ORCs may enable the mechanical energy recovery of a significant portion of low-temperature process surplus heat (i.e., waste heat from industrial processes). The optimization problem is described as a mixed-integer nonlinear programming problem based on the integrated superstructure to account for capital and operational costs, as well as revenue from the sale of the integrated system's shaft power.

Fouling is currently a major industrial issue with serious economic and environmental consequences. The use of dynamic fouling models in thermo-hydraulic simulations (such as those for chemical reaction fouling in pre-heat trains processing crude oil and mass transfer controlled fouling in cooling water systems) allows one to identify and propose industrially relevant and practically viable fouling solutions. When contemplating retrofits, this knowledge must be integrated with a heat recovery network study to produce reliable options. These points are illustrated in Polley et al. (2013).

Lira-Barragán et al. (2014) proposed a unique strategy for constructing sustainable trigeneration systems (i.e., heating, cooling, and power generation cycles) that are integrated with heat exchanger networks and account for economic, environmental, and social challenges all at the same time. The steam and organic Rankine cycles, as well as an absorption refrigeration cycle, make up the trigeneration system. The steam Rankine cycle is powered by a variety of sustainable energy sources, including solar energy, biofuels, and fossil fuels. The goal of the model is to establish the best working fluid for the organic Rankine cycle and the best system for the absorption refrigeration cycle. Both the organic Rankine cycle and the absorption refrigeration cycle may be performed using the remaining energy available in the steam Rankine cycle and/or process extra heat to create electricity and refrigeration below the ambient temperature, respectively.

A multiobjective optimization strategy for synthesizing water distribution networks integrating dual-purpose power plants is provided in a publication by González-Bravo et al. (2016). By accounting for greenhouse gas emissions, jobs, and net profit, the suggested model accommodates for environmental, economic, and social goals. Water and energy demands for home, agricultural, and industrial users are all factored into the model. Fossil fuels (natural gas and oil), biofuels (biomass, biogas, biodiesel, and bio-alcohols), and solar energy are all viable options for generating energy. Fresh water from dams, lakes, rivers, aquifers, and manmade storage tanks is used to meet water demands. The findings demonstrate the practicality of dual-purpose powerwater plants, the advantages of introducing solar energy into the system, and the economic, environmental, and social benefits of implementing the recommended strategy.

In the same optimization framework, a large paper divided into three articles from Professor Bagajewicz's research group presented the optimal design of heat exchanger networks under three approaches: minimal networks, non-minimal netwoks, and non-isothermal mixing in minimal and non-minimal networks (Chang et al. 2020, 2020a, 2021). His work was relevant for the introduction of the concept of minimal structures and its extension to various cases and constraints.

In many places of the world, water desalination looks to be an appealing option for providing fresh water. However, because of the high energy consumption, this process is highly expensive, and as a result, enormous pollution is created as a result of the burning of fossil fuels, which produces massive CO_2 emissions. Furthermore, most desalination procedures generate a significant amount of waste heat at low temperatures that may be recovered. As a result, González-Bravo et al. (2017) provide an optimization strategy for constructing water desalination systems that incorporates heat integration and waste heat recovery in order to minimize desalination costs, energy consumption, and overall greenhouse gas emissions. The suggested method integrates waste heat recovery systems and provides for the appropriate selection of existing and new desalination technologies based on heating and cooling requirements.

Picón Nuñez and Melo-González (2020) proposed an alternate method for determining the best turbulence promoter for heat transfer intensification in tubular heat exchangers. The thermal and hydraulic lengths are calculated based on the heat duty and pressure drop, which are the two fundamental design objectives of a heat exchanger. Exchanger dimensions in the form of plots of exchanger length are created to find the device that results in the smallest equipment size within the pressure drop limitations. The V-cut twisted tape, the square-cut twisted tape, and the straight tape with center wings are the turbulence promoters that display the biggest heat transfer enhancement with the lowest pressure drop out of a set of 25 distinct types of turbulence promoters investigated.

Picón-Nuñez and Rumbo-Arias (2021) aimed to demonstrate the application of welded plate heat exchanger (WPHE) technology in energy recovery systems to minimize the number of units and the possible advantages in project remodelling. The use of multifluid units in heat exchanger networks allows for a decrease in the number of units. The unit dimensions that meet the requisite heat duty within the pressure drop limits are determined using a thermohydraulic model. A crude oil preheat train with 12 heat exchangers is used to show the approach to multifluid instances. Various possibilities for network structure simplification are considered, but with the potential of adopting multifluid structures, two choices are considered: the reduction to seven units and the reduction to three units.

Through the use of heat exchanger networks and thermal engines, López-Flores et al. (2021) provide an innovative strategy to recovering industrial waste heat and integrating it into utilities, refrigeration, and power production (steam Rankine cycle, organic Rankine cycle, and absorption refrigeration cycle). Iteration between metaheuristic deterministic optimization algorithms is used to arrive at a solution. To acquire reliable modeling results, the MS Excel-VBA-Aspen Plus connected metaheuristic optimization is created.

The main goal of thermal integration in an industrial process is to ensure that the process's heat duty and temperature level are met. Other key goals must be addressed when integrating solar thermal energy into industrial processes, as the goal is to optimize its utilization. Martnez-Rodrguez et al. (2022) offered a thorough integration of solar thermal energy based on the Pinch Analysis and taking into account economics and environmental effect.

Similarly, unique heat exchanger design strategies have been generated. Note, that the majority of the articles that addressed this subject employed closed-form analytical solutions to describe the behavior of the equipment, such as the logarithmic mean temperature difference (LMTD) and effectiveness (ε-NTU) approaches. These analytical answers are based on the hypothesis of uniform values of the physical parameters and heat transfer coefficients. This assumption may indicate large inaccuracies in numerous scenarios. Aiming at overcoming these restrictions, Nahes et al. (2021) introduced a novel integer linear model for the optimal design of hairpin double-pipe heat exchangers. Their method discretizes the temperature field inside the exchangers and, coupled with suitably rigorous reformulations, gives a linear

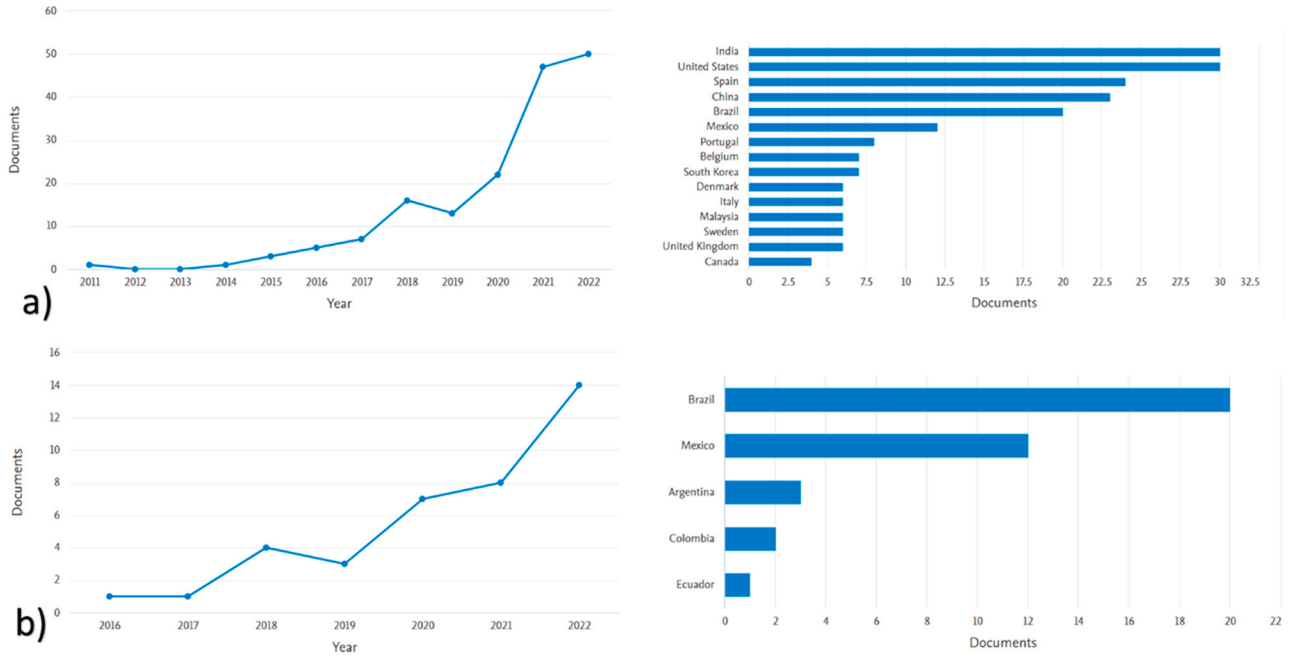

Fig. 4 – Research conducted in Valorization of biomass to Bioproducts, a) International, b) LatinAmerica.

model. Numerical findings highlight the performance of the suggested approach, revealing that the analytical solutions can drastically undersize or oversize the heat exchanger.

Finally, it is commonly said in the literature on the subject that energy policy has tended towards a sustainable approach to the exploitation and use of energy sources. Despite this general orientation, though, and notwithstanding the growth seen in per capita energy consumption, the region is a long way from having achieved adequate levels of efficiency in energy transformation and use. This is demonstrated by the stagnation of energy intensity (measured by energy consumption per unit of output), which is accounted for, among other factors, by the limited use made of energy-efficient technologies, the obsolescence of the industrial base and the high and inefficient consumption of the region's vehicles (CEPAL, 2020). It should be noted that the shift in the industrial composition of certain countries in the region (particularly Brazil) towards energy-intensive industries and, again in Brazil, the shift in the composition of tradable exports towards energy-intensive products (CEPAL, 2019). In this sense, the advances made in research in Latin America in the area of heat and energy integration have followed world trends regarding the pertinent strategies to solve the problem in a sustainable manner and have even proposed original methodologies that have contributed to growth. of the state of the art of the topic under analysis.

3. Valorization of biomass to bioproducts

The region is noted for its vast natural resources, including water, land and biodiversity, all of which are becoming increasingly crucial in a bio-based society.The area of Latin America and the Caribbean (LAC) is well positioned to contribute to and profit from the burgeoning bioeconomy. The fast agricultural revolution taking place in many nations, as well as the region's quick evolution into a world leader in the exploitation of biofuels markets and new agricultural technology, are significant indicators of this potential. Rapid examination of demand and supply parameters and indicates that the LAC area will play a vital role in reaching the requisite new global equilibriums in any future scenario. At the same time, the region faces its own challenges. Poverty and hunger, while not as severe as in other regions of the developing world, remain major concerns in the region, particularly in rural areas (CEPAL, 2019). Biomass production and agriculture are becoming critical components of any poverty and hunger reduction plan. In this framework, the bioeconomy in Latin America has two targets: a) new source of prospects for fair growth through enhanced agricultural using the bioeconomy and b) biomass production at the global level, while enhancing environmental sustainability within the region's borders. The transition to a LAC bioeconomy also provides the opportunity to move beyond the dichotomist vision of industrial vs agricultural development that has dominated development strategy discussions since the 1980 s, as industry-agriculture expand beyond traditional views to include a much more complex and strategic set of input-output relationships.

International and regional research has focused on particular countries. As shown in Fig. 4, the leaders in research on these topics are India, the United States and Spain. However, in these particular topics, Brazil and Mexico do appear in the top 10 countries conducting research that includes these keywords.

Interesting research has been conducted regionally. For example, Santibáñez-Aguilar et al. (2011) provide a multiobjective optimization model based on a mathematical programming formulation for the optimal design of a biorefinery, taking into account the processing technology, best feedstock and product set. Environmental effect minimization and profit maximization are both considered simultaneously in the multiobjective optimization problem. The economic goal function takes into consideration processing restrictions, bioresource availability and product demand, as well as product, feedstock and processing route costs. The environmental evaluation, on the other hand, considers the total environmental effect as evaluated by the eco-indicator-99.

An important component of the Mexican economy is the tequila business and it is linked to various agave (the plant

used to manufacture tequila) wastes, which are lignocellulosic matter that may be utilized as a bioethanol feedstock. Agave leftovers are sourced from harvesting sites in numerous Mexican states, as well as tequila distilleries, which are mostly situated in two locations in Mexico. An optimization framework for creating a supply chain for bioethanol production from agave bagasse leftovers collected during tequila processing in Mexico is studied by Murillo-Alvarado et al. (2014), which takes into account both spread and central bioethanol processing units. The bioethanol production process in dispersed and central facilities is modeled using conversion factors derived from experimental data for the various processing phases. The suggested optimization method also takes into account the overall amount of agave available and the demand for bioethanol in Mexico.

Quiroz-Ramírez et al. (2017) provided a multiobjective optimization to acquire the best butanol production planning, taking into account the best feedstock selection. Butanol purification and fermentation were both carried out using this multiobjective technique. As objective functions in the multiobjective optimization problem, the total yearly cost and environmental effect are minimized. The cost of feedstocks, the availability of bioresources, fermentation conditions, and separation units are all factors considered by the economic target function. The environmental evaluation comprises the total impact, which is quantified using the eco-indicator 99. Both objective functions were used in a case study for the best biobutanol production planning in Mexico. In the same line, in a second paper, Quiroz-Ramírez et al. (2017) used lignocellulosic material to model and optimize a process for producing acetone, ethanol and butanol. To complete this work, raw material selection was planned, followed by simulations of intensified simultaneous saccharification, fermentation, and separation –reactors. The fermentation stream was purified using three intensified purification arrangements. Through a stochastic technique, the entire enhanced process was assessed under an optimization process that considered economic, environmental and energy objectives. The results indicates that the optimal configuration for producing and purifying butanol is one that takes into account thermally coupled columns.

The modeling of conventional and enhanced hydrotreating methods to produce biojet fuel was presented by Gutiérrez-Antonio et al. (2018a, 2018b) in two papers. Microalgae oils and Jatropha curcas are considered renewable raw resources for all hydrotreating procedures. The works demonstrate that all hydrotreating procedures have identical total yearly costs. However, the traditional structure's CO2 emissions are 34% greater than those displayed for an enhanced alternative approach. As a result of the enhanced hydrotreating, biojet fuel may be produced with minimal environmental effect and at a competitive price when compared to fossil jet fuel.

García-Sánchez et al. (2019) devised an improved three-step hydrotreating reaction-separation method for the generation of bio-jet fuel from triolein and petro-diesel mixtures. The effect of several operational factors (oleic acid-petro-diesel feed ratio, triglyceride-water feed ratio, hydrogen consumption) on the performance of the intensified reactive-separation scheme was worked using complex simulations. The total pressure for the heterogeneous catalytic hydrolysis reactor and water excess are key operating and design parameters for the production of biojet fuel, and if high molar flows of fatty acid are considered, it is compulsory to have more reactive stages in a reactive distillation column to achieve ultra-clean (no-sulfur) petro-diesel at the bottom flowrate of the column.

The hunt for alternative energy sources has been prompted by environmental degradation caused by the excessive use of fossil fuels to create power to meet rising demand. Residual biomass from various crops has been suggested as an option in this area. However, there are considerable drawbacks to this energy source, mostly because of its and high transportation costs low density. An optimization technique for the utilization of waste biomass pellets in power plants for electric energy generation is provided in the study by Martínez-Guido et al. (2019). All operations in the supply chain: from the collecting of wastes until the burning of pellets in power plants are evaluated. The design and placement of pelleting facilities in a macroscopic region, as well as the transportation routes and biomass are all taken into account to meet the demands of power plants at the least environmental effect and with the lowest cost.

After bean harvesting, coffee cut-stems (CCS), a biomass with a high lignocellulosic content, is a coffee crop waste. The primary use of this material is as agricultural fuelwood, regardless of its carbohydrate content for biotechnological operations. In this context, Aristizábal-Marulanda et al. (2020) analyze three process scenarios for the experimental valorization of C5 fraction from CCS to create furfural and biogas with and without the manufacture of bioethanol from the residual C6 fraction. As a result, an experimental step based on a previously diluted acid pretreatment was carried out to acquire these products. Biogas and furfural were produced from the hydrolysate fraction.

Furfural is a versatile chemical that may be used as a fungicide extractant base, a solvent or a platform for other chemicals. The simultaneous optimization of control qualities and design parameters, which are extremely significant goals according to green chemistry principles, is done inside the reaction zone in the process of production of urfural from biomass in the work by Romero-García et al. (2020). The multiobjective optimization is carried done using the Differential Evolution with Taboo List method. As environmental, economic and controllability criteria, which indicate the goal functions for a sustainable process, are combined.

Fish oil is a healthy substance that contains omega-3 polyunsaturated fatty acids, which are known for their health advantages. Many seafood enterprises dump fish oil as waste due to a long-term refinement procedures and lack of profitable. Monsiváis-Alonso et al. (2020) addressed issue by offering a methodology for integrating environmental, economic, and social factors into crude fish oil refinery process design decisions. The synthesis of omega-3 polyunsaturated fatty acids concentrations from waste oil from a tuna processing company in Mexico exemplifies the framework's studied. This is handled by modeling and solving a multi-objective optimization problem.

The manufacturing and characterisation of pellets derived from rice husks and wheat straws are given in Ríos-Badrán et al. (2020). The physicochemical and energetic characterization of pellets made from rice husks and combinations of rice husks and wheat straws was carried out for this, followed by a comparison with the ISO 17225–6 parameters. The rice husk pellets had the lowest calorific value and the most ash, whereas the mixed pellets had the highest calorific power and the least quantity of ashes. Furthermore, pellets made from both biomasses exceeded moisture, ash,

and nitrogen content while meeting diameter, length, and durability requirements. These findings imply that biomass mixes increase pellet quality and combustion characteristics, paving the way for more study into the production of sustainable biofuels.

The mechanical extraction of Jatropha curcas L. oil using a screw press type expeller is the subject of a research by Yate et al. (2020). The extraction method was tested under various operating settings to see how it affected oil production, oil recovery, extraction capacity, energy intensity, and the qualities necessary for use as a drop-in biofuel or biodiesel feedstock.

Romero-Izquierdo et al. (2021) offer modeling and simulation of the alcohol-to-jet fuel (ATJ) conventional process using bioethanol generated from lignocellulosic wastes as the raw material. Process intensification technologies are used on the separation zone, followed by energy integration of the entire process, to minimize energy needs and environmental effect. The total yearly cost and CO_2 emissions of the ATJ conventional and intensified-integrated processes are compared. In comparison to the conventional sequence, the intensification on the separation zone allows for a 5.31% reduction in energy requirements; additionally, the energy integration of the intensified process reduces the heating and cooling requirements by 34.75% and 30.32%, respectively; as a result, the total annual cost and CO_2 emissions are reduced.

To improve the oleochemical industry's sustainability, waste lipids will be used to make more value-added and green chemicals in the future. Waste lipids, on the other hand, are very heterogeneous and include a wide range of contaminants that might obstruct possible valorization pathways. As a result, refining methods are required to acquire acceptable oleochemical feedstocks. The present and possible methods for the pre-treatment, purification, and refining of waste lipids are reviewed by Cárdenas et al. (2021), with a focus on the transformation of used cooking oils (UCOs) into oleochemical raw materials (UCOs can be exploited as second-generation raw materials for the synthesis of green chemicals, in particular for biobased epoxides and polyols). Initially, an overview of global UCO production and supply is provided, as well as some prospective valorization options. The chemical nature and content of typical UCOs are next evaluated, as well as the primary physicochemical features, in order to discover effective impurity removal separation procedures. Acidity and moisture reduction are particularly important because they influence subsequent thermal, chemical, and biological reactions. To allow its usage as fermentation substrates or as a raw material for a value-added application, hazardous chemicals must also be eliminated. To improve sensory characteristics and minimize detrimental consequences during further transformations, nitrogen, phosphorus, and sulfur-containing molecules, as well as polar components, must be eliminated. In a similar vein, Rincón et al. (2021) evaluated several UCO pretreatment procedures in order to create an acceptable feedstock for further valorization. Prior to processing, UCOs were collected from chicken restaurants in Bogota, Colombia, and described. Physical and/or chemical pretreatment was carried out using water degumming, filter earth adsorption, hydrogen peroxide bleaching, and solvent extraction, similar to edible oil refining (methanol, ethanol, isopropanol). The success of treatment was evaluated in relation to the original features of UCOs. Tracking the change in the photometric color index and describing acid value and polar component concentration in bleached samples were used to characterize the samples.

The growing energy demand in the transportation sector has prompted researchers to look for alternative biofuels production methods that have lower manufacturing costs, more process efficiency, and better environmental performance. Lignocellulosic biofuels are comparable to petroleum products and may be tailored to fit the needs of modern engines. Their significant drawbacks, however, are high manufacturing costs and a lack of infrastructure. The focus of Ibarra-González et al. (2021) is on the deployment of a multi-objective optimization technique for the synthesis of innovative intensified biomass-to-liquid (BtL) technologies with reduced environmental impact, prices, and process safety and efficiency. The evaluation of a BtL processing superstructure under multiple economic restrictions and product profile scenarios was undertaken using an unique optimization approach applied to two process configurations. The two case studies with the highest output of both gasoline and diesel were chosen for this study from the configurations. The ideal separation unit design parameters that meet the combination of economic, safety, and environmental indices, as well as two green chemistry metrics, were chosen for the synthesis of intensified BtL technologies.

Biochemicals made from lignocellulosic waste look to be a viable replacement for traditional fossil fuels. However, obstacles such as biomass seasonality, feedstock selection, harvest selection, prospective geographical biorefinery site, and various economic, environmental, and social constraints must be solved before they can be implemented. Contreras-Zarazúa et al. (2019) present a multi-period supply chain model for the manufacture of platform biochemicals like furfural from agricultural wastes. The most prevalent lignocellulosic residues in Mexico are considered. Furfural was picked as a requirement because it can replace the feedstocks used to make the terephthalic acid imported into Mexico. The supply chain solution was evaluated based on economic, environmental, and social goals. The maximum of net profit is the economic component. The environmental goal is to reduce eco-indicator 99, while the social goal is to increase the number of employment created. The findings demonstrate that furfural synthesis in Mexico to replace present raw materials is viable.

Lignin is abundant in biomass sources, and its aromatic structure makes it a viable candidate for usage as a precursor or platform for the production of value-added chemicals. In the pulping industry, however, lignin is regarded as a low-cost by-product or low-value fuel for energy recovery. As a result, the development of technologies and techniques that enhance the valorization and effective exploitation of this biopolymer, particularly in biorefineries, becomes a critical feature of biobased processes. Poveda-Giraldo et al. (2021) demonstrated the possibility of using thermochemical, chemical, and biochemical methods to target lignin as a viable by-product for value-added compounds, with or without the use of catalysts. Similarly, lignin valorisation incorporates new processes for producing carbon and polymer compounds. This research also focuses on describing the technological, economic, and environmental factors that impact lignin in various biorefinery stages.

