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Challenges and opportunities in process intensification to achieve the UN's 2030 agenda: Goals 6, 7, 9, 12 and 13

Juan Gabriel Segovia-Hernández [a,*], Salvador Hernández [a], Enrique Cossío-Vargas [b], Eduardo Sánchez-Ramírez [a]

[a] División de Ciencias Naturales y Exactas, Departamento de Ingeniería Química, Universidad de Guanajuato, Campus Guanajuato, Noria Alta s/n, Guanajuato, Gto 36050, Mexico

[b] Universidad Tecnológica del Suroeste de Guanajuato, Carr. Valle-Huanímaro km 1.2, Valle de Santiago, Guanajuato 38400, Mexico

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ABSTRACT

The 2030 Agenda is a call to global action to eradicate poverty, protect the planet and ensure prosperity for all. Process intensification, in this context, refers to improving the efficiency and effectiveness of production and service processes, in order to reduce environmental impact and improve people's quality of life. By optimizing and consolidating various steps within a production process, process intensification aims to achieve higher yields, reduced waste, and lower resource consumption. This approach aligns with the sustainability goals set by the United Nations, including: energy efficiency, waste reduction, resource conservation, emission reduction, circular Economy and sustainable development. Process intensification primarily impacts Goals 7, 9, 12, and 13 of the United Nations' 2023 Sustainability Agenda due to its potential to address key aspects related to energy, industry, sustainable consumption and production, and climate action. This review shows how process intensification directly impacts those Goals of the 2023 Sustainability Agenda by promoting affordable and clean energy, fostering innovation in industry, encouraging responsible consumption and production.

1. Introduction

Sustainability is crucial in society and industry, aiming to meet present needs without compromising future generations. It addresses the negative impact of human activities on the environment, including climate change, deforestation, and pollution. Sustainable practices mitigate these impacts, promote a healthier planet, and benefit industries through increased efficiency, waste reduction, lower costs, improved reputation, and competitiveness [1]. The United Nations (UN) 2030 Agenda is vital for sustainability, consisting of 17 Sustainable Development Goals (SDGs) that address economic, social, and environmental challenges. These goals cover issues like poverty, hunger, climate action, and sustainable cities. The agenda advocates a holistic approach considering economic, social, and environmental dimensions, aiming for a just and sustainable future [1].

The UN 2030 Agenda is a comprehensive blueprint adopted by all 193 UN Member States in 2015. It includes 17 SDGs and 169 targets with a deadline of 2030. The agenda's primary goal is to eradicate poverty, reduce inequality, promote peace, justice, and strong institutions. It outlines plans to end poverty, ensure sustainable economic growth, reduce inequality, and promote inclusive societies [2]. Additional goals include ensuring quality education, gender equality, clean water, sanitation, and affordable clean energy. These goals are critical for sustainable development and the well-being of society and industry. They require collaborative efforts among governments, businesses, and civil society to address global challenges [2]. For businesses, the UN 2030 Agenda offers a roadmap for sustainable practices. It aligns business strategies with the SDGs, creates a common language for sustainability communication, and fosters innovation. Businesses that embrace the SDGs are more resilient to challenges like climate change and resource scarcity, while also contributing to societal needs [2]. Governments benefit from the agenda by using it as a policy-making framework, prioritizing actions, and engaging citizens in sustainable development. The SDGs encourage ownership and accountability among governments, fostering long-term planning and policy alignment [2].

The relevance of the UN 2030 Agenda to future society and industry is significant. Sustainable development requires a shift in lifestyles, work, consumption patterns, and substantial investments in technology, innovation, and infrastructure. It also addresses emerging challenges

* Corresponding author.
E-mail address: gsegovia@ugto.mx (J.G. Segovia-Hernández).

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List of abbreviations

SDGs	sustainable development goals
PI	process intensification
TRL	technology readiness level
TES	thermal energy storage
PCMs	phase change materials
AI	artificial intelligence
ML	machine learning
GHG	greenhouse gasses
LED	light emitting diode
CHOSYN	carbon–hydrogen–oxygen symbiosis networks

such as climate change, digitalization, and demographic shifts, which will require new solutions [2]. This review demonstrates the direct influence of process intensification on the objectives outlined in the 2023 Sustainability Agenda, such as the promotion of accessible and renewable energy, the facilitation of innovation within industries, and the promotion of responsible consumption and production practices [2].