Butanol is an intriguing biofuel and product precursor that can be made by fermenting acetone and ethanol. Biofuel manufacturing has been found as being unprofitable; thus, parallel production of high-value-added goods, such as

xylitol, might be a viable alternative. Xylitol may be made from xylose, a coproduct of a second-generation biorefinery. Based on experimental and computational methodologies, Morales-Rodríguez et al. (2021) offer a systematic biorefinery process design for simultaneous acetone, butanol, ethanol (ABE), and xylitol synthesis. Experiments on sugarcane bagasse pretreatment and ABE fermentation were conducted. To undertake robust calculations of the ABE and xylitol manufacturing processes, the simulation section employed experimental findings and experimental data from the literature. The economic analysis was conducted using indicators such as net present value and payback period; the EA covers many scenarios for generating solely ABE as well as scenarios for producing ABE and xylitol simultaneously. When compared to merely generating butanol, the results revealed that combining butanol and xylitol production might cut the selling price of butanol by 17%. The study also looked at residual solids combustion and carbon dioxide depletion.

Combustion of leftover (waste) biomass is both environmentally hazardous and economically inefficient. The manufacturing of specialized chemicals is a more appealing approach to dispose of residual biomass; nevertheless, one issue with recovering goods from waste is that there are presently no well-established marketplaces that bring all parties involved together (e.g., biomass production, collection, transportation, and processing). Because all stakeholders in the supply chain (SC) rely on the money provided by the derived products, coordination is critical. We propose a market coordination framework for levulinic acid and furfural synthesis from lignocellulosic biomass in this paper (obtained from agricultural residues). Coordination provides significant economic benefits that would be impossible to obtain under current market conditions (which are uncoordinated and based on peer-to-peer transactions). Alcocer-García et al. (2019) used a case study for the Mexican state of Guanajuato to demonstrate the insights provided by our framework. These findings imply that 330,0 0 0 tonnes of levulinic acid and 394,0 0 0 tonnes of furfural may be produced per year. This accounts for 3% of worldwide methyltetrahydrofuran consumption each year.

Sotol (Dasylirion spp.) is a plant native to northern Mexico that has been utilized by North American Indians from prehistoric times. The transformation of lignocellulosic Sotol Bagasse (SB) components as a feedstock for bioethanol 2 G production was explored by González-Chávez et al. (2022). SB was processed with dilute acid (AP) and alkali for this purpose (BP). In AP, biomass was exposed to various acid concentrations, and reactions occurred at various periods based on a 32-experiment design. The sugars were fermented in the presence of Kluyveromyces marxianus, yielding an ethanol yield of 81.85%. Fermentation also produced ethanol as well as modest levels of iso-butanol, acetaldehyde, and isoamyl alcohol. These findings demonstrated that the suggested technique is viable and may be utilized to produce bioethanol 2 G.

Biocompounds such as flavonoids, anthocyanins, betacyanins, and betalains may be found in the peel of the prickly pear (Opuntia streptacantha). Two techniques are usually utilized to get its biocompounds: drying and extraction. These traditional procedures, however, frequently lack the concepts of sustainability and circular economy. The design and multi-objective optimization to produce sustainable processes are presented in the work of Gómez-Salazar et al. (2022). The above is based on a hybrid stochastic algorithm of a drying process and subsequent extraction of the bio components found in the red prickly pear peel, taking into account multi-objective cost minimization and CO2 emission reduction. The model was created using experimental data collected under various drying circumstances and then extracted using one of two methods: traditional or microwave-assisted extraction. Multi-objective optimization was used to find the ideal conditions for extracting biocompounds from red prickly pear peel in a long-term manner.

In summary, the production of bio-based chemicals is not new. Current global bio-based chemical is estimated to be around 50 million tonnes (20% of this production is generated in Latin America). From a technical point of view, almost all industrial materials made from fossil resources could be substituted by their bio-based counterparts (Segovia-Hernández et al. 2021). However, the cost of bio-based production in many cases exceeds the cost of petrochemical production. Also, new products must be proven to perform at least as good as the petrochemical equivalent they are substituting and to have a lower environmental impact. The low price of crude oil acted as a barrier to bio-based commodity chemical production and producers focussed on the specific attributes of bio-based chemicals such as their complex strucFture to justify production costs. Also, the consumer demand for environmentally friendly products, population growth and limited supplies of non-renewable resources have now opened new windows of opportunity for bio-based chemicals and polymers (Segovia-Hernández et al. 2021). The Latin America industry is increasingly viewing chemical production from renewable resources as an attractive area for investment. In this sense, the research carried out on the subject in the region will allow industries to incorporate local technological developments in the generation of bioproducts.

4. Water treatment

The Community of Latin American and Caribbean States recognizes 33 sovereign countries in Latin America and the Caribbean (LAC), as well as a number of small dependent territories. The sovereign countries cover 20.5 million km2 (15.2% of the total land surface of the planet) and had a population of 609 million people in 2012 (8.6% of the global population) (Mekonnen et al. 2015). LAC's total renewable water resources are estimated to be at 18.5 billion m3/year, or about 34% of global resources (Mekonnen et al. 2015). As a result, the water resources in LAC are rather abundant. There are, nevertheless, significant regional variances. While some countries, such as Guyana and Suriname, had total renewable water resources of 318 103 and 228 103 m3/capita/year in 2012, others, such as the Bahamas, Barbados, and Saint Kitts and Nevis, had values as low as 57, 291 and 444 m3/capita/year (Mekonnen et al. 2015). Agriculture accounted for 68% of total freshwater withdrawals in LAC in 2011, while the industrial and household sectors each accounted for 11% and 21% (Mekonnen et al. 2015). The relative amount of water and residual arable land, combined with global trade liberalization, has increased LAC's position as a global exporter of agricultural commodities. Between 2000 and 2012, agricultural output climbed by more than 50%, with Brazil's output increasing by more than 70%. Rain-fed agriculture produces the majority of the food in LAC, accounting for 87% of the total agricultural area (Mekonnen et al. 2015). Agricultural growth in LAC is desirable in order to improve the

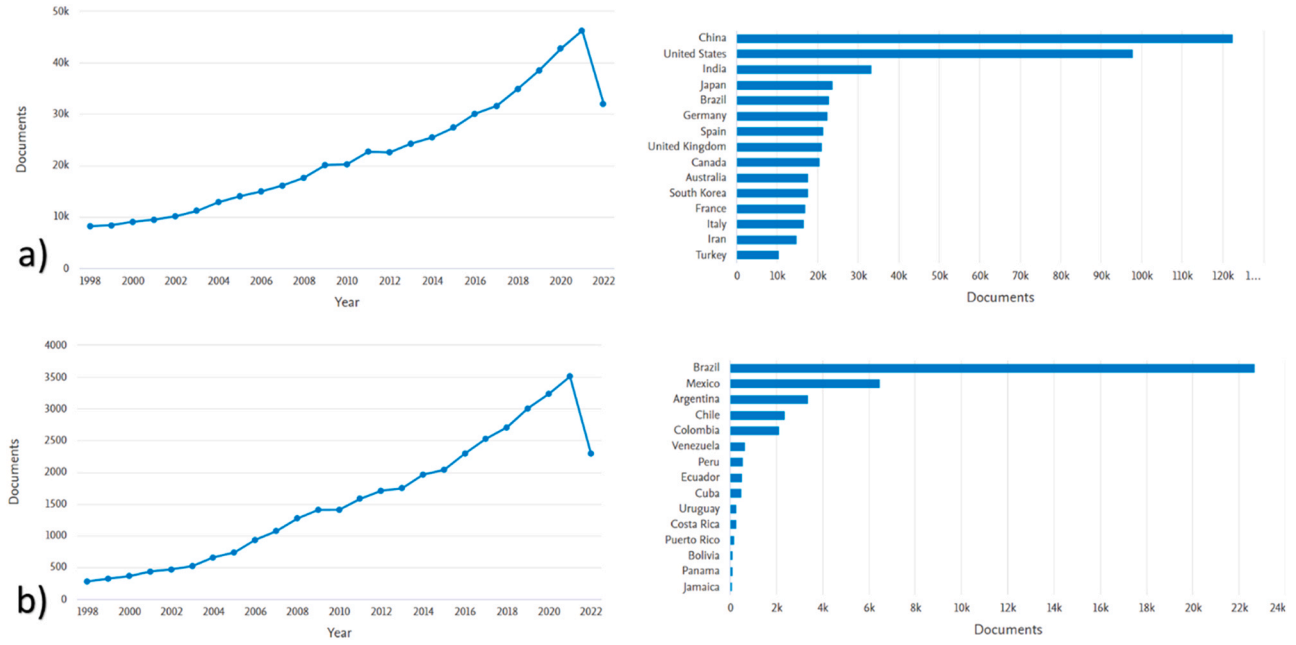

Fig. 5 – Research conducted in Water Treatment, a) International, b) LatinAmerica.

region's economic and social conditions, as well as to enhance food production for LAC and the rest of the globe, which can help to relieve strains on the world's freshwater resources and food security. This, however, must be done in a long-term manner, taking into account both changes in production processes and consumer behavior (Mekonnen et al. 2015). Significant climate differences exist within the LAC region, as well as varying levels of economic development within and between countries, vast social inequalities, a lack of appropriate accounting systems and transparency, and flaws in public administration and institutions that make policy implementation difficult. River basin managers need precise data on real water availability per basin for long-term water allocation planning, taking into account basic human needs, environmental water requirements, and the basin's ability to absorb pollution.

Furthermore, one of the major side effects of the global industrialization revolution is the introduction of wastes that may have a serious detrimental influence on both the ecosystem and human health. Because these compounds have mutagenic and carcinogenic properties, such as synthetic dyes, metals, drugs, and medicines, improper management and frequent discharge of these wastewaters into the environment pose a potential risk to ecosystems and populations, including significant damage to aquatic systems (Abu Sharib et al. 2021). As a result, in the coming years, developing low–cost and effective systems for water purification and recycling will be critical.

Latin America has contributed a significant number of papers in this area. Scopus reports the data presented in Fig. 5. However, the largest number of papers is contributed only by Brazil, which is in the top 10 of research. In Latin America, Brazil evidently leads in research, followed by Mexico, Argentina and Chile.

With this background, this section aims to present recent advances in water treatment for sustainable development. Efforts have been oriented to the treatment of water contaminated with chemical compounds of diverse origin, hydrocarbons, antibiotics, heavy metals, dyes, etc.

Anthropogenic contamination comes from the direct discharge of wastewaters from the textile, plastic, leather, cosmetics, paper, printing, and food processing industries into the environment. These industries are defined by the use of dyes as feedstocks in a variety of processes, necessitating the use of appropriate treatment technologies to lower the concentration of these pollutants in industrial effluents. Several dye compounds employed in industrial processes are carcinogenic, poisonous, and persistent in the environment, posing a threat to aquatic creatures and people. In this regard, several efforts have been made to develop strategies for the treatment of water with dyes. For example, in batch tests, Santander et al. (2020) used a cationic polymer (Amberlite IRA 402) and varied experimental factors such as resin amount, MO concentration, optimal interaction time, and pH. Following the kinetics of the pseudo first-order model in the adsorption process, the resin's maximum adsorption capacity was 161.3 mg g1 at pH 7.64 at 55 C and a contact duration of 300 min. The infinite solution volume model demonstrates that the film diffusion mechanism controls the adsorption rate. They conducted a thermodynamic research and discovered that when the temperature rises, the sorption capacity increases.

Rondán et al. (2020) employed anodic Fenton treatment (AFT). They concentrated on treating small volumes (90–350 mL) and low concentrations (20–400 M) of organic contaminants in short treatment times using three different bench-scale splits (salt bridge or ion membrane) reactors (2–40 min). Several trails with various H2O2 concentrations continually introduced were used to find the ideal experimental condition for AFT. A modified AFT reactor is proposed in this paper: a divided electrochemical flow cell (7.58 ×10–3 m s-1) with a treated cation permeable membrane separating the catholyte from the anolyte. This electrochemical method was employed to treat 2 L of aqueous solutions containing 1 mM acid orange 7, 0.5 mM methylene blue, and 0.12 mM reactive black 5. (RB5). At the start of the electrolysis, the requisite stoichiometric amount of H2O2 was added in a single dosage. All dye solutions were nearly

completely discolored after 40 min of electrolysis, with COD reductions of 85%, 84%, and 76% for AO7, MB, and RB5, respectively. Additionally, utilizing the suggested AFT reactor, an industrial textile effluent (300 ppm COD) was successfully oxidized in 40 min of electrolysis, decreasing 95% of the initial COD.

In the same research scope, Paz et al. (2021) created a CeMOF@Fe3O4 @activated carbon composite for the treatment of colored wastewater. At pH 7, the composite removed 97–98% of indigo carmine and methylene blue, compared to 83–85% for activated carbon. The Temkin and Elovich models were used to calculate the adsorption and kinetic data, respectively. This suggested that physicochemical forces were involved in the adsorption process. The thermodynamic analysis indicated that the adsorption process is endothermic, with better adsorption efficacy as the temperature rises. The adsorption of dyes onto the adsorbent was confirmed by the enhanced intensity of the bands at 824 cm^{-1} (CAH) and 1004 cm^{-1} (aromatic C@C) in the Raman spectra. The N 1 s peak at 400 eV for CAN@C in the dye-adsorbed composite further demonstrated dye adsorption. The involvement of electrostatic and cation-p interactions in the adsorption process was inferred by a 0.3–0.4 eV shift in the binding energy of Fe 2p and Ce 3d peaks. The adsorbent's dye removal capability of 90–98% even in the fourth cycle makes it a very stable and reusable adsorbent for colored wastewater cleanup.

López-Miranda et al. (2021) manufactured homogenous gold nanoparticles extracts from Sargassum species. The features and content of the nanoparticles were determined using a variety of approaches. The degradation of organic dyes methylene blue, methyl orange, and methyl red was used to test the gold nanoparticles' catalytic activity. The degradation rates varied based on the nature of each dye; methylene blue was the easiest to degrade, while methyl red was the most difficult. The findings suggested that using Sargassum spp. to synthesize gold nanoparticles could be useful in the treatment of water tainted with organic dyes. Furthermore, given the current major environmental and economic concerns caused by Sargassum spp. overpopulation in the Mexican Caribbean, the findings offer the potential for practical and long-term usage in nanomaterial fabrication.

Continuing with the development of materials, Jaramillo-Fierro et al. (2020) produced $ZnTiO_3/TiO_2$ using the sol-gel method. SEM pictures reveal that $ZnTiO_3/TiO_2$ particles have a typical particle size of roughly 100 nm and a quasi-spherical shape. The decolorization of Methylene Blue (MB) as an organic contaminant under UV irradiation in TiO_2 and $ZnTiO_3/TiO_2$ supported over different Ecuadorian clays was examined for adsorption and photocatalytic activity. The materials tested were cylindrical extrudates with a diameter of 0.2 cm and a length of 1.0 cm. After 150 min of irradiation, the degradation percentage of MB was roughly 85%. We may conclude from the results that these synthesized materials can be employed as adsorbents and photocatalysts.

Research aimed at the remediation of water contaminated with dyes is not only limited to the development of materials. There are also works oriented to the physicochemical modeling of adsorbents used to treat dyes. For example, Sellaoui et al. (2021) used a multilayer statistical physics model to produce a theoretical investigation of the adsorption mechanism of anionic dyes, such as reactive blue 4 (RB4), acid blue 74 (AB74), and acid blue 25 (AB25), on bone char. At 298–313 K and pH 4, this model was used to fit the equilibrium adsorption data of these colors. For the RB4, AB74, and AB25 dyes, the global number of produced dye layers on the bone char varied from 1.62 to 2.24 depending on the solution temperature, with saturation adsorption capacities ranging from 0.08 to 0.12 mmol/g.

A similar analysis, carried out by the same research group, was published in the work of Landin-Sandoval et. al (2021). Their paper examines the physicochemical properties of anionic dye multilayer adsorption on lignocellulosic biomasses. To understand and characterize the adsorption mechanism of the dyes Acid Blue 29, Acid Blue 113, and Reactive Blue 4 using low-cost adsorbents such as coconut shells, cauliflower cores, and broccoli stalks, researchers used experimental studies, statistical physics modeling, and density functional theory (DFT) calculations. An innovative multilayer statistical physics model was used to determine steric parameters and adsorption energies, which were then linked to biomass composition and dye molecular characteristics. Their findings revealed that the cellulose content of various biomasses influenced the multilayer adsorption of these anionic dyes, with the greatest adsorption capabilities found for cauliflower cores with a cellulose content of 11.2%. It was also verified that dye aggregation played a major part in the removal of these adsorbates, with adsorption temperature having a considerable impact on cluster formation.

Likewise, important efforts have been made to treat water contaminated with various pharmaceutical products. For example, in the work presented by García-Reyes et al. (2021) the physicochemical mechanisms of removal of the medicines ciprofloxacin (CIP), ranitidine (RNT), and chlorphenamine (CPM) utilizing lignocellulosederived granular activated carbon (GAC) were investigated. The findings revealed that GAC is a mesoporous material with a surface area of 940 m2/g and acidic nature, with a pH PZC of roughly 2. The adsorption isotherms for CIP, RNT, and CPM were consistent with the Prausnitz– Radke model, reporting adsorption capacities of 668, 521, and 582 mol/g (221, 173, and 193 mg/g), respectively, at an equilibrium concentration of 50 mol/L, pH 7, and 25 °C. Furthermore, tests at various pH levels, temperatures, and reversibility revealed that adsorption is governed by physical principles. The findings show that GAC can be used to remove drugs with a variety of properties in circumstances that are quite similar to real-life situations.

Carrales-Alvarado et al. (2020) studied the influence of carbon nanotubes (CNTs) surface chemistry and shape on their adsorption ability towards the antibiotics dimetridazole (DTZ) and metronidazole (MNZ) from aqueous solutions. Single-walled carbon nanotubes (SWCNTs), nitrogen-doped carbon nanotubes (N-CNTs), multiwalled carbon nanotubes (MWCNTs), and MWCNTs functionalized with carboxylic groups were all investigated (MWCNT-COOH). The Redlich–Peterson (R-P) isotherm model was used to evaluate the experimental adsorption equilibrium data. At a temperature of 25 °C and a pH of 7, the adsorption capabilities declined as follows: SWCNT > MWCNT > N-CNT > MWCNT-COOH, with maximum capacities of 101 mg/g and 84 mg/g for SWCNT towards MNZ and DTZ, respectively. The Sheindorf–Rebuhn–Sheintuch adsorption model correctly interpreted the results for DTZ and MNZ competitive adsorption on SWCNT.

Martinez-Costa et al. (2018) studied the sorption of diclofenac (DCF) and Cd(II) from aqueous solutions on an organobentonit. The surfactant hexadecyltrimethylammonium

(HDTMA) was adsorbing on bentonite to create the organo-bentonite. After that, the sorption of DCF and Cd(II) on OBHDTMA was investigated, as well as the sorption of Cd(II) on OBHDTMA saturated with DCF (OBHDTMA-DCF). At T = 25 °C and pH = 7, the OBHDTMA had a maximum sorption capacity for DCF of 388 mg/g, which was comparable to carbon materials. The reversibility of DCF adsorption on OBHDTMA was limited, while the percentage of desorption increased with pH.

From the same research group, work has been done on the adsorption of Ronidazole and diclofenac from aqueous solution using commercial activated carbon (Coconut, Wood, Merck, Darco and Norit). They reported that At pH = 7, Coconut AC and Wood AC presented the highest adsorption capacity towards RNZ (444 mg/g) and DCF (405 mg/g), correspondingly. Using activated carbon (CA) physically with CO2, Moral-Rodríguez et al. (2019) reported the adsorption of diclofenac in an aqueous solution. The CA was designated as F, F12, F24 and F40 corresponding to activation times of 0, 12, 24 and 40 h, respectively. The maximum adsorption capacities of the carbons F, F12, F24 and F40 towards diclofenac (DCF) from the aqueous solution were 271, 522, 821 and 1033 mg/g, respectively. With the same purpose of removing diclofenac from an aqueous solution, Moral-Rodriguez et al. (2020) presented a xerogel synthesized by polymerization of resorcinol and formaldehyde, catalyzed by cesium carbonate and by varying the molar ratio R/Cs. The CXs were labeled as XCs-100, XCs-500, XCs-1000, and XCS-2000, corresponding to the R/Cs ratio of 100, 500, 1000, and 2000, respectively. The adsorption capabilities of XCs-100, XCs-500, XCs-1000, and XCs-2000 towards diclofenac (DCF) in aqueous solution were 132.0, 184.6, 126.5, and 126.4 mg/g, respectively, at an equilibrium concentration of 800 mg/L.

Using activated carbon in the same manner as the previously mentioned works, Spaltro et al. (2021) analyzed the removal of the paracetamol from aqueous solutions using the adsorption technique. For this, three commercial adsorbents with different textural properties were used: two activated carbons (CAT and CARBOPAL) and silica gel. A series of batch adsorption experiments were conducted at different values of pH (3.0, 7.0 and 10.5) and ionic strength (0.01, 0.5 and 1 M) to investigate the effects on the removal of paracetamol from the aqueous solution. In addition, they investigated the adsorption mechanism using the density functional theory. Adsorption was found to be higher in the acidic pH range, as varying pH showed a significant influence on the surface charge of the adsorbents and the degree of ionization of the paracetamol. The adsorption capacity of the adsorbents increased with an increase in the ionic strength of a solution. At 25 ∘C, pH 3, ionic strength 1 M, 167 mg L– 1 of adsorbent and initial concentrations of paracetamol between 25 and 150 mg L– 1, the maximum adsorption capacity was 560 mg g– 1, 450 mg g– 1 and 95 mg g– 1, for CAT, CARBOPAL and silica, respectively. The experimental kinetic data fitted well the pseudo-second order model and the equilibrium isotherm data in the Langmuir model.

Several places in Latin America and around the world have high levels of hazardous substances in their water as a result of contact with weathered objects. Arsenic (As), fluorine (F), vanadium (V), heavy metals, nutrients, and organic elements are all known to contaminate water. As is the 20th most abundant trace element in the earth's crust, the 14th in seawater, and the 12th in the human body. The economic ramifications of procuring water with an acceptable percentage of arsenic have sparked a major discussion regarding the appropriate level in both industrialized and poor countries. In this regard, a considerable amount of research has been carried out in this area. For example, for the treatment of water contaminated with arsenic, P é rez-Cuadra et al. (2019) investigated the bioaccumulation capability of As of Senecio bonariensis (Asteraceae) using controlled laboratory studies and uncontrolled field trials in order to develop a low-cost approach that may be used in rural regions without water treatment infrastructure. Plants were taken from the natural environment and grown in hydroponic crops under controlled and uncontrolled settings, with increasing As concentrations for 45 days in the first case and a constant As concentration for 45–90 days in the second. For the As measurement, the plants were treated and dried. In both experiments, there was a notable accumulation of As in all of the samples, which was often bigger in the roots than in the leaves. Plants accumulated more As in controlled conditions when there was a higher concentration of this element in the water. Villela-Martínez et al. (2020) studied the impact of operation circumstances, water matrix, and fluoride content on BC's adsorption capability toward As(V). Because of the increased electrostatic interaction between the arsenate in water and the positive charge of the BC surface, the BC capacity is increased by lowering the solution pH. The adsorption capacity was increased by raising the temperature to the point where As(V) adsorption was endothermic. The Kinetic and Mechanistic Evaluation of Inorganic Arsenic Species Adsorption onto Humic Acid Grafted Magnetite Nanoparticles (HA-MNPs) was provided by Rashid et al. (2018). The elimination of harmful inorganic arsenic species from aqueous media was explored using humic acid-coated magnetic iron oxide nanoparticles (HA-MNPs), which were produced, described, and studied. With an absorption capacity of 12.212.6 mg/g from aqueous media, the HA-MNP nanoadsorbent absorbs > 95% of inorganic arsenic species and is effective under a variety of circumstances. Pilicita et al. (2021) proposed employing a magnetite-based adsorbent to develop a low-cost, environmentally friendly arsenic filter. The filter design containing magnetite nanoparticles (Mag-NPs) captures up to 5 arsenic species diluted in aqueous environments, according to density functional theory calculations. Fonseca Largo et al. (2020) looked into the possibility of using an artificial floating island with Vetiver (AFIV) to remove geogenic arsenic from the Ilinizas páramo reservoir in Ecuador. They built two AFIV systems with a 3.6 m3 treatment capacity utilizing PVC pipes in a reservoir batch type. Through 120 days, arsenic and iron were measured in duplicate at the affluent and effluent. Arsenic remediation rates averaged 97% in water and 84% in sediment, while iron remediation rates averaged 87% in sediment.

With an interest similar to that presented by arsenic, studies on other heavy metals, for example, cadmium, have been developed. In a work by López et al. (2020) the results of cadmium sorption on biochars made from pyrolysis of various agro-residues, including the coffee husk, quinoa straw, and oil palm kernel shell, were presented. Cadmium sorption was shown to be dependent on the concentration of base cations. Despite the high uptakes of quinoa biochars, it was discovered that base cations were supported on the biochars and could be eliminated by leaching. Celso-Gonsalves et al. (2020) presented the capacity for Cd+ 2 removal from water using canola meal-based adsorbents: canola meal chemically

activated with 1 M NaOH and 1-hour pyrolyzing at 500 °C (CAC), and a second product prepared using the same method but with second pyrolysis at 750 °C in CO_2 flow (CAC-CO_2). Their best results were achieved with 4.0 g L-1 of adsorbent, pH 7.0, an equilibrium period of 40 and 60 min for CAC, and recovery rates of 67.8%. Manfrin et al. (2020) presented a work with the goal to convert tobacco from smuggled cigarettes into activated carbons and investigate its use in the treatment of cadmium and lead-contaminated water. A triple activation (thermal – chemical H3PO4 – physical CO_2) was used to achieve the desired activated carbon (CT H_3PO_4 + CO_2). The activated carbon produced can be used in a wide pH range (3.00–7.00), with an optimal dose of 4 g L1 for better Cd_2 and Pb_2 removal effectiveness.

With regard to heavy metals or transition metals, the treatment of water with a high content of fluoride, chromium, copper, mercury and lead has also been considered, due to the danger they represent. For example, for copper remediation, Lazo et al. (2019) presented a work where after pre-treatment with a leaching solution for 24 h and electrodialytic remediation for 15 days with a continuous electric field of 2.7 V cm1, mine tailings were examined using a sequential extraction process. With H_2SO_4 + HNO_3 pH = 1.9, the maximum copper removal efficiency was achieved, removing 67% of the copper in the overall cell and 85% of the copper in the slice nearest to the anode. Leiva et al. (2021) investigated the use of ZnO nanoparticles (ZnO-NPs) to remove Cu(II) ions from acidic water. At pH 4.8 and pH 4.0, ZnO NPs adsorption capability for Cu(II) was up to 47.5 and 40.2 mgg1, respectively. Their results showed that at pH = 4.8, q_{max} (47.5 mg/g1) and maximum Cu(II) removal efficiency (98.4%) was reached. Furthermore, after adsorption of Cu(II) at pH 4, the surface roughness of ZnO NPs diminishes by around 70%. Aparicio et al. (2021) through the use of an actinobacteria consortium and a physicochemical treatment using a column filled with nano-scale zero valent iron particles immobilized on dried Macrocystis pyrifera algae biomass, a restoration strategy was developed for the treatment of two artificial liquid systems (Minimal Medium, MM, and Water Carbon Nitrogen, WCN) contaminated with Cr(VI), lindane (-HCH), phenanthrene (Phe), and reactive black 5 In MM and WCN, the maximum elimination of Cr(VI) and total Cr was recorded, respectively. Morales et al. (2021), in order to evaluate their efficiency in the photoreduction of Cr VI ions in aqueous solutions, the coaxial electrospinning technique was used to develop composite membranes based on poly(acrylonitrile-butadiene-styrene)/polyacrylonitrile (ABS/PAN) micrometer fibers loaded with ZnO nanoparticles (NpZnO). With a substrate concentration of 50 mg/l and 30% wt. percent NpZnO in the whole solid, the membrane's maximum effectiveness was achieved, allowing the decrease of Cr VI to 81.59% after 8 h. Ramírez-Llamas et al. (2015) presented the adsorption capability of uncalcined and calcined layered double hydroxide (LDH) for fluoride removal. Due to electrostatic interactions, the fluoride adsorption capacity of LDH declined as the pH was raised, reaching a maximum at 25 °C. The mass of fluoride adsorbed was 39.14 mg/g at an equilibrium concentration of 10 mg/l.

Ramírez-Rodríguez et al. (2020) presented a promising technology to remove heavy metals through the use of hybrid membranes produced with whey protein fibrils (WPF) and activated carbon (AC). In their study, the best conditions to produce WPF by heat treatment were determined to maximize the removal of mercury and chromium from water using a central composed design. The results indicated that the best conditions to prepare WPF were 74 ◦C, 7 h and 3.8% of whey protein with adsorption capacities of 25 and 18 mg/g and removal efficiencies of 81% and 57% for mercury and chromium, respectively.

In the work developed by de Jesús Ruíz-Baltazar (2022) a new synthesis approach for an environmentally friendly composite made of diatoms (Dtm) doped with gold nanoparticles (Dtm-AuNPs) is presented. An ultrasound-assisted heterogeneous nucleation technique was used to create the Dtm AuNPs composite. The reduction of AuNPs was accomplished using Piper auritum extract as a reducing agent. The suggested green synthesis is a non-toxic, easy, and environmentally acceptable way to make a functionalized adsorbent for removing Mn2 + ions from aqueous solutions. Using atomic absorption spectroscopy, the Mn2 + adsorption capacity of Dtm-AuNPs was evaluated experimentally (AAS). The concentrations of adsorbate (Mn^{2+}) and adsorbent (Dtm and Dtm-AuNPs) were 1.0 mg L^{-1} and 20 gL^{-1}, respectively. When the adsorption process was aided by sonication, adsorption efficiencies of 98% were observed in a maximum period of 240 min.

Ricardo-García et al. (2021) presented a study where the goal was to look into clinoptilolite zeolite as a Ni(II) sorbent in aqueous solutions. Sorption and desorption tests on natural pure, NH_3, NaCl, and NaOH treated zeolites were carried out in batches at the following optimal conditions: pH5, sorbent dose of 4 gL^{-1}, contact period of 30 min, and room temperature of 30 ± 2 °C. As the sorbent was added, the capacity of the sorbent rose as follows: Natural zeolite (19.7 ± 0.3), NH_3-treated zeolite (9.9 ± 0.6), NaOH-treated zeolite (24.0 ± 0.9), and NaCl-treated zeolite (28 ± 2) mgg^{-1}. The eluent in the sequence NaCl (43 ± 9%) improved the recovery of Ni (II) sorbed on NaCl-treated zeolite. HCl (59.3 ± 0.65%), HNO_3 (66.2 ± 0.2%), Na_2EDTA (84.6 ± 0.6%), and NH_4Cl (98.5 ± 0.5%).

Morrillo-Martín et al. (2017) presented a research where An effective adsorbent based on poly(ethylene terephthalate) (PET) nanofibers was created in their work using a low-cost, adaptable, and scalable technique. Electrospinning was used to create PET nanofibers, which were then chemically functionalized utilizing a simple aminolysis procedure. As a function of contact duration, pH, and initial metal ion concentration, the capacity of the resultant material to adsorb Pb (II) from synthetic solutions was investigated. After only 30 min, the adsorbent system had reached an unusually high maximum adsorption capacity of roughly 50 millimoles (mmol) of Pb(II) per gram of adsorbent system. Furthermore, the influence of competing metal ions such as Ni(II), Cd(II), and Cu(II) at various molar ratios was investigated.

The tailing storage facility is the largest water sink in most mines. An incorrect management of water content in mine tailings can become a threat to their stability, and consequently, their environmental safety. Also, water reuse and recycling are plausible options to mining companies for reasons pertaining to water scarcity. Dewatering technologies for tailings, desalination and water transport are energy intensive. Proper handling of mine tailings and water supply management can considerably improve the water-energy nexus. The work presented by Araya et al. (2021) evaluated the water-energy nexus in copper mining companies using a water reduction model focused on mine tailing facilities and water supply to the mine site to find the trade-offs between water and energy. The originality of this work consists in the application of a real options approach, enabling to increase

the flexibility of decision-making thanks to quantitative analysis. Their approach deploys the Monte Carlo simulation to perform sensitivity and uncertainty analysis to evaluate every cost component of water management strategy. Results show that if seawater is the primary source of raw water to the mining plant, water transport represents the largest cost due to the use of energy. So, improving the reuse of water by using dewatering technologies will improve the water-energy nexus, by improving energy consumption. Even though the costs of these technologies are elevated because they are energy-intensive, reduction of water use requirements in the mine will reduce the cost of its treatment and transport.

In order to tackle the water scarcity problems, seawater desalination plants integrated with power plants can be considered along with the recharge of overexploited aquifers. When designing desalination plants, it is important to identify the optimum processes and renewable energies that lead to more efficient systems involving savings in power consumption and costs. In a very interesting work of modelling, Munguía-López et al. (2019) presented an optimization approach for water distribution networks. The system incorporates powered salination facilities as well as tariffs and tax credits applied to carbon emissions and water management. To determine the ideal design of the system, the profit is maximized, whereas the influence of economic penalties and compensations on environmental and social functions were evaluated. The model considers energy and water demands for distinct users (domestic, agricultural and industrial), which can be satisfied by using fossil fuels, biofuels, solar energy, water storage tanks, water from natural sources (aquifers and dams) as well as water and energy generated in dual-purpose power plants. A water management problem in the Sonoran Desert from México is treated as a case study. Results reveal considerable economic advantages, decrease in emissions and development of jobs, especially when carbon tax credits are involved. With the biggest compensation, the avoided emissions are 59,984 ton CO2/year, equally, the maximum values for the number of employment and profit are obtained (12,647 produced jobs and 1635 MM$/year).

In the same pattern of process modelling, Nuñez et al. (2019) created and installed SCADA MOVICON 11.5, which integrates, synchronizes, and manages the operation of five parallel reverse osmosis seawater desalination lines, four coastal wells, and two end-of-line pumps of the resulting permeated water as a single facility. Each desalination line has a separate control system and is capable of working alone. As a result, script codes were used to add synchronization algorithms to the system, ensuring constant productivity in the desalination process and achieving synchronization between the aforementioned sub-processes.

Dias et al. (2021) considers desalination of naturally saline well waters as a potential solution to water and food security when used in conjunction with an integrated production system involving reject brine for farm-raised fish and the use of fish pond water to grow organic salt-tolerant vegetables and forage crops for small ruminants. Their results indicated that the use of desalination reject brine in family agricultural production is technically, economically, and socio-environmentally feasible, especially when using integrated and sustainable production systems.

The research presented by Herrera-León et al. (2022) incorporates and quantifies greenhouse gas emissions generated during the operation of desalination and wastewater treatment plants in the assessment of water stress levels using the water stress indicator adopted by the 2030 Agenda for Sustainable Development. Chile was chosen as a case study, as it is a country where there is a considerable difference between the availability of conventional water sources and the water demand, and the electrical grid is fed mainly by fossil fuels. The methodology proposed allows calculating the indirect greenhouse gas emissions due to electrical consumption for the operation of desalination and wastewater treatment plants, and the direct greenhouse gas emissions coming from biological processes used in wastewater treatment plants. The results showed that Chilean arid climate zones will not experience water stress in the future at the regional level, mainly because of the installation of several desalination plants by 2030. Meanwhile, recycled water from the urban sector will slightly contribute to the reduction in the level of water stress in almost all Chilean regions by 2030. Moreover, desalination and wastewater treatment plant will contribute only between 0.34% and 0.75% of total greenhouse gas emitted in Chile by 2030. Therefore, the operation of these industrial systems for facing water scarcity problems in northern and central zones of Chile is a suitable alternative because it does not generate large environmental problems.

Through the use of reverse osmosis membrane systems for water desalination, in a work of Tomaszewska et al. (2020) out of the several hundred areas in Latin America where the water environment is contaminated with As and where there is a severe water shortage issue, three regions with geothermal resources were chosen for the study. These are Lake Poopó in Bolivia, Momotombo in Nicaragua, and Cerro Prieto in Mexico. The sole heat-powered membrane technology, membrane distillation (MD), uses low-enthalpy geothermal energy sources and waste heat from geothermal power plants to produce potable water and/or water for crop irrigation. The study findings are presented in this publication. It was determined that MD may be utilized as a means of obtaining high-quality water.

With the same objective of obtaining water for human consumption, Souza Antas et al. (2019) They built the desalinator structure. The reverse osmosis system produced drinkable water as well as residue with a salt concentration greater than the salinity of the prior water. Between October 2013 and November 2014, four expeditions sampled water from wells, filtered water, and saline refuse in seven water treatment facilities of municipalities and/or rural settlements in Rio Grande do Norte State, Brazil. The following quality parameters were determined: electrical conductivity, pH, cations and anions, sodium adsorption ratio, calcium/magnesium ratio, and the influence of the Langelier saturation index and the Ryznar stability index on the recovery rate of reverse osmosis desalination systems. According to the findings, the average recovery rate for desalination systems in October/November 2013 was 32.11%; 52.42% in February/March 2014; 41.41% in June/July 2014; and 33.60% in October/November 2014.

This section, based on a large number of accessible sources of information on contamination in groundwater and surface water resources from the Latin American continent, suggests that both drinking and irrigation water sources contain certain contaminant levels that affect a large number of people, especially in areas without central water supply systems.

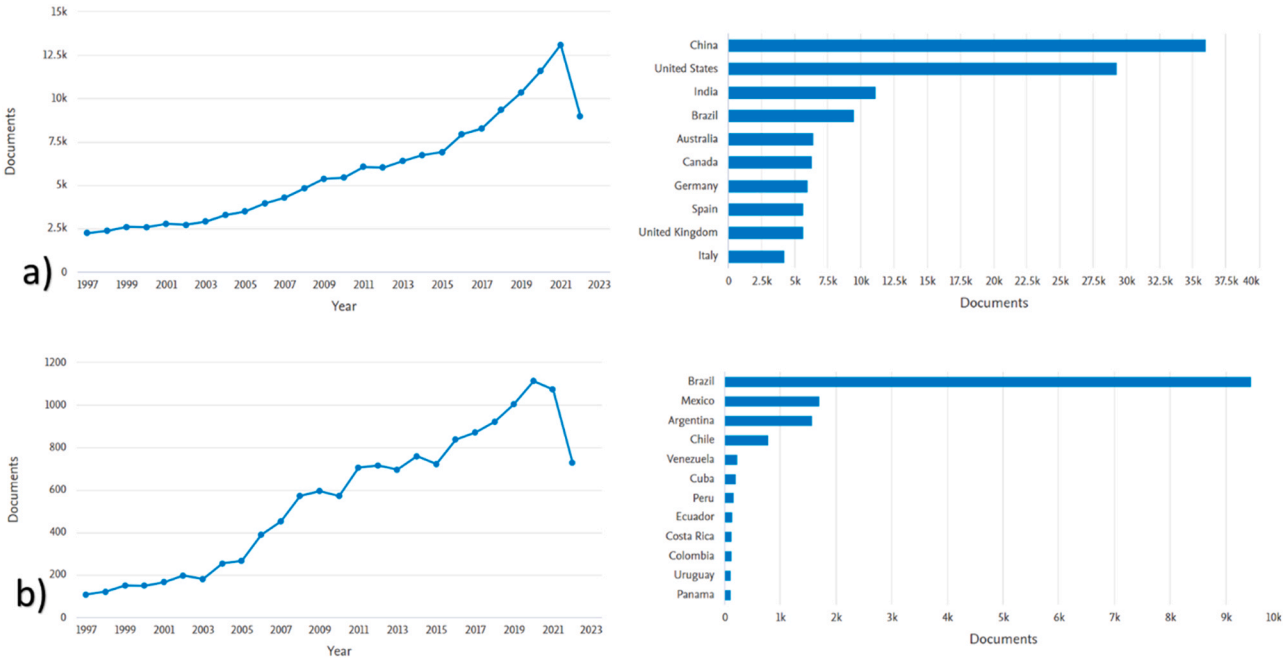

Fig. 6 – Research conducted in Soil Treatment, a) International, b) LatinAmerica.

For example, As problems have been described in 94 principal regions in 14 out of 20 countries comprising (in alphabetical order): Argentina, Bolivia, Brazil, Chile, Colombia, Cuba, Ecuador, El Salvador, Guatemala, Honduras, Mexico, Nicaragua, Peru, and Uruguay. The mitigation of the As-related problems is a huge challenge for this continent (Bundschuh et al. 2012).

Several contaminant of surface, groundwaters and soils in mining areas of various Latin American countries also present similarities. Solid waste deposits and acid drainage from sulfide ore processing have polluted sediments and waters in many areas of Bolivia, Brazil, Chile, Colombia, Ecuador, Guatemala, Honduras and Mexico. Natural and anthropogenic sources coexist in the same zones and have affected crops and human health. Specific remediation measures must be developed to remediate the anthropogenic polluted areas. This implies identification of the sources and environmental pathways of contaminants.

Contaminant assessment must be a standard parameter for drinking and irrigation water, and uniform international guideline values should be adopted by all countries. Multidisciplinary research in Latin America has to be strengthened by national researchers and by international interdisciplinary cooperation, to build-up a robust Latin American network to investigate the occurrence and mobilization pathways of contaminant release into the environment.

5. Soil treatment

Only 12.6% of accessible land is used for crop cultivation, indicating that fertile soil is a limited resource on the world (Cagnetta et al. 2018). Soil degradation is the primary cause of fertile soil depletion, a problem that must be addressed quickly in the near future in order to feed the world's rapidly rising population. Erosion, organic carbon loss, pollution, salinization, acidification, and other processes all contribute to this decline. The principal deterioration process is erosion, while pollution is the most damaging to human health.

Research conducted in Latin America aimed at reducing the effects of pollutants in soil is led by Brazil. Similar to the behavior observed in other sections, Brazil is the only country in Latin America that is present in the top 10 of research carried out with this orientation. In Latin America, Mexico, Chile and Argentina are the countries that follow Brazil in terms of published works (see Fig. 6).

Soil contamination by inorganic (heavy metals) and organic pollutants (polycyclic aromatic hydrocarbons (PAHs) and halogenated substances such as pesticides, polychlorinated biphenyls (PCBs), etc.) has a number of detrimental consequences on food safety and crop output (Pepper, 2013). For example, widespread pesticide usage has resulted in a significant loss of soil microbial biodiversity, resulting in a reduction in nitrogen fixation activities and, as a result, a loss of soil productivity (Jacobsen & Hjelmsø, 2014). Furthermore, organic and, in particular, inorganic contaminants enter the food web through direct consumption or bioaccumulation in animal tissues due to food crop absorption. Soil pollution can be localized or widespread. Industrial activity, poor waste management, and accidents are all common causes of local contamination. Atmospheric deposition, flooding events, and agricultural activities all contribute to diffuse pollution. Soil pollution is a global issue, particularly in wealthy countries.

Natural fertile soils account for approximately 10% of the surface area in Latin America allocated to the high-scale cultivation of coffee, sugar cane, bananas, and soybeans (Panis, 2015). Growing these crops necessitates agricultural intensification, which degrades soil quality. In Latin America and other emerging regions, pressures from agricultural intensification and overexploitation of natural resources (fishing and deforestation), as well as those stemming from climate change, socioeconomic inequality, and insufficient land-management practices, are serious challenges (Panis, 2015).

In this regard, several efforts have been made in Latin America to develop strategies to help to mitigate the ravages of soil contamination in search of a sustainable environment for future generations. Efforts have been focused on the treatment of hydrocarbons, pesticides, and heavy metals, among others. For example, for the treatment of hydrocarbons Vieiria dos Santos et al. (2017) used a surfactant-aided soilwashing (SASW) procedure, followed by sonolysis (US), photolysis, and boron doped diamond electrolysis (BDD-electrolysis). SASW is a very efficient strategy in soil treatment, entirely eliminating petrochemical compounds with dosages of roughly 5 g of extracting surfactant (sodium dodecyl sulfate (SDS) per kilogram of soil, according to the results. The dosage of SDS affects the primary properties of the effluents produced in this soil remediation method, as well as the treatment efficiency (US, photolysis, and BDD-electrolysis).

Adams et al. (2016) presented a work where surface soil samples were collected and studied pre and post-treatment to evaluate alkaline desorption as a treatment strategy. Total petroleum hydrocarbon concentrations in the samples ranged from 2800 to 63,100 mg/kg, with considerable water repellency and critical moisture levels 2–5 times higher than in situ, but no acute toxicity. As a result, rather than toxicity, water repellency is to blame for the loss of vegetation. In two doses (1:3; soil/solution), samples were treated with 0.1 N NaOH, with complete drainage between doses. To avoid soil hydrophobicity in field conditions, samples with initial water repellency values in the range of 5.0–6.7 M had their repellency decreased by 94–100% and below threshold limits. Other samples with initial water repellency values in the 10–13 M range could not be recovered with a single treatment, but sequential treatments reduced the hydrocarbon content by up to 87% and the hydrophobicity to levels low enough or nearly low enough to avoid severe water repellency in the field. Sabino da Silva et al. (2017) presented a work where electrokinetic soil remediation (ESR) technology was used to treat petroleum-polluted soil in a laboratory setting, followed by boron-doped diamond electrolysis (BDD-electrolysis) for washing liquid treatment. ESR was found to be an effective method for eliminating petrochemical chemicals from soil. Depollution of effluents by BDDelectrolysis is linked to liquid pre-treatment as well as increased petroleum removal from soil. The full removal of organic materials from liquid produced during ESR is favored by BDD-electrolysis. The ions in the effluent, on the other hand, play a key role during BDD-electrolysis because strong oxidants are electrochemically created at the diamond surface, increasing the process' efficiency.

In the same way Sales da Silva et al. (2021) discussed the use of green surfactants in the remediation of hydrocarbon-contaminated soils. Three green surfactants, including two biobased (biobased 1 and biobased 2) chemically synthesized surfactants and a microbial surfactant derived from the yeast Starmerella bombicola ATCC 22214, were utilized as soil remediation agents and compared to a synthetic surfactant (Tween 80). The capacity of the three surfactants to emulsify, distribute, and remove various hydrophobic pollutants was examined. The biosurfactant, which was able to reduce water surface tension to 32.30 mN/m at a critical micelle concentration of 0.65 g/L, was subsequently used to create a commercial formulation with lower toxicity and dispersion capacity than biobased surfactants. All of the green surfactants had excellent emulsification abilities, particularly in the presence of motor oil and petroleum. As a result, their ability to remove motor oil adsorbed on several types of soils (sandy, silty, clay soil, and beach sand) was tested in both kinetic (flasks) and static (packed columns) trials. Under static conditions, the commercial biosurfactant formulation was very effective at removing motor oil, especially from contaminated sandy soil (80.0 0.46%) and beach sand (65.0 0.14%), while in kinetic experiments, the commercial biosurfactant and the biobased 2 surfactants were able to remove motor oil from all of the contaminated soils tested more effectively than the biobased 1 surfactant. Oil degradation yield in the sandy soil reached about 90% after 60 days in the presence of the commercial biosurfactant, while it did not exceed 20% in the presence of simply S. bombicola cells in degradation trials on motor oil-contaminated soils treated with sugarcane molasses.

In a work presented by Kidd et al. (2021) the variety of cultivable bacteria associated with plants from phytomanaged soils contaminated with mixed trace metal (TM) and polycyclic aromatic hydrocarbon (PAH) contamination was assessed. Because the overall goal is to collect bioinoculants to assist the remediation of this type of contaminated site, the focus was on the cultivable bacterial community. The numbers of root endophytic and rhizosphere soil bacteria were calculated, and isolates were pooled and identified using amplified rDNA restriction analysis and 16 S rDNA sequencing. The synthesis of plant growth-promoting (PGP) chemicals and resistance to TM were also assessed in isolates. The ability of the chosen strains to break down PAHs was tested. The ability of cell-free microbial supernatant to promote PAH mobilization from Pierrelaye's polluted soil was also investigated. The isolates were dominated by Proteobacteria and Actinobacteria, with differences in taxonomic diversity identified between plant species (Populus or Zea mays) and remediation treatments (Populus inoculation with mycorrhizae or Populus intercropping with Alnus). The majority of isolates showed resistance to more than one TM and at least one of the assessed PGP characteristics. Fluoranthene and pyrene dissipation was shown to be high in several rhizosphere, endophyte, and even bulk soil isolates. The endophyte Rhizobium strain MR28, which was isolated from maize and degraded pyrene, created bioemulsifying molecules that improved PAH availability from Pierrelaye soil.

Gutiérrez et al. (2020) presented experimental activities to see how biostimulation and bioaugmentation with Pseudomonas fluorescens can help to remove total petroleum hydrocarbons (TPHs) from a soil. To determine the optimal bioaugmentation and biostimulation therapy, laboratory tests were conducted (measurements of released CO2, surface tension, and residual TPH). Glucose–yeast extract, NH_4Cl–$NaNO_3$, and K_2HPO_4–K_3PO_4 were used as supplies of C, N, and P, respectively. A factorial design 23, in a solid culture system, was used to assess the effect of culture conditions on the decrease of TPH and respiratory activity. Following an 80-day incubation period, it was discovered that the treatments yeast extract–NH_4Cl–K_2HPO_4 (Y4) and glucose–$NaNO_3$–K_3PO_4 (Y5) had a greater level of TPH elimination (20.91% and 20.00%, respectively). The generation of biosurfactants is favored by biostimulation, as indicated by the change in surface tension in soil extracts. The surface tension change values for treatments Y4 and Y5 were lower (23.15 and 23.30 mNm1 at 25 °C).

The addition of the inorganic nutrients C:N:P (yeast extract-glucose, NH_4Cl-$NaNO_3$, and K_2HPO_4-K_3PO_4) to soil

contaminated with crude oil was investigated by Gutierrez-Alcantara et al. (2019) as the best choice for increasing the breakdown of TPHs in the soil. A physicochemical evaluation of the contaminated soil was performed in order to determine the starting conditions of the inorganic nutrients. In the biostimulation strategy, the controlled settings were 20 days of incubation at an uncontrollable ambient temperature. Residual TPHs, surface tension, respiration activity, and microbiological counts were all measured after the tests. The best treatments were Y5, which contains the nutritional supply glucose-$NaNO_3$-K_3PO_4, and Y4 (yeast extract $NH_4ClK_2HPO_4$), which had degradation efficiencies of 14.0% and 12.8%, respectively, after a 20-day incubation period. Biostimulation with inorganic nitrogen and phosphorus boosted the metabolic activity of indigenous soil microbes, resulting in more petroleum hydrocarbon breakdown. Likewise, interesting diagnostic techniques for soil remediation have been developed. For example, Cavallari et al. (2018) presented the use of geophysical approaches combined with a chemical data history in a contaminated area caused by leaking hydrocarborn in a railway accident in Botucatu in 2005. (SP, Brazil). 5 parallel lines of electrical resistivity tomography in the Schlumberger array were programmed and altered from a history of chemical analysis of groundwater to employ the geophysical methods Electrical Resistivity and Induced Polarization. The data from the electrical tomography allowed for the creation of 2D inversion models as well as the display of 3D models. The data integrated analysis revealed an advanced state of hydrocarbon degradation, as evidenced by high chargeability values in relation to the natural pattern of the area, as well as areas of medium resistivity. During bioremediation of a sandy soil contaminated with diesel, biodiesel, and mixes, Anjos et al. (2018) compared fungal bioaugmentation to natural attenuation (B20 and B50). In Bartha flasks, which were used to assess microbial CO2 production, respirometric experiments simulating soil contamination were carried out. Penicillium sp. AV4 was isolated from a biodiesel factory's effluent and employed in bioaugmentation since it has the potential to breakdown the fuels. For all fuels, CO2 evolution showed no significant change in soil microbial activity after 111 days between fungal augmentation and natural attenuation treatments. The failure of Penicillium sp. AV4 to compete with soil microbes and/or boost metabolic activity could explain its lack of influence. B50 produced the most CO2, followed by B100, B20, and diesel, which is less biodegradable, during natural attenuation.

A highly hazardous contaminant is herbicides and pesticides because of the long-term negative impact that they can have on the human body and some other species. With this in mind, important research has been conducted, for example, Madalão et al. (2017) presented the bioremediation of a sandy soil contaminated with diesel, biodiesel, and mixes, and the researchers compared fungal bioaugmentation to natural attenuation (B20 and B50). In Bartha flasks, which were used to assess microbial CO2 production, respirometric experiments simulating soil contamination were carried out. Penicillium sp. AV4 was isolated from a biodiesel factory's effluent and employed in bioaugmentation since it has the potential to breakdown the fuels. For all fuels, CO2 evolution showed no significant change in soil microbial activity after 111 days between fungal augmentation and natural attenuation treatments. The failure of Penicillium sp. AV4 to compete with soil microbes and/or boost metabolic activity could explain its lack of influence. B50 produced the most CO2, followed by B100, B20, and diesel, which is less biodegradable, during natural attenuation.

Regarding the same contaminant Ferraco et al. (2019) developed a study to see how density in Crotalaria juncea affected the phytoremediation of contaminated soils using the sulfentrazone herbicide. Plastic pots were used in the experiment, which was conducted in a greenhouse. The treatments were a combination of C. juncea density (0, 60, 120, and 240 plants m2) and sulfentrazone dosages (0, 200 and 400 g i.a. ha-1). The herbicide was administered to the pots, and then the phytoremediation species were planted. Dinis Melo et al. (2019) presented a study to assess the potential for bioremediation of sulfentrazone-contaminated soils utilizing a previously chosen bacterial consortium, phytoremediator plants, and their combination. A single crop of Canavalia ensiformis, a single crop of Helianthus annuus, both species under mixed culture, tilled soil with the presence or absence of bacterial consortium inoculation, and varying bioremediation times were used as treatments (25, 45, 65 and 85 days after thinning). In comparison to soil cultivated with C. ensiformis without inoculation, the Helianthus annuus single crop and mixed cultivation reduced the half-life of sulfentrazone by 64% and 43%, respectively, when compared to untilled soil and a single crop of C. ensiformis in the presence of inoculation.

Treating the same kind of contaminant, Alves et al. (2019) studied how effective winter plant species are at phytoremediating soil contaminated with fomesafen and sulfentrazone, using cucumber as a residue indicator. The phytoremediator species were harvested near the soil 45 days after sowing. The bioindicator species of herbicide residues in the soil (cucumber) was then planted in the pot. Herbicides were tested for phytotoxicity on cucumber plants at 7, 14, 21, and 28 days following emergence (DAE). When applying the authorized amounts of fomesafen and sulfentrazone, black oats, radish, and white lupine had the highest capacity to phytoremediate soil polluted with the herbicides. Ortíz and Velasco (2019), using zero-valent iron (Fe0) and iron-copper Fe0/Cu0 in microcosms and bench-scale batch tests, the remediation of polluted soils including DDX (DDT, DDE, and DDD), endrin, and endosulfan were examined. At both scales, the treatments allowed for a reduction in the initial concentrations of DDX (30 mg/kg), endrin (150 mg/kg), and endosulfan (40 mg/kg), showing that they were effective. The accumulation of the intermediate compound DDNS in DDX-polluted soil, on the other hand, was observed. The Fe0/Cu0 ratio of 10/3 (w/w) resulted in the highest DDX degradation percentage in microcosms testing. For endrin and endosulfan-polluted soils, the degradation observed in the bench-scale reactor was improved, whereas DDX degradation was comparable to that observed in microcosms tests. The Fe0/Cu0 method primarily enhances DDD, DDE, and endrin degradation rates while cutting treatment duration in half from eight to four days. Because the extent of remediation was similar in most studies, except for DDD and DDE, choosing Fe0/Cu0 or Fe0 as a remediation strategy should consider the cost of copper versus the length of treatment. Further research is needed since pesticide breakdown was not finished and intermediary chemicals accumulated.

Regarding soil treatment with clopyralid (herbicide), Vidal et al. (2018) studied the remediation of clopyralid-spiked soil using two types of zero valent iron (ZVI) barriers, as well as electrokinetic soil flushing (EKSF). These barriers are made

up of soil that has been mixed with iron particles. Granular millimetric iron was employed in one of the tests, while iron in the form of nanoparticles was used in the other. This unique technology's performance is compared to that of a single EKSF technology. The tests lasted one month and were conducted in bench scale prototypes (175 L). During this time, an electric field of 1.0 V/cm was applied to soil between a row of three anodes and a row of three cathodes. The findings show that ZVI barriers have a significant impact on electrokinetic flushes by preventing contaminants from moving to the electrode wells. They do, however, dehalogenate clopyralid more than a single EKSF. There are no significant variations in the findings obtained utilizing the two sizes of ZVI, and the volatilization of contaminants connected with temperature effects was nearly completely prevented by putting capillary barriers on top of the mockups. Because the pollutant was concentrated in very precise areas during remediation, the majority of the clopyralid that was not removed is concentrated near the anodes wells, and a significant fraction can be easily retrieved by excavating a very tiny percentage of the soil.

Heavy metals are also an important form of soil contamination due to their bioaccumulation. In this regard, several studies have been carried out for the treatment of contaminated soils. For example, Rodriguez et al. (2019) presented research to assess the efficacy of biochar made from corncob gasification for the immobilization of lead in polluted soils. Biochar made from corncob was utilized as an amendment for lead-contaminated soil (extracted from the municipality of Malambo, Colombia) in order to assess its ability to immobilize leaching lead. Modified biochar generated with a 10% hydrogen peroxide chemical treatment was used in a comparison laboratory test. In addition, a 33-day pot experiment was conducted with both biochar and Pennisetum clandestinum seeds. During this time, plant growth was assessed for various biochar concentrations and inputs. In laboratory testing, normal biochar retained 61.46% of the lead, while modified biochar retained only 44.53%. In pot trials, the enhanced biochar resulted in high seed germination and growth (up to 89.8%).

Electrokinetic remediation (ER) techniques for removing Pb2 + from polluted soils are investigated in the study of Silva et al. (2018). Different cathodic supporting electrolytes (NaNO3 0.1 M, EDTA 0.1 M, and citric acid 0.1 M) were utilized in the catholyte reservoir, while a solution of NaNO3 0.1 M was used in the anodic compartment. In addition, the use of direct current (DC) and reverse polarity (RP) for eliminating Pb^{2+} from soil was investigated. According to the findings of this investigation, RP and citric acid favored effective electromigration of Pb^{2+}, allowing it to be removed from the soil. This behavior can be explained by the fact that the elimination of Pb^{2+} was dependent on the dissolution/precipitation of ionic species as well as the pH in the soil, both of which were maintained in different sections of the soil, with RP and citric acid helping to maintain the pH conditions and thus promoting lead elimination. The adsorptive stripping voltammetry (AdSV) technique was utilized to produce sufficient confidence and adequate sensitivity for the concentration of Pb^{2+} with LOD around 0.1 mg L1 in order to adopt a realistic approach for monitoring Pb^{2+} concentration. Phytotoxicity experiments revealed that the ER process might be used as a therapeutic method for lowering Pb^{2+} polluted soil toxicity. The results showed that using DC with $NaNO_3$ and EDTA as cathodic solutions significantly reduced germination in the anodic and cathodic zones for ER. However, by utilizing $NaNO_3$ and citric acid solutions in cathodic compartments and applying RP or DC, substantial germination (60–80%) was achieved for ER. Finally, the effluent created by ER technology was electrocoagulated with Al electrodes in each experiment, resulting in full elimination of Pb^{2+} from the liquid after 60 min.

Costa et al. (2022) presented a work to see how aça seed biochar (Euterpe oleracea Mart), impregnated with iron (BFe) or not (BC), affected the bioavailability of PTEs in a multi-contaminated soil from an Amazon gold (Au) mining area, using Ipomea asarifolia as a plant test because it grew naturally on the tailings. BC raised the pH of the soil, whereas BFe decreased it. Biochars boosted the oxidizable fraction's PTEs (linked to soil organic matter). PTE immobilization was improved by using BC and BFe, and BC increased arsenic (As) in the soil's easily soluble portion. Furthermore, biochar-grown plants had lower dry matter yield, higher PTE concentrations, and lower nutritional content than control plants. Ipomea asarifolia can be classed as a species with capacity for Zn phytostabilization and tolerance to other PTEs, primarily As, based on phytoextraction and translocation parameters.

The utilization of plants in the waste dump to remediate soils affected by heavy metals is a strategy. The investigation of Soto Carrión and Jiménez Mendoza (2019) presented the study of three native plant species in the Quitasol-Imponeda de Abancay waste dump. The goal of their research was to determine the levels of heavy metal contamination in the waste matrix in the root, stem, and leaves, including lead, cadmium, nickel, chromium, and zinc. Three species and five heavy metal treatments, each with two repetitions, were used in three different plots in a complete factorial design (A, B, C). The results show that in plots two and three, Amaranthus hybridus had the largest accumulation of zinc, lead, and cadmium, with 23.03 parts per million in the root, 5.87 parts per million in the stem, and 8.83 parts per million in the leaves. The highest concentrations of zinc, lead, and cadmium were found in the roots of Brassica rapa, which resulted in a reduction in leaf growth and stem thickness. In the roots and leaves, Amaranthus spinosus had higher zinc accumulation of 24.28 parts per million, zinc 11.63 parts per million, lead 1.74 parts per million, and cadmium 0.55 parts per million. The conclusion is that the three native species have quick development, do not require chemical controls, and absorb significant quantities of heavy metals, making them a viable option for garbage dump restoration due to their high phytoremediation capability. Regarding Mercury, Hibiscus cannabinus (kenaf) was tested for its ability to treat oxisol polluted with Hg^{2+} potential in the work of Lavezzo et al. (2021). The experiment was carried out in a controlled setting in pots with soil polluted with HgCl2 solution, using a completely randomized design with four treatments: control (no Hg^{2+}), 5, 24, and 36 mg Hg^{2+} kg^{-1} of soil, and five duplicates per treatment. Atomic absorption spectrometry was used to measure total Hg levels in plant and soil samples. The toxicity of kenaf growing in polluted pots was not visible. Plant height did not change between treatments, however, the dry shoot phytomass in the control was 21.65% higher than the average of Hg treatments. Dry root phytomass was higher in the 24 mg kg^{-1} group than in the control and other groups. In general, oxisol was shown to be more effective at retaining Hg than plants. Hg accumulates in roots at a higher rate than in shoots. Plants in pots receiving 36 mg kg-1

accumulated an average of 2.57 mg kg-^{1} of Hg / pot, which was significantly higher than the other treatments, and the Hg transfer factor (TF) in plants was computed as the ratio of the concentration in shoots and roots. The following were the values: T1 is 3.11, T2 is 1.26, T3 is 0.05, and T4 is 0.02. There was no change in treatment between T3 and T4, and TF reduced as the Hg dose was increased. Hg was more absorbed by oxisol than by plants, it was concluded. Plants demonstrated tolerance to various Hg concentrations in the soil and might be used as a Hg^{2+} stabilizer.

In recent decades, high levels of naturally occurring Cadmium (Cd) in Jamaican soils have become a problem. A study of Sanderson et al. (2021) was conducted in the northern community of Devon, which was known for having high Cd levels in its soils. For the treatment of Cd polluted soil in a pot and a field investigation, an innovative Integrated Cadmium Extraction System (ICES) was created. Starting with the pot research, both studies were carried out for 42 days in a row. For pot and field studies, the ICES found removal efficiencies of 47.01% and 43.43%, respectively. The removal efficiencies are promising, indicating that ICES can be scaled up from bench-scale research to field use. Electrokinetic (EKR) and soil solution extractor (SSE) were utilized to treat soil in two distinct pots during the pot research. For the soil treatment approaches used, the residual Cd level in the soil at the end of the pot study was in the order SSE > EKR > ICES.

Initial planting density control can be a method for increasing barium phytoextraction from soil and lowering soil cleaning time. Gomes-Viana et al. (2021) conducted a 300-day experiment in an area accidentally contaminated with barite to determine the appropriate planting density for barium (Ba) phytoremediation using Typha domingensis. Planting densities of 4, 8, 12, and 16 plants per m2 (D4, D8, D12, and D16 treatments, respectively) were investigated. The phytoextraction efficiency was determined at the end of the trial after the plants were checked on a regular basis. Ba phytoremediation by T. domingensis monoculture was influenced by the initial planting density. The mass-based translocation factor (mTF) indicated phytoextraction potential better than the concentration-based translocation factor. The ultimate number of plants and biomass output were highest in D16, while the mass of Ba in the aerial section was similar in D8, D12, and D16. D4 resulted in 6.3 times more Ba accumulating belowground than aboveground, but D12 and D16 had the highest mTFs. With fewer T. domingensis individuals at the start of the treatment (D4 and D8) but substantial accumulation in belowground tissues, more Ba absorption from soil can be attained.

Locally in México, The Zimapán mining district in the state of Hidalgo produces high–concentration Cu, Pb, and Zn residues that have been disposed of for decades on places that could be harmful to the surrounding environment. Simultaneously, an invasive species known as water hyacinth (Eichhornia crassipes) has impacted the district's water dams, necessitating attention and treatment. With that background Núñez Balderas et al. (2020) presented a study to a) evaluate biochar made from water hyacinth (H) in mining acid wastes; and b) compare its performance to monopotassium phosphate (F), lime (L), and phosphate blends with biochar (FH) or lime (FL) using a bioassay of barley root development, soluble metal, and pH. To simulate pollution gradients, four substrates were used: 100% neutral virgin soil (M1), 100% acid mine residues (M4), and two mixtures of soil: residues (w/w) of 65:35 (M2) and 35:65 (M3) (M3). H (10% substrate), L (3.4% residues), F (0.06% soil + 0.6% residues), FH (0.06% soil + 0.6% residues + 10% substrate) y FL (0.06% soil + 0.6% residues + 3.4% residues) were used to treat the substrates (22 total treatments, blanks-included). By converting water hyacinth to biochar, this study indicates that it can be used to treat acid mine wastes. When residues were present, it induced an increase in root length, pH, and a reduction in soluble Cu and Zn, the same as the other amendments. Although, in the residues-substrates, the reduction of soluble Pb with biochar was significantly smaller than with lime.

A large number of heavy metals are generated in tailings of precious metal extractive operations, which could cause high levels of water contamination. Because of the environmental and health concerns, many conventional technologies have been applied to capture heavy metals from mining-polluted streams with limited performance in terms of effectiveness and immobilization efficiency. In this context, Bolaños-Guerrón et al. (2021) evaluated the retention of mine generated heavy metals using Technosols prepared with iron-rich soils and multicomponent nanoparticles of Fe/FeS (MCNPs). Firstly, nanoparticles were synthesized using orange-peel extract and sodium borohydride (NaBH4) as reductant agents and FeCl3.6H2O and Na2SO4 as metal precursors. The TEM and SEM images showed nanoparticles with roughly spherical morphology with a size in the range of 35.9 11.7 nm arranged in a kind of filamentous structure. Secondly, Soils were dosed with 1% and 3% (w/w) of multicomponent nanoparticles and then used to capture heavy metals present in mine tailings using batch and fixed-bed column tests. The Technosol prepared with 97% soil, and 3% MCNPs reached on average 70% retention of heavy metals for fixed-bed setups. While, in batch experiments using the same Technosol, the capture of heavy metals was 80% after 6 min of treatment, and upon reaching 30 min, 90% removal was attained.

In Ecuador, mining activities generate a large amount of solid waste and acid drains that contain heavy metals in high concentrations. In wastewater of gold mines from Southern Ecuador (Portovelo), arsenic concentrations between 4.8 and 27.5 µg/L have been detected. In this context, Bolaños-Guerrón et al. (2018) prepared a technosol, which was used in the capture of arsenic dissolved in the acid drains. Technosol was elaborated using a clay-silty soil (iron-rich soil), collected in the mining area, and iron nanoparticles synthetized with the extract of orange peel. -e technosol was experimentally characterized using adsorption isotherms and uptake kinetics. Besides, a mathematical model was developed using Vensim® to scale the process and predict the dynamic behavior of the adsorbent. Results indicate that adsorption behavior of technosol can be fitted to Langmuir isotherms (R2 > 0.9), with 95% of adsorption of As from an input of 4.5 mg/L. -e model will be useful to predict the time needed to remedy contaminated water and the duration of the adsorbent (until its saturation).

In the region of Matehuala, San Luis Potosi (SLP), Mexico, a highly productive mining area, arsenic concentrations of 138.1 mg/kg have been found in soils—6.2 times higher than what is allowed in domestic soils, while in water it is reported up to 158 mg/L, exceeding permissible limits for human consumption. In addition to As pollution, the region suffers from water shortage both in the city and in rural communities. Therefore, it is necessary to explore new technologies to provide the population with fresh water. The

paper presented by Mendoza-Escamilla et al. (2019) a feasibility study on the use of an atmospheric water generator (AWG) to capture fresh water in the region of Matehuala, SLP was developed. The region was found to have the necessary environmental conditions to use AWGs, with an annual average relative humidity (RH) of approximately 60%. Using a mathematical model of a dehumidifier, water harvesting can be evaluated under the region's prevailing climatic conditions. The month with lowest harvest was found to be January, with 0.89–3.6 L/day, while the month with largest harvest was August at 3.9–18 L/day and water production costs of 0.0093 and $ 0.038 USD/L, respectively. The study concludes that the use of AWGs would help alleviate water shortages, thus benefiting marginalized people or communities, preserving ecosystems and the environment.

For centuries, Chile has been a territory with significant mining activity, resulting in.

associated social benefits and impacts. One of the main challenges the country faces today is the presence of a great number of mine tailings containing heavy metals, such as Cu, Cr, Ni, Zn, Pb, As, Cd, and Fe, which make up a potential risk for the population. The study presented by Lam et al. (2020) intended to develop a methodology for determining tailings requiring urgent treatment in Chile, based on risks associated with heavy metals. Geochemical data from 530 Chilean tailings were compared to the Dutch norm and the Canadian and Australian soil quality guidelines for residential use. Additionally, criteria about residents and water bodies were used, considering a 2-km area of influence around tailings. To do this, QGIS (Böschacherstrasse 10a CH 8624 Grüt (Gossau ZH), Zurich, Switzerland), a geospatial tool, was used to geolocate each deposit, considering regions, communes, rivers, lakes, and populated areas. To evaluate potential ecological contamination risks, Hakanson's methodology was used. Results revealed the presence of 12 critical tailings in Chile that require urgent treatment. From the 530 tailings evaluated, 195 are located at less than 2 km from a populated area and 154 at less than 2 km from a water body. In addition, 347 deposits require intervention: 30 on Cu, 30 on Cr, 13 on Zn, 69 on Pb, 138 on As, 1 on Cd, and 5 on Hg.

On the other hand, Peru is a country with a lot of mining activities; however, these activities have a bad reputation due to pollution water. Therefore, the objective of a study presented by Delgado et al. (2021) was to determine the water quality of the Alto Huallaga watershed, Peru, due to the presence of nearby mining companies and urban populations. The main purpose of their work was to compare the quality of water that has been influenced by contaminants from mining and non-mining activities. The results obtained show that the environmental management of the mining companies close to the rivered reduces the pollution produced by mining and non-mining activities to levels acceptable by law. On the contrary, it is observed that the absence of mining units has an influence on the increase in urban pollution produced by cities and towns near the watershed, which affects water quality. This research shows that formal mining activity in the watershed has a positive impact on water quality and allows future research to be opened regarding the influence on other environmental factors such as air, soil, biodiversity and even the social environment. Finally, this research is the beginning of a change in perspective on mining in the country.

In the same way, mining resources have played a prominent role in the evolution of civilization, and the demand for these raw materials is likely to expand in the foreseeable future. In addition, new technologies also demand the extraction of new key materials. These trends pose numerous issues as there is a finite supply of natural resources, and normal mining and mineral processing processes are associated with major environmental implications, such as waste generation, energy and water use, and CO2 emissions. The work given by Cisternas et al. (2022) assessed the existing efforts toward the implementation of Circular economy in mineral processing. Although gains have been achieved, their assessment suggests that the most substantial material flows and environmental impacts occur near the manufacturing sites, which now hinders the closure of loops. Besides, mining sectors are conservative about the adoption of new technologies or processing processes, which is another impediment to the implementation of the CE. Thus, and with rare exceptions, although certain sectors are currently facing advanced stages of CE (specifically, CE 3.0), the mineral processing area struggles to develop from the basic CE standards (i.e, CE 1.0 to CE 2.0).

Nearly 20 years after Lacher and Goldstein (1997) review on tropical ecotoxicology, many of the problems and research gaps still exist and are pertinent to the soils in LA. Contrary to the rise in soil hazards, research on soil ecotoxicology has lagged. It is crucial to gain a deeper grasp of these problems. Improved knowledge and comprehension can be utilized to create new laws and regulations or to uphold already-existing soil preservation rules.

Researchers in LA are most concerned about the use of pesticides in agriculture and the intensification of agriculture. Due to how widely they are used, related issues like agricultural uses of industrial wastes or byproducts from livestock production (such fertilizers) are becoming more important. Complex matrices of metals, pesticides, salts, veterinary medicines, and other contaminants are included in contamination profiles. Furthermore, given the necessity to strengthen specialized environmental rules for this industry, risk assessment of polluted land arising from large-scale industrial activities (such mining and oil extraction) is another field of research that is of current interest.

The majority of current research focuses on single-species experiments employing populations that are comparable to those of commonly utilized species in Europe. By using native species to LA and more test species from other soil organism groups, effects assessment of chemicals might benefit. Making ensuring that "local populations" of standard test species are reliable surrogates with sensitivity to toxicants comparable to that of local species from the same taxon is an alternative to utilizing native species. When there are still questions about potential dangers, the use of native species may be limited to higher-tier impacts assessments if the sensitivities are equivalent. Use of soil mesocosms (such the Terrestrial Model Ecosystems), which may be used to assess the effects and risk of stressors at the community level, could be one such strategy.

6. Air remediation

Due to the fact that air contaminants are dangerous and provide a greater risk of death, they have always received special attention. The deterioration of air quality has a negative impact on the natural system (e.g., living organisms and vegetation) as well as human health, potentially leading to fatal diseases such as cardiovascular disease, respiratory

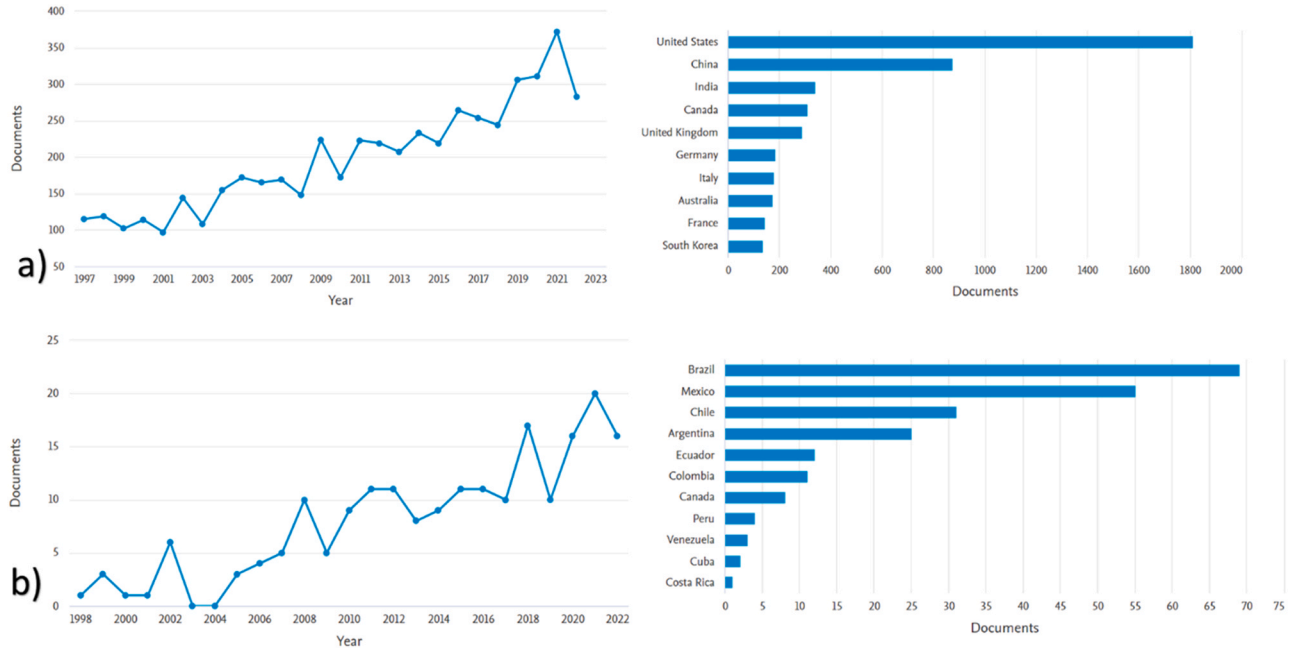

Fig. 7 – Research conducted in Air Remediation, a) International, b) LatinAmerica.

disease, and cancer (Occelli et al. 2020;). According to the World Health Organization (WHO), air pollution kills over seven million people per year around the world. According to WHO data, over nine out of ten individuals breathe air with high levels of pollutants (https://www.who.int/healt, 2020). As a result, obtaining accurate information on air pollution sources and developing novel solutions for air remediation is critical. Changes in the natural atmospheric composition caused by the addition of biological, physical, or chemical compounds released by biogenic, geogenic, or anthropogenic sources are referred to as air pollution. Interior and exterior air pollutants may exist as particulate or gaseous particles (Spinazzè et al. 2020). Small-sized masses of complex chemical constituents with sizes ranging from nanometers to micrometers, including aerosols of biologic origin such as fungi, bacteria, and viruses, are classified as particulate, whereas chemical molecules such as ozone (O_3), sulfur dioxide (SO_2), and carbon monoxide (CO) are classified as gaseous (Zhao et al. 2020).

Fossil fuels, being the most significant cause of air pollution, currently meet the bulk of the world's energy needs. It should be mentioned that the use of fuels is necessary for both daily life and industrial operations. The release of various toxins, including volatile organic compounds (VOCs), HgO, SO_2, NOx, CO, and CO_2, has significant ecological implications. Industries' gas wastes account for the majority of hazardous gases such as volatile organic compounds and carbon monoxide (Thangadurai et al. 2020). Furthermore, ash could be produced during a variety of occurrences.

The most serious effect of outdoor air pollution is global warming, which has the potential to produce serious worldwide variations in the atmosphere, water resources, and on land. Fluorinated gases, nitrous oxide, methane, and carbon dioxide are all known greenhouse gases that contribute directly to global warming. Fortunately, all of the aforementioned contamination species can be technologically managed before being released into the environment, as there are various possible strategies for transforming them into less dangerous forms. Several management and treatment strategies have been developed to eliminate and monitor the release of these gases, as well as to eliminate the threats that these gases pose to the environment and human health (Idrees and Zheng, 2020).

In Latin America, several efforts have been made to reduce and remediate existing air pollution, and various methodologies, materials and strategies have been proposed for this purpose. However, in this particular area, no Latin American country appears in the top 10 countries with the greatest contributions. Although the contributions are not comparable to those made internationally, Brazil, Mexico and Chile lead in the number of works published in this area of knowledge. Fig. 7 shows the metrics in this area.

In the following sections, some examples of the work done in this geographical area will be briefly mentioned.

A considerable amount of work has been focused on the development of materials that aid in air remediation. For example, TiO_2 (titanium dioxide) has shown great potential in solar cell applications as well as chemical pollution and toxin cleanup. Nanophotocatalysts have advanced tremendously in recent decades for a range of industrial applications (e.g., water purification and reuse, disinfection of water matrices, air purification, deodorization, and soil sterilization). Ramos-Delgado et al. (2016) describe traditional and new industrial routes for producing nanophotocatalysts, as well as the characterization techniques used to determine physical chemical properties such as surface area, potential, crystal size, phase crystallographic, morphology, and optical transparency. Finally, they discussed several industrial nanophotocatalyst uses.

Torrente-Murciano et al. (2017) add to our understanding of the critical parameters that lead to high activity and stability of catalysts in order to achieve low temperature VOC (volatile organic compound) activity in air pollution remediation applications. In comparison to their monometallic equivalents, bimetallic gold–iridium catalysts have a synergetic activity effect on the total oxidation of volatile organic molecules (e.g. toluene), resulting in catalytic activity at lower temperatures. The interaction of the iridium and gold species, which alters the electrical environment of the active sites and aids oxygen activation at lower temperatures,

facilitates activity augmentation. In addition, in contrast to monometallic situations, the bimetallic system exhibits a significantly stronger metal–support contact capable of reducing the deleterious loss of activity associated with metal sintering at high reaction temperatures. On the other hand, Urdapilleta-Inchaurregui et al. (2020) described a single-step thermal technique to synthesis a nanocomposite using natural clays from a Phaeozem soil, designed Ag-nanoparticles (NP), TiO 2-NP, and exhausted coffee grounds to breakdown or filter contaminants from soils, water, or air. Through nitrogen gas adsorption and the Brunauer-Emmett-Teller (BET) equation, the surface properties and porosity of the composite were investigated, and the microporous composites had a surface area of 17.36 m 2 g-1. The crystalline structure and crystalline phase of the nanocomposites were revealed by X-ray diffraction. TiO2-NP surrounding Ag-NP, and both were impregnated on natural soil NP, according to high-resolution transmission electron microscopy (HR-TEM) and scanning transmission electron microscopy (STEM). X-ray photoelectron spectroscopy was used to investigate the oxidation states of Ag-NP and TiO2-NP (XPS). Ultraviolet–visible diffuse reflectance (UV–Visible DRS) was used to evaluate the energy gap of nanocomposite 8NC. This nanocomposite's photocatalytic activity was tested. The nanocomposite with Phaeozem-soil-NP (8NC) decomposed 82.31% of the hazardous organic molecule methylene blue (MB) in 150 min, while the antibacterial activity and resistance against Escherichia coli and Staphylococcus aureus, as well as the zone of inhibition (ZOI), were all 15 mm. The nanocomposite Ag-NP/TiO2-NP/natural-soil NP/exhausted coffee-ground demonstrated its promise as a material for environmental remediation with photocatalytic and antibacterial properties.

According to Habran et al. (2018), the efficiency of photo-oxidation of pollutants catalyzed by semiconductors is still limited for real-world applications due to several drawbacks, including a) insufficient absorption of visible radiation, which dominates in the solar spectrum, b) rapid free electron to hole recombination, c) small surface area, which is built from equilibrium crystallographic facets with low adsorption capacities, and d) photo-corrosion. Their research revealed new mesoporous heterostructures made of exfoliated lepidocrocite-like ferrititanates and a TiO2 (anatase)-acetylacetone charge transfer complex, which are capable of reducing free electron-to-hole recombination rates through a robust charge separation and are visible light sensitive. Soft chemistry and low-temperature calcination at 300 °C are used in the synthesis. HM-1 and HM-2 are two separate partially pillarized heterostructures that have been created. In compared to the benchmark photocatalytic material P25, the heterostructure HM-1 was shown to be four times more active in photocatalytic NO gas degradation. The high value of Urbach energy, which implies a large number of defect sites inside the energy band-gap of the constituent semiconductor components, was related to the reduced activity of the heterostructure HM-2, which was comparable to that of P-25. The mol ratio of [Ti] anatase to [Ti] ferrititanate could also affect photocatalytic effectiveness.

Plant surfaces have long been recognized as a significant sink for a variety of air pollutants, including particulate matter and its potentially hazardous constituents. Furthermore, the leavessurface, or phylloplane, is a habitat for a variety of bacterial populations (epiphytic). However, little is known about their potential roles in the phytoremediation of air pollutants such as PTE. Sánchez-López et al. (2018) reported a study of plant leaf epiphytic bacteria colonizing mineresidues (MR) containing PTE as a key to understanding and exploiting plant–epiphyticbacteria interactions for air phytoremediation. They wanted to characterize the functions of epiphytic bacteria isolated from the phylloplane of Brickellia veronicifolia, Flaveria trinervia, Gnaphalium sp., and Allionia choisyi growing spontaneously on multi-PTE contaminated MR, and (ii) compare them to the same plant species in a non-polluted control site (NC). PTE concentrations on MR leaf surfaces of A. choisyireached up to 232 for Pb, 13 for Cd, 2728 for As, 52 for Sb, 123 for Cu inF. trinervia, and 269 for Zn in Gnaphaliumsp (mg kg1). The amount of colony-forming units per cm2 was higher in MRleaves than in NC ones in all four plant species, with A. choisyi being the plant species with the highest value. Furthermore, in MR leaves, the proportion of isolates tolerant to PTE (Zn, Cu, Cd, and Sb), UV radiation, and drought was higher than in NC leaves. Strain BA15, derived from M. veronicifolia, tolerated 150 mg Zn L1, 30 mg Sb L1, 25 mg Cu L1, and 80 mg Pb L1 and was able to thrive despite 12 h of continuous UV exposure and 8 weeks of drought. Plant growth promotion-related features of bacterial isolates [nitrogen fixation, indole acetic acid (IAA) synthesis, and phosphate solubilization] differed between plant species and between MR and NC sampling conditions. The epiphyticisolates investigated have functions that are relevant to phytoremediation of air pollution. The findings of this study could aid in the creation of new and more effective inoculants for microbe-assisted phytoremediation, which is used to enhance the air quality in places where metal mine tailings have been dispersed.

Ruiz-Gil et al. (2020) evaluated and addressed current achievements in the research of airborne bacterial communities in outdoor contexts, as well as the potential variables influencing their abundance, diversity, and seasonal change, in an interesting review. Furthermore, airborne bacterial activity and bioprospecting in several industries (for example, textiles, food, medicine, and bioremediation) are covered. Their review discloses the importance and influencing aspects of airborne bacteria in outdoor contexts, as well as spark new research on the atmospheric microbiome, particularly in locations where air quality is a public concern. In comparison to indoor aerosols and nonbiological components, microbial entities (such as bacteria, fungi, archaea, and viruses) in outdoor aerosols have been investigated sparingly, and only in the last few decades have their investigations expanded. Bacteria make up a significant portion of the microbial diversity and abundance in a variety of rural and urban outdoor bioaerosols. Airborne bacterial populations are now primarily sampled in two aerosol size fractions (2.5 and 10 m) and characterized using culture-dependent (plate-counting) and culture-independent (DNA sequencing) methods. Proteobacteria, Firmicutes, Actinobacteria, and Bacteroidetes are among the most common phyla found in bioaerosols, according to research. Seasonal differences in the dispersion of bacterial populations, as well as their association with certain meteorological conditions, have been identified between geographical areas. Several studies have also suggested that airborne bacteria are important in the fields of public health and agriculture, as well as remediation and atmospheric processes. However, despite recent proposals for factors influencing airborne bacterial communities and standardized methodologies for their assessment, the use of bacterial taxa as microbiological markers of specific bioaerosol sources and seasonality has not been widely investigated.

Passalía et al. (2017) developed an integrated reactor design approach to address the optimal design of photocatalytic wall reactors for air pollution control. The suggested methodology starts with a mechanistic determined reaction rate to remove a target pollutant from an air stream. The employment of a basic geometry laboratory scale reactor, kinetic control, and a uniform incident radiation flux, which allows estimating the local superficial rate of photon absorption, is related to the measurement of intrinsic kinetic parameters. As a result, a simple model may be used to represent the mass balance, and a solution can be found. A combination of the mathematical model and the experimental results can be used to determine the kinetic parameters. The validated intrinsic kinetics that were acquired can be used to scale up any reactor type and size. To determine the fields of velocity, radiation absorption, and species concentration for the bench-scale reactor, complicated computational tools may be required. The entire process was used to successfully eliminate airborne formaldehyde. A flat plate reactor was utilized to estimate the kinetic parameters, while a bench size corrugated wall reactor was employed to demonstrate the scaling-up process. Additionally, using computational fluid dynamics methods, an ideal folding angle for the corrugated reactor was discovered.

As noted so far, various materials or technologies have been developed for air treatment. In addition, several works stand out for the proposal of novel strategies or methodologies developed for the same purpose. For example, a strategy developed particularly in a city near the center of Mexico was presented by Barrón-Adame et al. (2012). Salamanca is regarded as one of Mexico's most polluted cities. A Self-Organizing Maps (SOM) Neural Network was constructed at three monitoring stations from January 1 to December 31, 2006, to study the behavior and clarify the influence of wind conditions on Sulphur Dioxide (SO_2) concentrations. The greatest and minimum daily SO_2 concentrations measured in 2006 were associated with wind parameters measured during the same time period. The SOM Neural Network's key benefit is that it allows input from various sensors to be combined and results to be easily interpreted. It is particularly useful as a mapping and categorization tool, as it makes the work of establishing a priority order between distinct groups of concentrations based on the need for additional research or remedial activities in later management steps much easier. SOM classifications were compared to pollution levels provided by health authorities for each monitoring station. The classification system can aid in the development of a better air quality monitoring methodology, which is necessary for evaluating the efficiency of imposed pollution controls and policies, as well as facilitating the reduction of pollutants.

The urban vortex system (UVS) was proposed by Rodriguez-Lucas et al. (2021). The UVS combines a vortex generator (V.G.) that creates an artificial updraft with a vortex stability zone (VSZ), which is made up of four structures that operate as a chimney. A stable, upward vortex flow can be created with this method. The flow field in the UVS was investigated using a Reynolds Averaged Navier–Stokes (RANS) simulation. To address the complex turbulent flow, the Renormalized Group (RNG) k–turbulent model was chosen. A comparison with the large-scale experimental model was used to validate the numerical results. When a vapor-air mixture at 2 m/s and 450 K enters the vortex generator, a steady-state vortex can be created, according to the findings. The maximum negative central pressure was 6.81 Pa, and the maximum velocity was 5.47 (m/s) in this vortex. Finally, the similarity method identified four dimensionless parameters that enabled the large-scale transmission of all flow properties. The suggested large-scale UVS application is expected to be capable of generating winds of 6.1 m/s (20 km/h) at 200 m up to 1.5 m/s (5 km/h) at 400 m, with a maximum power of 2 M.W., a specific work of 3 kJ/kg, buildings 200 m high, and the potential to generate winds of 1.5 m/s (5 km/h) at 400 m. These winds would force the heat island phenomenon's gas capsule to explode. As a result, the city's temperature would be balanced with that of the surrounding rural areas.

Exposure to heavy metals has been related to serious health issues. The Monterrey metropolitan area (MMA) in Mexico is regarded as one of the most polluted industrial areas in the country. The levels of lead, cadmium, and arsenic in Great-tailed grackles (Quiscalus mexicanus) feathers from two sites within and one site outside the MMA were determined because birds have been employed successfully as environmental biomonitors. A hundred birds were taken, and atomic absorption spectrometry was used to evaluate the samples. The highest mean concentrations of lead and cadmium were found in Ciudad Universitaria, with 11.91 ppm d.w. and 1.66 ppm d.w., respectively. This was at least ten and eight times higher than the other two sample locations. Guzmán-Velasco et al. (2021) employing Great-tailed grackles as bioindicators in conjunction with air pollution sampling from meteorological stations in Monterrey City could aid in environmental remediation decision-making as well as the selection of housing, school, and job locations, among other things.

On the other hand, at certain quantities, ozone is a significant pollutant. High levels of ozone (O_3) in the atmosphere are a global issue that persists. Although studies have shown that trees can remove O_3 and one of its precursors, nitrogen dioxide (NO2), the cost-effectiveness of peri-urban regeneration for O3 abatement has not been investigated. To analyze the performance of reforestation for O3 precursor abatement, we construct a methodology that leverages available air quality and meteorological data, as well as simplified forest structure growth mortality and dry deposition models. Kroeger et al. (2014) described a methodology for determining the most cost-effective design for a hypothetical 405-hectare peri-urban reforestation project in Texas' Houston–Galveston–Brazoria O3 nonattainment area. Over the course of 30 years, the project would remove an estimated 310 tons of (t) O3 and 58 tons of NO_2. This is comparable to 127–209 t of regulated NOx, based on its placement in a nitrogen oxide (NOx)-limited area and the range of Houston area O3 production efficiencies used to convert forest O_3 removal to its NOx equivalent. If no land expenditures are required, the cost of reforestation per ton of NOx abated compares well to the cost of additional conventional controls, especially if carbon offsets are generated. Purchasing agricultural areas for reforestation eliminates this financial advantage, however, cost-share opportunities exist due to the public and conservation advantages of reforestation, therefore this problem could be solved. Our findings imply that peri-urban reforestation should be addressed in O3 control efforts in Houston and other nonattainment locations in the United States, as well as areas with O_3 pollution problems in other nations, where O_3 generation is mostly controlled by NOx.

In the south of the continent, Chile's housing stock accounts for 15% of the country's total final energy consumption, prompting the government to regulate housebuilding. However, models must be developed to assist governments in determining the appropriate direction. The Chilean Housing Archetypes AiR quality Model (CHAARM) and a stochastic framework for estimating uncertainty in indoor pollutant concentrations, ventilation and infiltration rates, and associated energy consumption during the heating season are provided in the work of Molina et al. (2021). PM2.5 is emitted by cooking, and unflued heaters, which are found in 80% of homes, are pollutant sources. Even if their windows are kept closed, CHAARM anticipates that 66% of homes have a daily mean PM2.5 concentration below the WHO 24-hour guideline limit of 25 lg/m3. Houses are not found to be airtight, with $Q_{50} > 10\,m^3\ h^{-1}\ m^{-2}$ in 60% of cases. With 90% confidence, dwelling ventilation and infiltration heat loss is predicted to be 0.25–42.3 MWh, accounting for at least 15% of the stock's anticipated total energy consumption. As a result, many homes require remediation steps to improve airtightness and lower annual space heating demand. Kitchen ventilation, such as a cooking hood, should be installed, and unflued heaters should be changed, to reduce harmful health impacts from PM2.5 exposure.

In this section, we have shown several strategies that have been used in Latin America to mitigate the effect generated by the presence of pollutants in the air. The strategies shown consider different stages, from the modeling of pollutants in the air, to the implementation of strategies for the capture or removal of pollutants.

In general, emissions generated by combustion represent an important challenge to abate. However, the strategies used in this section are supported by state-of-the-art scientific and technological support that can generate viable alternatives.

7. Biofuels production

In 2010, the global energy consumption was 5.5 × 1020 J. According to the studies, the value will increase by a factor of 1.6 by 2040, reaching 8.6×1020 J. The transportation and industrial sectors are the primary drivers of oil demand (European Commission Transport, 2019). The transportation industry, which consumes a quarter of the world's energy and emits half of all carbon dioxide, is also responsible for half of the expected growth in oil consumption between 2003 and 2030. Despite the fact that electricity has been proposed as a viable option for lowering CO2 emissions in transportation (Yabe et al. 2012), transport biofuel is expected to be the most important alternative energy in the industry. According to the IEA's mobility model results, biofuels will account for 31% of global transportation fuel use by 2060, followed by electricity at 27%. Biofuel can refer to any type of fuel obtained from biomass, and it can be used in a variety of applications, including home energy (cooking and heating), electricity generation, and transportation. Biofuels are typically divided into the following categories (Awogbemi et al. 2021):

1. First-generation biofuels (1 G) are made from biomass that is commonly consumed.
2. Second-generation biofuels (2 G) are fuels made from a variety of diverse feedstocks, including lignocellulosic feedstocks and municipal solid wastes.
3. Third-generation biofuels (3 G) are currently tied to algal biomass but could be linked to some extent to the use of CO2 as a feedstock in the future.
4. Genetically modified fourth-generation biofuels (4 G). 4 G is being developed from algal modification, albeit it is still in the experimental laboratory stage.

Regarding research work carried out in Latin America, valuable efforts have been made and are reflected in international statistics. Considering the keyword biofuels, scopus projects what is shown in Fig. 8. Brazil is the only Latin American country in the top 10 of products oriented to biofuels production, with a number of published documents that places it in fourth place worldwide. Focusing only on Latin America, Brazil is followed by Mexico, Colombia and Chile.

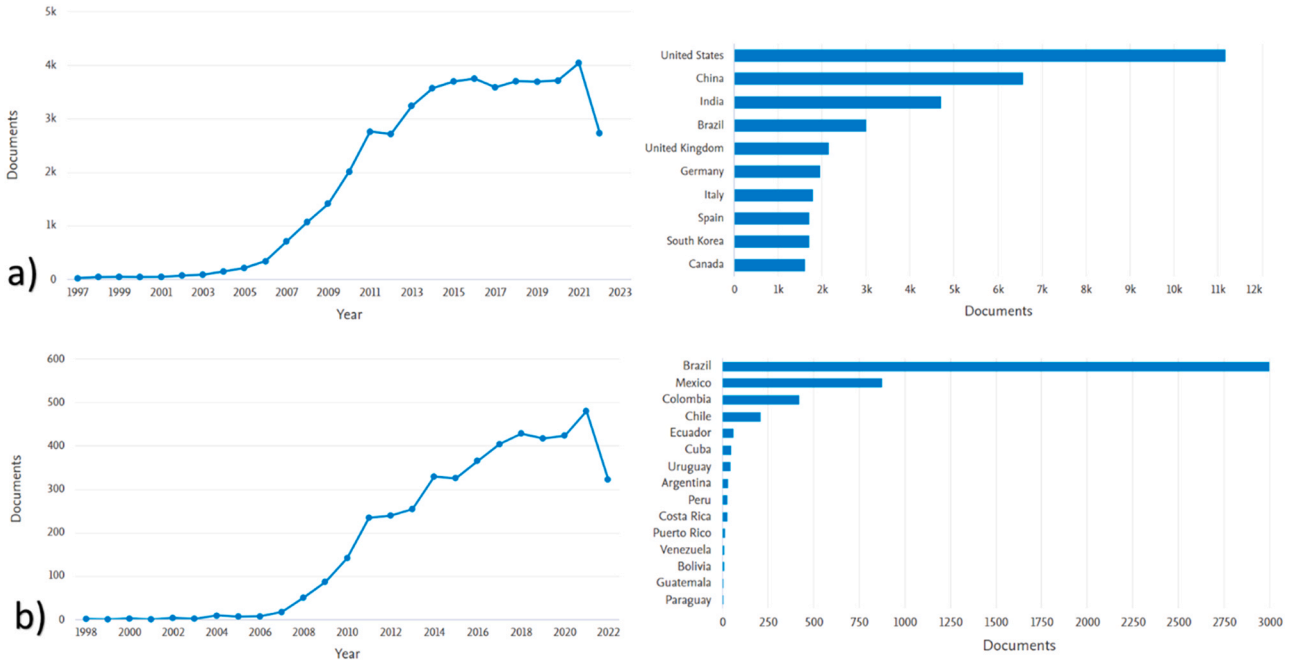

Fig. 8 – Research conducted in Biofuels, a) International, b) LatinAmerica.

Much work has been put into modeling and simulation of various biofuel manufacturing processes throughout Latin America. Many countries' legislation requires bioethanol to be combined with gasoline to achieve environmental sustainability by lowering the usage of fossil fuels (E5, E10, E15, etc). Bioethanol is made by fermenting a large amount of organic waste or biomass in diluted aqueous media.

The thermally coupled extractive distillation column and the extractive dividing wall column are the most popular enhanced systems for the purification of bioethanol in the early stages of bioethanol production. According to published studies, thermally coupled extractive distillation systems save energy when compared to traditional distillation columns (Gutiérrez-Guerra et al. 2009; Bravo-Bravo et al. 2010).

Hernández (2008) investigated three sophisticated extractive distillation solutions for the purification of a dilute mixture of ethanol and water in a groundbreaking article. The first option employs an extractive distillation column, whereas the second and third choices employ thermally coupled extractive distillation sequences. According to the findings, the fully thermally connected extractive alternative can cut energy usage by 30% when compared to the extractive distillation column scheme. This fully thermally coupled extractive distillation process can generate ethanol with a mass fraction of 0.995 as the distillate, the entrainer as the bottoms product, and a mixture of ethanol and water as the sidestream.

Mulia-Soto and Flores Tlacuahuac (2011) study focuses on the modeling, simulation, and control of an internally thermally integrated pressure-swing distillation process to separate the ethanol/water azeotropic binary system into a high purity ethanol stream.

Tututi-Avila et al. (2014) investigated the design and control of an extractive dividing wall column, with the dividing wall at the top half of the column, as an alternative to a traditional extractive distillation sequence for dehydration of bioethanol to 99.5 wt percent ethanol. In Aspen Plus, the process is mimicked with a 93% ethanol in water supply. The genetic algorithm and Aspen Plus were used to optimize the aforementioned two sequences. When compared to a standard extractive distillation design, the ideal extractive dividing wall column saves 12.4% in TAC.

To formulate hybrid units and divided wall columns obtained by lignocellulosic fermentation broth, Torres Ortega and Rong (2016) proposed replacing flashes with column sections, hybridizing unit operations by reformulating column sections, and relocation of column sections as novel synthesis approaches. The new intensified options saved money, with TAC (total annual costs) savings ranging from 17% to 23% and energysavings ranging from 18% to 28%. Furthermore, the number of separation units was reduced from eight to three from the original eight. The cost reductions from the intensified system were 15–20% higher than the multi-effect approach.

Oseguera-Villaseñor (2018) investigated the energy optimization of thermally connected distillation sequences for the purification of bioethanol utilizing glycerol as entrainer. Three possibilities for the heat duty provided to the reboiler were discovered during the energy optimization. According to the literature, these multiplicities have been identified in binary distillation and complex reactive distillation columns. Nonlinearities in the model, physical qualities, and interactions between the reaction and the separation can all be blamed for these multiplicities. This conclusion is significant because we're trying to figure out how to use energy efficiently in order to lessen the environmental impact of using and producing petroleum-based energy.

Guzmán-Martnez et al. (2022) propose an economic and environmental evaluation of different ethanol dehydration processes based on ethylene oxide/propylene oxide hydration and azeotropic distillation with benzene and cyclohexane, using simulation. These reactive methods include traditional reaction separation processes as well as intensified processes such as reactive distillation, both of which are combined with organic Rankine cycles to provide an additional value-added product (ethylene glycol or propylene glycol), electric power generation, and the ability to reduce the number of global process steps in anhydrous ethanol production. The results show that among all the processes evaluated for anhydrous ethanol production, reactive dehydration, specifically the reactor–separator process using propylene oxide at a low ethanol concentration, is the most cost-effective and environmentally friendly.

Biodiesel is a sustainable energy source that is made mostly from renewable lipid feedstocks and is therefore environmentally benign. Biodiesel production research is an economic field that aims to reduce greenhouse gas emissions and promote long-term economic growth by addressing the worldwide dilemma of limited energy resources (Chen et al. 2022). In general, the main processes in prevalent biodiesel manufacturing are esterification/transesterification of free fatty acids/triglycerides with alcohol using catalytic (chemical and biological catalysts) and non-catalytic methods. Because of the faster reaction time and high yield, biodiesel manufacturing employing a chemical catalyst is the most marketed of all the catalytic processes (Bharathiraja et al. 2014). Chemical catalysis, on the other hand, has some drawbacks, including catalyst recovery and recycling, an excessive amount of alkaline effluent, and the difficulty of downstream product purification.

da Silva et al. (2010) proposed an efficient approach for producing biodiesel and bioethanol from soybean oil utilizing reactive distillation columns. Catalyst concentration, reaction temperature, agitation level, ethanol/soybean oil molar ratio, reaction time, and raw material type are all important factors in the biodiesel synthesis process. The experimental design was utilized to find the best catalyst concentration and molar ratio of ethanol to soybean oil.

Pérez-Cisneros et al. (2016) devised an integrated heterogeneous two-step reactive distillation process for biodiesel synthesis in their article. The creation of reactive residue curve maps in terms of elements was used to conceptualize the reactive distillation columns. The esterification reactive distillation column had one reactive zone filled with Amberlyst 15 catalyst, while the transesterification reactive distillation column had two reactive zones filled with MgO. The proportion of fatty acids in the vegetable oil feed has a significant impact on the performance of the integrated esterification–transesterification reactive distillation process (energy cost, catalyst load, methanol flow rate), according to the findings.

Gómez-Castro et al. (2010) propose a modification of the supercritical method for the generation of biodiesel fuel. Reactive distillation or thermally coupled reactive distillation are used in the process. The reactive distillation column consumes more energy than the thermally connected system. Gómez-Castro et al. (2013) extend the research by presenting a simulation analysis of a biodiesel synthesis

process with methanol at high pressure and temperature. Energy, cost, and environmental impact are all factors considered in the study. Modifications to the original process have been proposed and tried, including the intensification of the esterification section through the use of reactive distillation systems. The paper highlights the advantages of utilizing reactive distillation for the esterification stage and addresses the supercritical production process' environmental impact.

Miranda-Galindo et al. (2011) investigated reactive distillation with thermal coupling (using the generation of fatty esters for use as biodiesel as a case study), generalizing the usage of a multiobjective evolutionary algorithm with limitations coupled to Aspen Plus. The Pareto front results show that changing operational conditions can greatly reduce the energy consumption of the complex distillation sequence. The thermally connected reactive distillation sequences' energy consumption, total annual cost, and greenhouse gas emissions were studied.

López Ramírez et al. (2016) built a laboratory-scale dividing wall column to explore the esterification reaction of oleic acid and methanol using sulfuric acid as a homogeneous catalyst. The optimal conditions for the formation of fatty acid methyl esters, according to experiments, are molar ratios of methanol/carboxylic acid, reaction duration temperature, and catalyst weight. These findings are useful as a first step toward producing biodiesel with an acid homogenous catalyst in a reactive dividing-wall distillation column.

On the other hand, in work provided by Laborde et al. (2019) was analyzed the potential of biodiesel generation from Jatropha curcas oil. The proposed process was simulated in the software Aspen Plus involving the stages of trans-esterification reaction, methanol recovering, purification of the produced methyl esters, catalyst removing, purifying of glycerol and the energy integration through heat exchange networks (HEN) (HEN). The biodiesel process was carried out through the catalytic reaction of transesterification of Jatropha oil with methanol utilizing a molar ratio of methanol oil of 6:1, and with 1% w/w of NaOH (related to oil mass) as catalyst. Under these conditions, it is technologically viable to carry out the production of biodiesel. With energy integration through the synthesis of HENs, reductions of 8.5% and 6.5% of hot and cold utilities were realized. This way, the utility cost decreases 7.2%. The net present value (NPV) for the integrated process was 7.3% greater than the one corresponding to the non-integrated process under the identical production conditions.

Butanol may be utilized as a fuel in addition to being a solvent, chemical intermediary, and extract agent, which has piqued people's interest in recent years. Butanol has the potential to be a good fuel in the future due to its favorable qualities of high heat value, high viscosity, low volatility, high hydrophobicity, and low corrosivity. Butanol, when compared to ethanol, overcomes the shortcomings listed above and indicates possible benefits. Butanol, for example, has a higher energy content and burn efficiency, allowing it to be utilized over extended distances. Butanol has a similar air-to-fuel ratio and energy content to gasoline. As a result, butanol can be combined with gasoline in any ratio.

Sánchez-Ramírez et al. (2015) investigated various process strategies for purifying biobutanol from sugarcane molasses. Three of the four options are exclusively dependent on distillation columns. The first column in these three designs is responsible for concentrating the solution from the fermentation broth up to the azeotropic point. Depending on the strategy, the second column can be utilized to obtain acetone or to further distribute the components. The existence of the heterogeneous azeotrope is employed to obtain a butanol-rich stream using a decanter after the components have been redistributed. Finally, two high purity streams of butanol and water can be obtained utilizing two final distillation columns. A liquid-liquid extraction column, on the other hand, is used to set up the configuration that finally proved to be the most promising. With the use of a solvent, this column can break down the azeotropes present. The organic stream from the extraction column is separated in three distillation columns in a more straightforward manner, with the solvent recirculated. A differential evolution technique was used to optimize the designs. The results showed that a hybrid process consisting of a liquid-liquid equilibrium column followed by steam stripping distillation was a viable design in today's economic conditions, as determined by a total yearly cost calculation. González-Bravo et al. (2016) describe an optimization approach for constructing energy integrated biobutanol separation processes, which can be considered a reference case because various designs were proposed based on those schemes. The optimization includes appealing hybrid separation options involving integrated heat exchanger networks, stream Rankine cycles, organic Rankine cycles, and absorption refrigeration cycles, as well as several options for waste heat recovery involving integrated heat exchanger networks, stream Rankine cycles, organic Rankine cycles, and absorption refrigeration cycles. Angelina-Martínez et al. (2015) investigated the dynamic behavior of the four alternatives proposed by Sánchez-Ramírez et al. (2015). In general, the results show that intensified systems for the purification of biobutanol have greater dynamic performance.

Sánchez-Ramírez et al. (2017b) were the first to describe the purification of the ABE mixture using a hybrid separation based on liquid-liquid extraction and dividing wall column technology. The proposed configurations are the outcome of a multi-objective optimization process that tries to find solutions that balance the three objectives of cost reduction, environmental impact reduction, and controllability. Among the four systems assessed, the plan with a separating wall column thermally coupled to a standard distillation column has the most balanced design, with the lowest overall annual cost values, as well as favorable environmental effect and dynamic behavior.

Segovia-Hernández et al. (2020) investigated 10 hybrid and intensified configurations for purifying butanol to fuel grade, based on liquid-liquid extraction and dividing wall columns. By using the singular value decomposition technique, the study examines sustainability using green metrics, including the inherent safety and control qualities. The findings show that as long as the process is highly intensified, the inherent safety and sustainability improve, but not necessarily the control properties. The loss of degrees of freedom in intensified processes is the main reason for this.

Quiroz-Ramírez et al. (2018) modelled and optimized a lignocellulosic material-based process for producing acetone, butanol, and ethanol. The raw material selection was planned first, followed by simulated intensified simultaneous saccharification, fermentation, and separation reactors, and finally, the fermentation stream was purified by assessing three intensified separation systems. Using a hybrid stochastic technique, the entire enhanced process was

evaluated in an optimization process that considered environmental, economic, and energetic objective functions. The collected results revealed that the optimal scheme for producing and purifying butanol is one that takes into account all of the products created during the fermentation process using thermally linked columns.

Using pervaporation, pressure swing distillation, and azeotropic distillation, Sánchez-Ramírez et al. (2021) suggested purification strategies to get high purity butanol from a butanol-water mixture in compositions created by reduction of volatile fatty acids. The model's multiobjective optimization was used to assess the sustainability indicators, which included four objectives: total annual cost, environmental effect, intrinsic safety, and control features. The pervaporation method proved to be the most promising option.

Biojet fuel, on the other hand, has emerged as a critical component of the aviation industry's plan for lowering operating costs and reducing environmental effect. This jet fuel must fulfill ASTM International requirements and be a direct substitute for current petroleum jet fuel. Conceptual intensified process design, process economics, and life-cycle assessment of greenhouse gas emissions are the primary hurdles for the technology pathway. Despite substantial constraints such as feedstock price, availability, and process energy intensity, biomass-derived jet fuel has the potential to replace a considerable amount of conventional jet fuel (Wang and Tao, 2016). It's worth noting that research into the development of the biojet fuel production-purification process is a relatively new field with a lot of potential. To yet, just a few research have been published.

Romero-Izquierdo et al. (2020) presented the modeling and simulation of the traditional alcohol-to-jet-fuel process (ATJ), using bioethanol produced from lignocellulosic wastes as the raw material. The ATJ process uses the effluent from the co-fermentation reactor, which is part of the bioethanol production process that uses lignocellulosic wastes as a raw material. This effluent is made up of 257,673 kg/h of bioethanol, as well as traces of glycerol, water, and ammonia. The ATJ process includes dehydration, oligomerization, and hydrogenation, as well as a separation zone.

The total annual cost and CO2 emissions of the ATJ conventional and intensified-integrated processes are compared. In comparison to the conventional sequence, intensification on the separation zone allows for a 5.31% reduction in energy requirements; additionally, energy integration of the intensified process reduces heating and cooling requirements by 34.75% and 30.32%, respectively; as a result, total annual cost and CO2 emissions are reduced.

Modeling and simulation of a comprehensive biojet production plant has been attempted; for example, Gutiérrez-Antonio et al. (2018a, 2018b) presented the modeling of a conventional and enhanced hydrotreating process to create biojet fuel. The regenerated hydrocarbon stream exits the reactive section at 480 °C and 80 bar, which is a high pressure for a stream that will be fed into a distillation train. As a result, a turbine is used to condition the stream before sending it to the distillation train, as well as to create electrical energy for the process. The hydrocarbon stream is transferred into a distillation train once its pressure is reduced, where it is split into four products: light gases (C1-C4), naphthas (C5-C7), biojet fuel (C8-C16), and green diesel (C17-C21). Using conventional distillation, these products can be divided into five distillation sequences. Separation of the light components, on the other hand, involves the use of refrigerant as a cooling service; as a result, all sequences in which the light gases were not obtained in the first distillation column are eliminated. They also suggested installing a partial condenser in the train's first column to save on refrigerant. As a result, they exclusively consider direct and direct-indirect distillation methods. Jatropha curcas and microalgae oils are considered renewable raw resources for all hydrotreating procedures. The findings demonstrate that all hydrotreating procedures have identical total annual costs. However, the traditional structure's CO2 emissions are 34% higher than those indicated for an intensified alternative approach. As a result of the enhanced hydrotreating, biojet fuel can be produced with minimal environmental impact and at a competitive price when compared to fossil jet fuel.

Modeling, simulation, and intensification of the hydroprocessing of chicken fat to produce renewable aviation fuel were given by Moreno-Gómez et al. (2021). Traditional hydrotreating processes are modeled and used to define intensified hydrotreating methods, in which sophisticated configurations are used to purify the water. In terms of economic and environmental indicators, all processes are compared. The process that comprises conditioning and reactive zones, as well as a direct intensified sequence, is the optimal scenario in terms of economic and environmental indicators; in this scenario, there is the best trade-off between the price of biojet fuel and carbon dioxide emissions.

Sánchez-Ramírez et al. (2019) research the effect of several operational variables (triglyceride-water feed ratio, oleic acid-petro-diesel feed ratio, hydrogen consumption) on the performance of the intensified reactive separation process was investigated using intensive simulations. The water excess and total pressure for the heterogeneous catalytic hydrolysis reactor are key design and operating parameters for the production of biojet fuel, and if high molar flows of fatty acid are considered, it is mandatory to have more reactive stages in a reactive distillation column to achieve ultra-clean (no-sulfur) petro-diesel at the bottom of the column.

Gutiérrez-Antonio et al. (2020) present the application of intensification and energy integration strategies for the production of renewable aviation fuel in one of the most comprehensive publications on the subject to date. According to the authors, one of the most plausible options for designing economically profitable and sustainable processes for the large-scale manufacture of Biojet fuel from diverse biomass will be intensification.

In summary, although in Latin America and the Caribbean, sustainable energy generation from biomass represented only 4% in 2019, biomass makes up the majority of the growth of installed renewable capacity in the region. Brazil is the main driver. Countries are gradually incorporating more renewables into their energy mix. Costa Rica, for example, gets just under 99% of its electricity from renewable sources. Honduras doesn't get a majority of its electricity from renewable sources, but it's close – 48.9% (as of 2015). And other nations are planning on ramping up their use of renewables in the short-term; for example, Nicaragua hopes to reach 94% renewable energy by 2027 (CEPAL; 2020). As the price of oil inevitably rises – and as carbon emissions become curtailed by increasing amounts of regulation – the need for taking advantage of this region's natural resources will grow. Fortunately, there is both political will and abundant resources at work throughout Central and South America. Governments are perhaps even more willing, for

the most part, to incorporate biomass into their energy matrices than the United States (CEPAL; 2019),. The main thing that Latin America and the Caribbean will need is the technical expertise to create and expand renewable energy infrastructures, as well as the capital investment to make it happen. For those purposes, international companies and investors are well-equipped and are beginning to show more interest in energy development in these emerging countries (CEPAL; 2020). As can be seen from the review of the literature, advances in the area of energy derived from biomass in Latin America and the Caribbean are substantial and even pioneering original research has been carried out at the international level.

8. Process intensification

The importance of the chemical industry has been highlighted by the Covid-19 pandemic: masks, gloves, and other protective items, as well as alcohol and hand sanitizer, have become a staple of daily life for the global population, while plastic products have allowed for safe food packaging during lockdowns. All of this said, the petrochemical and chemical industries have been working to close the life cycle of plastic items for some years, and the pandemic will not solve the problem in Latin America. Environmental stewardship is simply one of many components of improving sustainability in a company's operations. These include not just trash management and recycling, but also greenhouse gas reduction and the utilization of greener raw materials. Sustainability also entails being a responsible employer, ensuring the health, safety, and decent remuneration and working conditions of employees, as well as being a good neighbor, supporting the communities in which operations are located, especially during times of crisis, such as the current one with Covid-19. The effective supply of green, sustainable chemical solutions on a large scale will necessarily need the development of revolutionary processing and engineering technologies capable of fundamentally and radically changing industrial processes. Process intensification (PI) can provide much-needed equipment design and processing innovation to boost process efficiency. PI attempts to reduce plant volume by a factor of 100–1000 by replacing traditional unit activities with unique, generally compact designs, which often combine two or more classic processes in one hybrid unit (Boodhoo and Harvey, 2013). Although cost reduction was the initial goal, it soon became clear that PI could provide other significant benefits, notably in terms of better intrinsic safety and lower environmental impact and energy usage, as will be detailed later in this section. The concept of PI has therefore developed over the previous two decades, from the simple statement of 'physical downsizing of process equipment while maintaining throughput and performance' to the complicated description provided lately by Tian et al. (2018). This definition refers to the activities that result in intensified processes, such as combining multiple process tasks or equipment into a single unit (e.g., membrane reactors, reactive distillations), miniaturization of process equipment (e.g., microreactors), equipment operation on a regular basis (e.g., simulated moving bed, pressure adsorption swing), and tight process integration (e.g., dividing wall distillation). Stankiewicz and Moulijn (2000) suggested another widely recognized PI definition. According to them, PI encourages the development of new technologies and techniques that, when compared to traditional methods, are predicted to enhance production and processes. Furthermore, smaller equipment, lower energy usage, and lower waste output are envisaged, resulting in cheaper and more sustainable solutions. Distillation is a critical component of PI since it is the most widely utilized separation technology in the chemical industry. Distillation is a method of separating liquid mixtures by taking use of variances in the boiling points of the various components. In industry, the process is commonly employed in the production and purification of nitrogen, oxygen, and rare gases, for example. The refining of crude oil into its principal fractions, such as naphtha, kerosine, and gas oil, is one of its most well-known applications. Distillation columns are notorious for using a lot of energy, which is an intriguing sustainability issue because distillation sequences use more than 40% of the energy used in the chemical industry (Kiss and Smith, 2020). This is an intriguing sustainability issue, and PI can assist in alleviating and improving it. PI has been used to achieve numerous significant breakthroughs in Latin America to make distillation and its uses in the industry more sustainable.

Scopus shows multiple papers on process intensification from Latin America. However, according to Fig. 9, there are not enough published papers containing these keywords from this region to place any Latin American country in the top 10 at the international level. Fig. 9 shows that the United States leads this category, followed closely by China. On the other hand, in Latin America, Brazil leads by a considerable margin over Mexico, Argentina and Colombia.

Other than Mexico, there have been few publications published in Latin America about the use of PI to make distillation more sustainable. The study by Hernández and Jiménez (1999) is a ground-breaking effort in Mexico on DWC. A approach for designing an energy-efficient completely thermally connected distillation column (Petlyuk system) is provided in this paper. The technique is based on a dynamic model that use two recycle streams as design variables to determine the reboiler's minimal energy supply. The dynamic model may be used for design and control research, which is why the approach is so important.

Jiménez et al. (2001), used the singular value decomposition approach and closed-loop responses under feedback control to analyze the controllability of seven distillation sequences for the separation of ternary mixtures. Nontraditional distillation sequences, such as the Petlyuk column, have higher control qualities than nonintegrated systems, according to the findings. This is significant since the presence of recycling streams was predicted to generate control issues.

Santaella et al.(2015) published a study on the reactive dividing Wall column (DWC). They compared several ethyl acetate manufacturing processes. The traditional procedure, reactive distillation, reactive distillation with pressure swing, and dividing wall column with reactive reboiler were all investigated for the synthesis of this chemical. When comparing sustainability factors, reactive DWC was shown to be the best option, saving 46% in energy and 26% in cost over the standard procedure.

Santaella et al. (2017), from the same research group, proposed a reactive DWC as an option for the manufacture of triethyl citrate. The enhanced method was compared to the conventional reaction-separation method. Final designs exhibited citric acid conversions of more than 99.9%, energy usage of 3–5 MJ/kg, and a TEC manufacturing cost of 1.5 USD/kg.

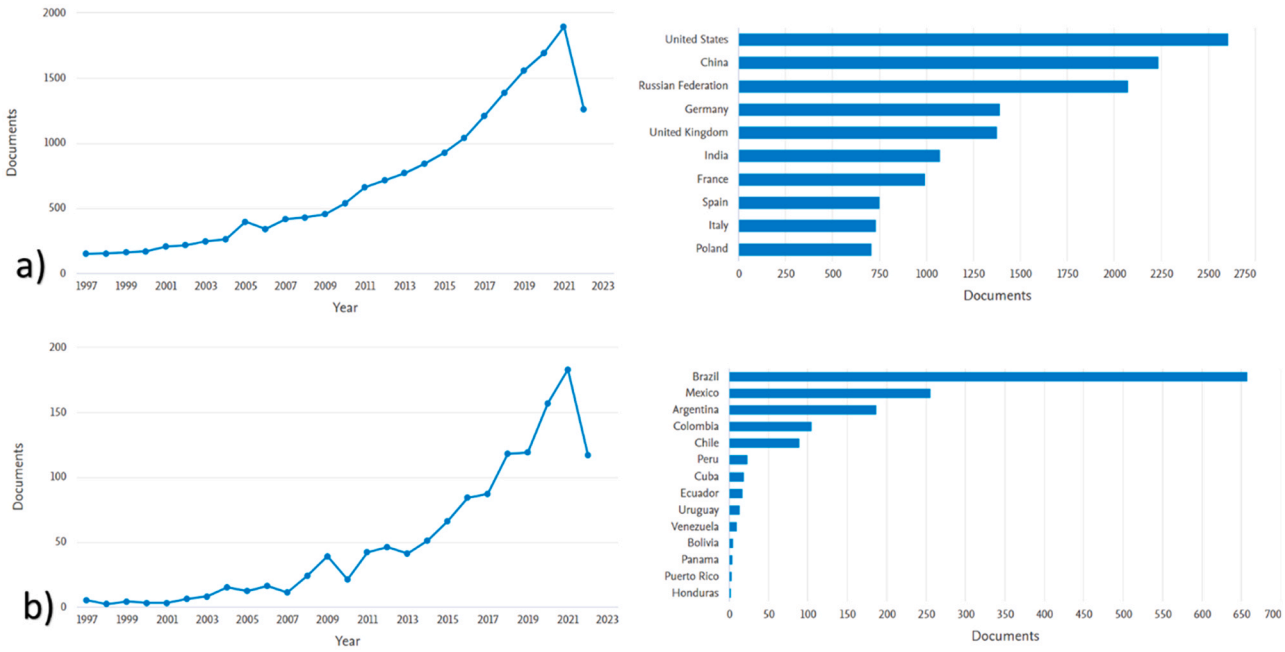

Fig. 9 – Research conducted in Process Intensification, a) International, b) LatinAmerica.

Cordeiro et al. (2017) proposed a systematic DWC technique for an extractive distillation process. In terms of total yearly cost, columns with a distinct number of steps in each portion of the wall produced the greatest results; nonetheless, these columns did not surpass the optimized traditional systems.

Junqueira et al. (2018), on the other hand, provided six cumene manufacturing technologies: the standard process, transalkylation, heat-integrated, dividing wall column, reactive distillation, and double-effect distillation. To examine all six possibilities, they employed two performance indices. The economic study involved assessing each company's gross yearly earnings, while the environmental examination involved computing seven eco-indicators. The research revealed that enhanced methods are not only more cost-effective but also more ecologically beneficial.

Biasi et al. (2020) suggested a unified model to mimic columns with many phase divisions, such as the DWC. For parastillation, metastillation, and standard distillation, their proposed model employs a distinct set of MESH-equations. When compared to traditional columns, all columns save 19% and 15% on operating and total yearly expenditures, respectively.

Segovia-Hernández et al. (2002) did a similar investigation on ternary mixtures, comparing the controllability features of thermally connected distillation sequences (including the Petlyuk column) to those of standard direct and indirect sequences. The controllers were tweaked to decrease their ISE values by performing closed-loop responses to setpoint changes. The results show that integrated systems have greater control qualities than standard distillation column sequences.

Blancarte-Palacios et al. (2003) improved the design approach for four-component mixture separation using thermally linked distillation sequences. A sequence with a prefractionator is among the designs investigated (Petlyuk-type column). The findings support energy savings of around 30% for complicated distillation sequences used in the separation of various quaternary hydrocarbon combinations.

Segovia-Hernández et al. (2005) investigated the control qualities of six alternative thermally connected distillation schemes to the Petlyuk system, as part of a series of studies that assess the control properties of dividing wall columns in the context of traditional separation schemes. The singular value decomposition approach is used to investigate the theoretical control characteristics. To supplement the theoretical approach, rigorous closed-loop simulations are employed. The findings show that reducing the number of interconnections in the Petlyuk architecture does not always result in improved controllability features.

Abad-Zarate et al.(2008) published one of the first papers on the investigation of DWC with non-equilibrium models. The data given in the literature agrees with the results derived by the non-ideal model. The thermodynamic equivalence and control features of six equivalent systems to the DWC were investigated by Hernández et al. (2006) and Tamayo-Galván et al. (2008). The DWC has operational and controllability advantages over thermodynamically comparable methods, notwithstanding their simplicity.

Segovia-Hernández et al.(2007) constructed a PI controller with dynamic uncertainty estimates for the control of the Petlyuk column. To evaluate the performance of the suggested controller in the face of unknown load disruptions in feed composition and setpoint changes, it was compared to the traditional PI control law. The results reveal that implementing the controller with a dynamic assessment of uncertainty significantly enhanced the PI controller's closed-loop responses.

For systems with large vapor loads, the DWC with trays design is critical. Thus, Rodríguez-Ángeles et al. (2015) provide an approach for the mechanical design of sieve trays in a dividing wall column. A computational fluid dynamics (CFD) operational study of the trays is also presented. Weir flooding, active zone flooding, and flow regime are all evaluated on designed trays. A reported approach enables for the creation of operational designs for the entire column's trays.

Zavala-Guzmán et al. (2016) devised a systematic method for tuning PI controllers for a class of DWCs with periodic

discrete measurements. This approach estimates effective gains for each DWC controller in a straightforward and simultaneous manner, using classical process dynamics parameters (static gains and time constant of open-loop response) and the sampling-delay time of data.

Lucero-Robles et al. (2016) suggested separating a multicomponent hydrocarbon mixture in a sequence including one or more DWC. Sequences were examined in terms of overall energy usage, environmental effect, and controllability in a simulated environment. The position of the DWC in the separation train is determined by the parameters of the purified mixture and has an impact on control and energy consumption.

Tututi-Avila et al. (2017) investigated the design, dynamics, and control of a satellite column, also known as an extended dividing wall distillation column, and compared its performance to that of a DWC column and a straight distillation sequence for the separation of BTX mixtures. The satellite column is the most energy-efficient form in terms of dynamics, according to the results of the optimum designs for these distillation structures. When compared to the DWC column and the typical direct separation sequence, the satellite column performs similarly, demonstrating that the increased energy savings given by the satellite design may be obtained without compromising control behavior.

Segovia-Hernández et al. (2018) investigate the dynamic performance of a dividing-wall-based structure for the separation of a five-component mixture. A sensitivity analysis of the structure in terms of interlinking streams is carried out, with a singular value decomposition analysis applied to chosen scenarios with various operating conditions. The open-loop qualities of the systems with the lowest energy duties were also the best.

Castillo-Landero and Jiménez-Gutiérrez, (2018) and Castillo-Landero and Ortiz-Espinoza (2019) introduced an intensification approach that reduces the number of equipment units needed to convert raw materials into finished goods. It is demonstrated how an initial flowsheet with one chemical reactor and three distillation columns is progressively turned into an intensified process (DWC) that offers a more cost-effective and sustainable alternative.

The quaternary dividing wall column has not been regarded as an alternative, and it is currently not a well-explored choice due to its architectural and dynamic qualities. A group of quaternary dividing wall columns was studied by Sánchez-Ramírez et al. (2020). They were created and tested to meet a variety of performance criteria, including energy consumption, environmental effect, intrinsic safety, and dynamic qualities. This proposal takes an innovative approach in that many traditional thermal couplings are replaced with liquid splits, which increase the performance metrics already indicated.

The optimal design of dividing wall columns is a nonlinear and multivariable issue, with numerous local optimums in the objective function utilized as the optimization criterion. Several relevant works have been published on this topic, for example, Gómez-Castro et al. (2008), Gutiérrez-Antonio et al. (2009), and Vazquez–Castillo et al. (2009) studied the design of dividing wall columns for separation of ternary and quaternary mixtures, using a multi-objective genetic algorithm with restrictions written in Matlab as a design tool and the process simulator Aspen.

Ramírez-Corona et al. (2010) provide an optimization strategy for DWC for the separation of ternary mixtures. The method employs a quick design technique that allows the system to be described as a nonlinear programming problem. Several case studies demonstrate the usefulness of the suggested method.

A multi-objective optimization strategy was presented by Vázquez-Castillo et al. (2015) and Cabrera-Ruiz et al. (2017) to incorporate the design and control of multicomponent distillation sequences. The dividing wall distillation column has been discovered to have greater control qualities than traditional separation systems in this method. Additionally, the designs' environmental elements, particularly their environmental consequences and control qualities, may be determined.

Lopez-Saucedo et al. (2016) look at how to improve a nonconventional dividing wall batch distillation column with and without chemical reaction. Two techniques are used to solve these systems of differential and algebraic equations simultaneously: a pure equation-oriented approach based on orthogonal collocation over finite elements and control vector parameterization.

At the DWC, research lines have been broadened throughout time to study complicated applications. The study of Bravo-Bravo et al.(2010) for example, is one of the earliest in this line. The authors offer a restricted stochastic multiobjective optimization approach that was used to construct a unique extractive dividing wall distillation column. The method relies on evolutionary algorithms to find the design that uses the least amount of energy and has the lowest overall yearly cost. To demonstrate the practicality of extractive separations in DWCs, many case examples are provided. Kiss et al. (2012) explored the design of a reactive Petlyuk distillation column (using the synthesis of fatty esters as a study case), generalizing the application of a multiobjective genetic algorithm with limitations tied to Aspen Plus in a comparable scenario.

Bravo-Bravo et al. (2013) investigated a hybrid distillation/melt crystallization technique that combined traditional and DWC methods. The design and optimization were carried out utilizing a multi-objective genetic algorithm with limitations as a design tool, as well as the process simulator Aspen Plus for the objective function assessment. In terms of energy savings, capital investment, and control characteristics, the findings demonstrate that this hybrid configuration with DWC is a viable solution.

Torres-Ortega et al.(2013) suggested and simulated a DWC based on cryogenic extractive distillation utilizing Aspen Plus and a multi-objective stochastic optimization approach (differential evolution). The suggested designs were evaluated for their effectiveness in the ethane–carbon dioxide azeotrope separation using various liquid hydrocarbon fractions as entrainers. The alternatives to the traditional chemical absorption mechanism were compared. In comparison to a typical chemical absorption system, the suggested cryogenic extractive DWC sequences achieved carbon dioxide removal with a lower TAC.

The design, building, and operation of a prototype of a dividing-wall distillation column were described by Hernández et al. (2009), Barroso-Muñoz et al. (2010), Barroso-Muñoz et al. (2011), and Delgado-Delgado et al. (2012) as a consequence of different fundamental engineering investigations involving the DWC. These papers detail the installation of the first experimental DWC in Latin America. The reaction between ethanol and acetic acid was carried out within the prototype, and the findings show that the top product is a heterogeneous combination of ethyl acetate and

water. In cyclic operation mode, the temperature profile observed during the experimental run may be used to manage the batch distillation column. López-Ramírez et al. (2016) investigated the manufacture of Methyl Oleate in the same prototype.

In recent years, the use of DWC in the production and purification of biofuels and bioblocks has been investigated, with significant energy savings and reductions in total annual costs, when compared to conventional distillation configurations: biodiesel (Gomez-Castro et al. 2010, and Cossio-Vargas et al. 2011), bioethanol (Hernández, 2008; Tututi-Avila et al. 2014).

Soraya Rawlings et al. (2019) conducted research on the modeling, optimization, and conceptual design of a dividing wall column for the separation of four goods using three distinct formulations: NLP, MINLP, and GDP. To address the conceptual design problem associated with these complex configurations, the authors propose a rigorous tray-by-tray model and compare the results with commercial software, followed by reformulation to include a mixed-integer nonlinear programming and a general disjunctive programming formulation.

Tusso-Pinzón et al. (2020) apply a method for incremental process intensification (using DWC) to a traditional flowsheet for the synthesis of the green solvent ethyl lactate from ethyl alcohol and lactic acid. At each level of the intensification work, the technique takes the base design and combines two pieces of equipment into one. Economic, environmental, sustainability, and intrinsic safety factors are used to grade each enhanced structure.

The 21st century in Latin America has been markedly characterized by increased environmental awareness and pressure from legislators to curb emissions and improve energy efficiency by adopting “greener technologies”. In this context, the need for the chemical industry to develop processes which are more sustainable or eco-efficient has never been so vital (CEPAL; 2019). The successful delivery of green, sustainable chemical technologies at industrial scale will inevitably require the development of innovative processing and engineering technologies which can transform industrial processes in a more fundamental and radical fashion. Process Intensification can provide such sought-after innovation of equipment design and processing to enhance process efficiency and most of the research carried out in Latin America and the Caribbean goes in the direction of these topics given that they are the world's leading areas.

9. Sustainability of supply chains

In today’s business environment, sustainability is gaining more importance in supply chains. In addition to economic issues, supply chains should also take some actions in order to preserve environmental and social resources. Economic sustainability is concerned with economic growth in the long run, but this growth should not damage the environmental and social systems. Environmental sustainability aims to preserve the ecological system and balance the usage of natural resources. Finally, social sustainability concerns preserving the well-being of humanity, and considers social equity and justice, and also inherent human rights such as security and healthcare. These three dimensions should be considered holistically to achieve a sustainable supply chain. This awareness has also changed the purchasing behaviors of customers so that they demand more sustainable products and services. A more sustainable supply chain is expected to be eventually more competitive. Another important factor to improve sustainability is the collaboration among supply chain members. Accordingly, besides taking their own sustainability actions, companies have increased their cooperation with other supply chain members (Toktas-Palut, 2022).

Latin America and the Caribbean are privileged to be one of the regions with the greatest abundance of natural resources on the planet. The lack of planning in the use of natural resources, as well as appropriate technology and regulations to assure their preservation, has resulted in severe environmental degradation in the region, as seen by biodiversity loss, soil degradation, and reduced freshwater availability (CEPAL, 2020). Motivated by these circumstances, certain studies are currently being presented with the goal of analyzing the impacts and coordination on the long-term sustainability of Latin American supply chains.

As shown in Fig. 10, Brazil leads in the generation of scientific papers when searching for the topic of this section. Unfortunately, at the international level, there is no direct comparison with the United States, United Kingdom, Italy or China.

However, there are important efforts. For example, Andersen et al. (2012) present a MILP multiperiod formulation for the optimal design and planning of the Argentinean biodiesel supply chain, taking land competition and alternative raw resources into account. The country is organized into twenty-three areas, each with present and potential crops, oil and biodiesel factories. Seed, flour, pellets and expellers, oil, pure and blended biodiesel, and glycerol are all included in the model as intermediate and final products. Crop fields, storage and manufacturing units, as well as internal and external market distribution centers, are all represented. In marginal regions, we are considering introducing active crops such as Jatropha curcas.

In LA, the medicine purchasing and distribution system is one of the most crucial operations within a Hospital Supply Chain (HSC) principally owing to the high costs involved and the requisite tight medical-administrative controls. An appropriate decision-making procedure is therefore required to maximize the efficiency of the system, guaranteeing a solution that respects medical and administrative limits. The work presented by Kees et al. (2019) created a novel multiperiod strategy that gives an alternative framework to identify managerial strategies, integrating financial factors with logistic decisions in a public HSC in Argentina. The problem is formulated as a mixed-integer linear programming (MILP) model addressing the lack of assurance in the data through fuzzy constraints and considering two conflicting objectives: the total cost and the total product deficit. To deal with the multicriteria optimization, the original model is further converted into a fuzzy mixed-integer goal programming (FMIGP) one, that allows inclusion of imprecise aspiration levels for each goal, and its equivalent crisp form permits finding an efficient compromise solution of the problem.

In the same way, the development of an ideal schedule of elective surgery cases for a hospital surgery services unit is a well-known subject in the operations research field. The intricacy of the problem is further amplified when uncertainties in the parameters are included and is a subject that has been addressed in few studies in the literature. Uncertainties emerge in operation durations and the availability of downstream resources such as surgical intensive care units (SICU), exhibiting considerable deviations from their expected value

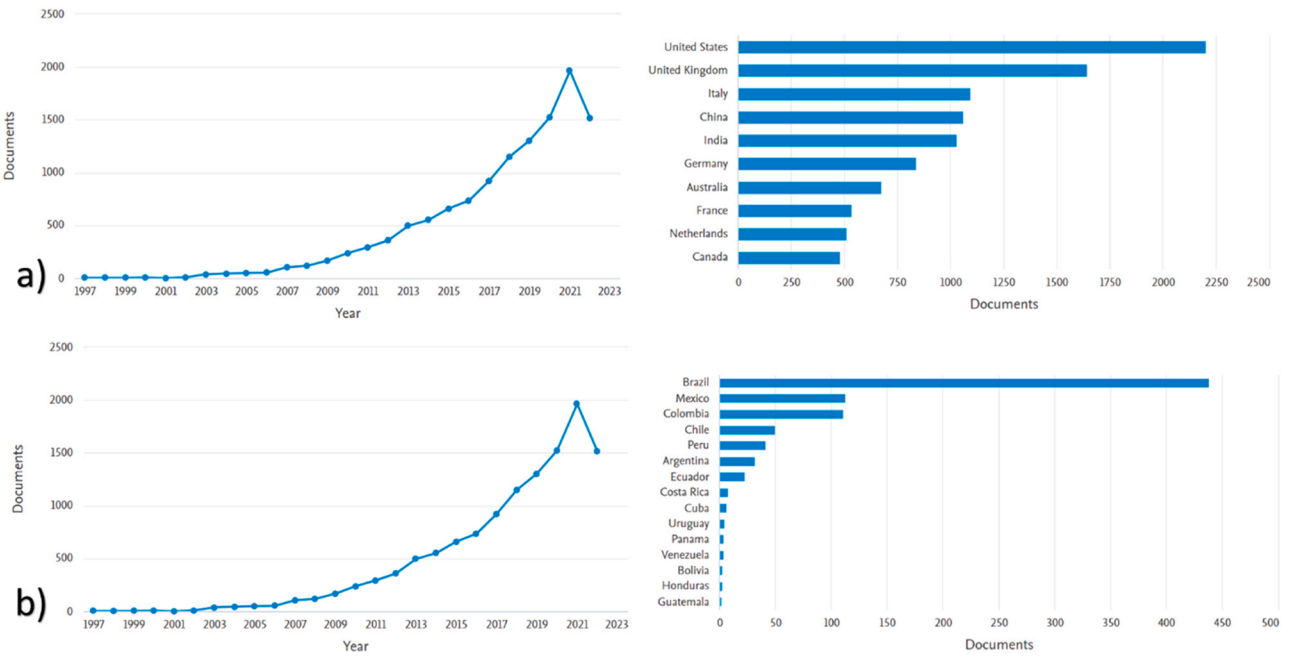

Fig. 10 – Research conducted in Sustainability of Supply Chains, a) International, b) LatinAmerica.

and interfering in the performance of the scheduling process. The technique developed by Durand and Bandoni (2020) addressed the uncertainty in the best scheduling of a given collection of elective surgical cases by means of simulated-based optimization. The key advantage of this approach over earlier efforts is that detailed systems' simulations may be generated without losing computing efficiency, thus boosting the resilience of the scheduling solution.

The tequila business in Mexico creates a lot of lignocellulosic wastes, both in the cultivation areas and in the processing sectors. These wastes are now discarded, however they might be utilised as biorefinery feedstock. It is vital to examine the economic and environmental performance of the complete supply chain for biofuel generation before constructing a biorefinery system to handle leftovers from the tequila industry in Mexico. Developing a comprehensive optimization framework for supply chain management in the Mexican tequila sector that takes into account all of the activities involved as well as the competing objectives of daily operations is a scientific problem. Murillo-Alvarado et al. (2015) provide a multi-objective optimization strategy for constructing such a supply chain that takes into account the simultaneous maximizing of the net present value and the network's environmental performance. The environmental goal function takes into account environmental quality, human health, and resource harm. The eco-indicator 99 approach is used to quantify them. The development of a biorefinery system in Mexico based on tequila wastes can deliver considerable economic and environmental advantages, according to numerical calculations.

Biomass is a renewable resource with appealing qualities for energy generation, but the accompanying supply chain may be vulnerable to a number of unknown variables that might substantially impact the ideal configuration, which have not been adequately accounted for in earlier publications. As a result, in the work of Santibañez-Aguilar et al. (2016), a new strategy for optimum planning under uncertainty for a biomass conversion system encompassing both economic and environmental considerations is described. The Eco-indicator 99 approach was used to assess the environmental effect, while the net yearly profit was used to assess the economic component. The proposed method took into account the uncertainty in raw material prices by using the Latin Hypercube method to generate stochastic scenarios, then applying the Monte-Carlo method to solve a deterministic optimization problem for each scenario to select the structure of a more robust supply chain based on statistical data. A case study for a distributed biorefinery system in Mexico was used to test the suggested method.

The manufacture of methanol from natural gas has grown in response to recent discoveries of large deposits of natural/shale gas. Such expansion necessitates the creation of dependable infrastructure and supply systems. A mathematical programming model for the strategic planning of methanol supply chains to fulfill regional demands is provided in the study by Villicaña-García et al. (2019). Economic incentives are regarded to stimulate the use of local resources. The unit selling cost, natural gas supply, and methanol demand uncertainties are all taken into account. Several sustainability goals are listed, including reducing freshwater usage, reducing CO2 emissions, and increasing profit. A case study from Mexico was used to demonstrate the applicability of the developed technique.

The majority of disenfranchised people live and work in rural regions, where they are poor and have limited access to basic resources like as energy, water, and food. Individuals and families in rural areas experience adversity, which frequently leads to inequity and disenfranchisement. They are more prone than their urban counterparts to suffer from the effects of poverty, and they face massive difficulties related with malnutrition, which often result in human casualties. The Human Development Index (HDI) aids in the identification of healthy life conditions and a reasonable level of living, both of which are directly linked to life quality. Several initiatives have been described to help disadvantaged populations across the world better their living situations. However, there is no integrated approach to decreasing poverty and guaranteeing sustainable use of the environment and natural resources in these areas, taking into consideration the

water–energy–food nexus in order to increase HDI. As a result, Martínez-Guido et al. (2019) provide a new optimization technique that accounts for the water–energy–food nexus in order to raise HDI in underserved regions while concurrently addressing economic, environmental, and social sustainability requirements. The proposed technique was tested in a case study including fourteen of the communities in the Mexican state of Michoacán with the lowest HDI.

Management of municipal solid waste (MSW) is a critical yet difficult logistical issue. The ever-increasing amount of garbage, as well as sometimes insufficient infrastructure to manage, process, and dispose of waste, make the adoption of MSW management systems difficult. Munguía-López et al. (2020) provide a coordinated approach for complicated MSW management systems in their article. Multiple major parties in MSW systems are accommodated by the framework, including waste suppliers, waste consumers and derived goods, and transportation and processing service providers. The stakeholders submit bids to a coordinator, who solves an optimization problem to establish allocations and clearing prices that optimize the aggregate profit for all stakeholders while also balancing waste and product supply and demand. Additionally, the clearing procedure ensures that individual earnings are not negative (no stakeholder loses money). The framework, in particular, functions as a competitive market that speeds up transactions between stakeholders and manages complicated logistical restrictions that would be impossible to manage in peer-to-peer interactions. The platform also makes it easier to combine legislative incentives and monetize environmental consequences. In this context, we assess the impact of a tax on open dump disposal. An MSW system in Mexico was studied as a case study to demonstrate the applicability.

Rapid urbanization, unsustainable resource use, population increase, and climate change have all put strain on resources to fulfill socioeconomic needs, making the security of the Water-Energy-Food Nexus a worldwide problem. The Water-Energy-Food Nexus is critical for long-term development and resource management efficiency. Nonetheless, an effective and long-term Water-Energy-Food Nexus design necessitates the involvement of a variety of stakeholders in the decision-making process. Cansino-Loeza and Ponce-Ortega (2021) presented a multi-objective optimization model for the design of a Water-Energy-Food system, which entails the sustainable production of water, energy, and food in areas where economic activities are shared through the industrial, agricultural, and livestock sectors. A multi-stakeholder evaluation is also presented in order to develop a set of options, with varied priority assigned to the various stakeholders. This method allows each stakeholder's degree of satisfaction to be quantified. The integration of resources is done in accordance with economic and environmental goals, such as system cost reduction, water abstraction, and greenhouse gas emissions. A area in Mexico was chosen as a case study because of its industrial activity and the present issues it has in satisfying resource needs owing to poor water availability.

Agricultural leftovers are produced during the growth and harvesting of crops, therefore their availability is determined by local demand, socioeconomic situation, weather conditions, and national policy. Only a small percentage of these residues have a specialized application, mostly in poultry and animal breeding; nonetheless, they have the potential to be used as a bio-energy feedstock. A heavy reliance on oil as a key energy source has resulted in major environmental issues, most notably climate change. As a result, using agricultural wastes as a feedstock for power production, particularly those that appear to have little environmental or economic value, might be an appealing option in terms of economic, environmental, and social advantages. As a result, Martínez-Guido et al. (2021) are focusing their research on examining the potential benefits of producing fuel pellets from agricultural leftovers derived from various crops, as well as their usage as a renewable feedstock for electricity generation in existing power plants. The research includes a life cycle evaluation to achieve the best possible integration of conventional and non-conventional feedstocks for generating power. In addition, the economic element was assessed by taking into account all of the activities included in the fuel pellet production supply chain. In addition, the Human Development Index method was used to assess the social advantages of using renewable fuel pellets. The suggested mathematical model covers all of the material balances involved in the fuel pellet supply chain, as well as binary variables as decision variables for evaluating the plant installation, resulting in a mixed-integer linear mathematical model optimization. The specifications of the Mexican electric power system were employed in this case study.

Contreras-Zarazúa et al. (2021) suggested a multiperiod supply chain model for the synthesis of platform biochemicals like furfural from agricultural wastes. The most prevalent lignocellulosic residues in Mexico are considered. Furfural's requirement was chosen to replace the feedstocks needed to create the terephthalic acid imported into Mexico. The supply chain solution was evaluated based on economic, environmental, and social goals. The maximum of net profit is the economic component. The environmental goal is to reduce eco-indicator 99, while the social goal is to increase the number of employment created. The findings demonstrate that furfural synthesis in Mexico to replace present raw materials is viable.

In recent years, the necessity to generate power from clean sources has been a hot issue of debate. Many countries have started to harness solar energy by manufacturing solar panels for electric power generation. Furthermore, knowing people's preferences enables for better macro-level planning by forecasting their behavior. Villicaña-García et al. (2021) presents a mathematical programming approach for dealing with human behavior. The goal is to figure out their preferences using the matching law, which incorporates users' actions in various situations involving economic incentives and penalties. It contains strategic planning for the manufacture and distribution of solar grade silicon (supply chain) utilized in the building of solar panels to satisfy the power demands in Mexico's residential sector as a case study. Different methods of obtaining solar grade silicon were improved through process intensification.

The majority of supply chain evaluation approaches have focused on environmental and economic aspects. Although several techniques have addressed social effect, these methodologies have not examined the site where social influence occurs, which is a critical problem for measuring social impact. As a result, the study goal of Santibaez-Aguilar et al. (2022) is to analyze social effect as a function of supply chain facility location. This is performed using a multi-objective approach to biomass supply chain planning that considers many objective functions at the same time: a) social effect at the function's location, b) net profit, and c) net

CO2 emissions. The suggested mathematical model, in particular, takes into account a social objective function based on the marginalization index. To help the bioenergy industry flourish, the proposed technique is applied to an important industrial process, the Acetone-Butanol-Ethanol (ABE) process.

Combustion of leftover biomass is both environmentally hazardous and economically inefficient. The manufacturing of specialized chemicals is a more appealing approach to dispose of residual biomass; nevertheless, one issue with recovering goods from waste is that there are presently no well-established marketplaces that bring all parties involved together (e.g., biomass production, collection, transportation, and processing). Coordination is critical in this situation since all stakeholders in the supply chain rely on the money provided by the resulting goods. A market coordination framework for the synthesis of levulinic acid and furfural from lignocellulosic biomass is presented by Alcocer-García et al. (2022). (obtained from agricultural residues). Coordination provides a number of significant economic benefits that would be impossible to obtain under current market conditions (which are uncoordinated and based on peer-to-peer transactions). The article uses a case study for the Mexican state of Guanajuato to highlight the framework's findings.

The construction of a mathematical model for the supply chain of biofuels and bioproducts manufacturing was proposed by Espinoza-Vazquez et al. (2022). This approach uses generalized disjunctive programming to solve a multi-objective optimization problem. The model considers economic, environmental, economic, and social objectives while analyzing the production of bioethanol and/or biobutanol to meet at least 10% of the country's gasoline consumption, as well as the development of high value-added goods. We found Pareto-optimal solutions. Biobutanol synthesis, according to the findings, is the procedure that achieves the best compromise between the four target functions, reaching a balance. Bioethanol production, on the other hand, is only practicable if the water footprint is ignored, as large values are achieved, posing a challenge with water distribution to complete the process.

Some locations now have limited access to power, preventing the afflicted population from maintaining a decent level of living. The human development index (HDI) is a metric that assesses a country's growth in terms of its population's quality of life, and access to electricity has been linked to an increase in HDI. Murillo-Alvarado and Ponce-Ortega (2022) offer a mathematical optimization model to estimate the feasibility of generating electric energy from biogas and delivering it to underserved communities via a supply chain. It also believes that biogas may be produced using animal waste from the region, such as manure from cattle and pigs. The suggested mathematical model addresses the yearly profit maximization by installing biogas producing plants for the use of manure and power generation plants in two types of systems: dispersed and centralized.

In summary, Latin America Stakeholders are increasingly holding companies responsible for damage in the environment created by their supply chains and putting pressure on firms to extend their environmental responsibilities with the adoption of Green Supply Chain Management (GSCM) practices (Santibañez-Aguilar, et al. 2022). These pressures also reach to include the incorporation of environmental requirements along the supply chain in supplier selection activities, the manufacturing of products, and delivery processes to the final customer. There is, accordingly, growing interest to elucidate the extent to which GSCM practices have the potential to improve not only environmental protection but also firms' performance, thus offsetting implementation costs. In this 'business case' for GSCM, positive impacts of GSCM practices have been proposed and documented in terms of financial, operational performance and competitive advantage. Finally, further research (similar to the papers described in this section) can explore how differences in organizational and managerial traits influence the extent and mutuality of collaboration with stakeholders in the implementation of GSCM practice and the implications that these differences have for innovation (Santibañez-Aguilar, et al. 2022). For instance, different types of leadership could be explored as some leaders would be more prone to collaborate than others would.

10. Challenges and opportunities in the future

The eight grand challenges and opportunities below were chosen because they were considered to pose the technical challenges and greatest science for addressing environmental, sustainability balanced economic and societal progress—in the chemical industry in Latin America (adapted from National Research Council, 2006).

10.1. *Green and sustainable chemistry and engineering*

Identify appropriate control thermal conditions, solvents and recover, purify, and formulate products that prevent waste and that are economically viable, environmentally benign and generally support a better societal quality of life. This criterion is relevant from the point of view that companies and public policies in Latin America and the Caribbean should seek to promote the design of processes and products under the principles of green chemistry and enroll the region in the circular economy and to be able to make it participate in compliance with the United Nations 2030 Agenda.

10.2. *Life cycle analysis*

There is a need in the to understand in companies policies in Latin America and the Caribbean the long-term impacts of chemicals in the environment and to account for such properties within a large complex systems analysis. This involves having a keen understanding of the metabolism of chemical products (their industrial ecology) from the extraction of raw materials and creation of products, to their use and management of any resulting wastes. Life cycle analytical tools are especially needed for comparing the total environmental impact of products generated from different processing routes and under different operating conditions through the full life cycle. This is another area that is already being explored, but will play an increasingly significant role in the chemical industry in Latin America in the longer term as fossil fuels are phased out of use and application of green chemistry and engineering practices become critical.

10.3. *Toxicology*

Development of critical tools for improved understanding of function-structure relationships for chemical mixtures and chemicals in the environment and humans. This includes

genomic and computational approaches and development of methods to communicate this information to effectively move it from bench research and science disciplines to application in product designs. Improve biomass processing—including pretreatment as well as the breakdown processes for transforming biomass material into chemicals. This requires a better understanding of the basic chemical pathways involved in biomass conversion processes as well as extraction processes or separation to isolate the basic chemical blocks from biomass. This is a great area of opportunity and development, both academically and industrially, for the Latin American region.

10.4. *Renewable fuels*

Biomass is the only renewable resource that produces carbon-based fuels and chemicals. Develop chemical feedstocks together biomass derived fuels with while addressing the energy intensity of chemical processing. While the growing need for sustainable energy can be met by improvements in capturing and utilizing renewable resources such as wind, solar, geothermal and biomass, among other. Latin America and the Caribbean are positioning themselves in the world with large research groups that have developed highly relevant advances in the field of biofuels. This is one of the points where the region could pay heavily in the fulfillment of the United Nations 2030 agenda.

10.5. *Energy intensity of chemical processing*

Develop more cost efficient chemical separations with low energy consumption, especially effective alternatives to distillation. Explore biotechnology and other emerging technological solutions. Development and research needs in these areas include increasing stability, reducing production costs and discovering catalysts with greater specificity. Better understand the mechanisms of lubrication, friction and wear of interacting surfaces (tribology)—which leads to one third of the loss of the world's energy resources in present use. These approaches present ways of creating innovative solutions to fuel growth for future generations, without harming the environment or human health. Research and development needs in these areas in Latin America and the Caribbean include reducing production costs, increasing stability, and discovering catalysts with greater specificity.

10.6. *Separation, sequestration, and utilization of carbon dioxide*

Cost efficient technologies and develop energy for CO_2 separation from flue gas and the atmosphere. Develop technologies for CO_2 sequestration that will address the technical feasibility of storing and making compressed forms of CO_2 in geological formations and elsewhere. Explore utilizing nontoxic, low cost and renewable CO_2 as a feedstock for entirely novel materials and for new routes to existing chemicals such as salicylic acid, urea, polycarbonates and cyclic carbonates. Because of the region's vulnerability to this global process, climate change represents a challenge of huge proportions for Latin America and the Caribbean, hence the relevance of the topic of separation, sequestration, and utilization of Carbon Dioxide. It would make sense for the region to work for remedial action on a global scale, in accordance with the principle of common but differentiated responsibility among countries, on the basis of the United Nations Framework Convention on Climate Change, and to promote adaptation activities, something that will be very important over the coming decades, when climate patterns will undoubtedly change as this very slow-acting phenomenon takes effect.

10.7. *Renewable chemical feedstocks*

In order to provide desired chemical functionality in a way that is sustainable, another grand challenge for sustainability in the chemical industry, in Latin America and the Caribbean, is to derive chemicals from biomass. This includes any plant derived organic matter available on a renewable basis, including dedicated energy crops and trees, agricultural food and feed crops, agricultural crop wastes and residues, wood wastes and residues, aquatic plants, animal wastes, municipal wastes, and other waste materials (Latin America and the Caribbean can be considered a region in abundance of these materials). Provide the research community with starting points in the development of alternative pathways to achieve the desired end materials, developing a catalog of biomass derived chemicals. Explore obtaining current basic chemicals such as simple aromatics and aliphatics, as well as fundamentally new compounds from platforms such as lignin, sugar, or cellulose.

10.8. *Sustainability education*

Provide professional development opportunities for educators to learn more about sustainability and climate change and how it can be advantageously incorporated into their teaching and research, it is one of the great challenges to be solved in the educational systems of Latin America and the Caribbean. This includes providing incentives for faculty to change curricula while addressing the needs of graduate students. Persuade professional societies in Latin America and the Caribbean to integrate green chemistry and sustainability and engineering concepts into standardized accreditation, testing and certification programs. Provide professional development for current and future executives and managers. Equally important is the communication of sustainability thinking to middle and upper level executives and managers in business management and incorporation of sustainability objectives in annual performance targets as well as corporate strategy.

11. Final thoughts

To make the transition to sustainable development, the region needs to introduce far-reaching economic and social changes, starting by restructuring production in a way that meets the threefold objective of increasing the region's competitiveness, reducing social disadvantage and checking the environmental deterioration associated with current patterns of production specialization. It is important to ensure that the investigation and final report gets into the hands of CEOs, or most relevant executives, in the (bio)chemical industry. Engage policy experts, economists, and politicians on these highly relevant issues. They may be able to help by setting up incentives to make big changes. Latin America and the Caribbean need to define a broad and deep vision of a sustainable future and a viability vision of the necessary and desired development process for the region.

As shown in Figs. 3–10, valuable efforts have been made in the field, but up to this point in the state of the art, there is a notable gap between the number of publications in Latin America compared to the international context. Diversity in the cultural, biological, information and knowledge domains can be crucial for sustainable development in Latin America and the Caribbean during the 21st century. Taking into account these important issues in various economic activities, the region can mitigate the effects of Covid-19, since according to CEPAL studies (2020), the region's gross domestic product has fallen back 10 years due to the pandemic. Finally, today, more than ever, the region needs to make progress in science, technology, innovation and adaptability in order to deepen knowledge of its natural resources, undertake research that addresses its own priorities, restore appropriate technologies and promote the sustainable use of biotic resources based on appropriate risk assessment using a precautionary approach. Mechanisms for protecting intellectual property relating to biodiversity are becoming especially important. In this respect there is an ongoing demand for international financial agencies and the mechanisms of the United Nations system to support the development of scientific and technological capacities in the region.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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