2. Process Intensification and UN's 2030 agenda

The 21st century has witnessed a growing emphasis on environmental awareness and the need for greener technologies to reduce emissions and improve energy efficiency. The United Nations' 2030 Agenda for Sustainable Development sets a transformative vision for economic, social, and environmental sustainability over the next 15 years. To achieve this vision, various efforts are required at the national, regional, and global levels, including resource assessment, strategy development, and institutional design. In this context, the chemistry industry plays a crucial role in developing sustainable and eco-efficient processes. The industry must embrace innovative technologies that can fundamentally transform industrial processes and enable the delivery of green and sustainable chemical technologies at a larger scale. Chemical processes, spanning diverse sectors such as oil refining, gas processing, pharmaceuticals, and more, have a significant impact on the environment due to resource consumption. The challenge is to make the chemical process industry a major contributor to sustainable development, considering technical, economic, environmental, and societal objectives. This involves the systematic development of strategies, concepts, technologies, and tools for Sustainable Chemical Process Design, which aim to transform raw materials and energy into value-added products while promoting economic growth, social well-being, environmental protection, and the conservation of natural resources [3].

The Sustainable Chemical Process Design and Operation Section aims to establish a platform for disseminating and advancing the understanding of design and operational issues in sustainable chemical manufacturing. To address the complex challenges at the intersection of sustainability and manufacturing, the integration of technological, economic, social, policy, and environmental factors is crucial. Systems approaches are effective in tackling sustainable manufacturing issues in the chemical process industry.

In the future, society will face significant global challenges related to energy transition, climate change, healthcare, and resource scarcity. The chemical and related process industries play a vital role in addressing these challenges, particularly concerning materials and energy efficiency, environmental impact, and operational safety. Process intensification (PI), which focuses on enhancing material and energy efficiency, safety, and environmentally friendly processing, is recognized as a promising approach in chemical and process engineering to overcome these challenges and drive progress [4].

PI is a strategy that aims to significantly reduce plant volume by replacing traditional unit operations with compact, hybrid designs. It offers substantial advantages in the manufacturing of (bio) chemical products through novel equipment, processing techniques, and process development methods [5]. PI can be achieved by independently intensifying each unit to minimize size and maximize yield, or by intensifying multiple units simultaneously to optimize process yield, raw material usage, and inventory. Various interpretations of PI exist, including miniaturization, functional integration, synergistic integration of process tasks and phenomena, and a function-oriented approach. PI technologies have appealing environmental implications, as compact and intensified plants are less visually disruptive and enable waste minimization at the source. They also contribute to improved product quality and reduced downstream purification costs. Economic, social, and environmental considerations have driven the chemical process industry to focus on PI technologies to meet sustainability goals [6]. PI enhances energy efficiency by reducing mass and heat transfer resistances and overcoming thermodynamic limitations through integrated design and operation. The academic interest in PI has grown due to its potential for process improvement and sustainable production. By innovating future plant designs, PI contributes to energy and resource savings in the production of various chemicals and consumer products. Overall, PI promises long-term solutions to challenges such as energy and waste minimization, economic improvement, and environmental sustainability, aligning with the United Nations' 2030 agenda [7,8].

The United Nations 2030 Agenda seeks to address global sustainability challenges through the implementation of simple and cheap technologies. However, despite being technologies in development, expensive and often having a low TRL (Technology Readiness Level), chemical intensified processes should be preferred due to their potential to solve the challenges posed by the 2030 Agenda in a more effective and sustainable way in the long term. Some of the reasons are [2]:

a) Responsiveness to complex challenges: The challenges posed by the 2030 Agenda are complex and multifaceted, and require innovative and efficient solutions. Chemical intensified processes, despite being under development and having a low TRL level, offer the ability to address these challenges more comprehensively and effectively. These technologies allow the optimization of processes, the efficient use of resources and the reduction of emissions, which makes them a viable option to achieve sustainable development.
b) Technological advancement and long-term cost reduction: While chemical intensified processes can be expensive in the early stages of development, it is important to note that investment in research and development leads to technological advancement. As these processes are refined and scaled, costs are likely to drop significantly. In addition, in the long term, the implementation of more efficient technologies result in resource and energy savings, which will pay off initial costs and provide long-term economic and environmental benefits.
c) Strengthening the industry and economic growth: The preference for chemical intensified processes is not only based on their ability to solve complex challenges, but also on their potential to boost industry and economic growth. These developing technologies provide opportunities for job creation, establishment of new industries and fostering innovation. In addition, by promoting research and development in the field of intensified chemical processes, the scientific and technological base of a country is strengthened, which contributes to its international competitiveness.
d) Collaboration and knowledge transfer: The adoption of chemical intensified processes implies close collaboration between different actors, including scientists, engineers, companies and governments. This collaboration encourages the transfer of knowledge and technology, which allows accelerating the development and implementation of solutions. Furthermore, investment in developing technologies and their application in the context of the 2030 Agenda serves as a platform for global collaboration, promoting the exchange of best practices and international cooperation.

Despite being developing, costly and low TRL technologies, chemical intensified processes should be preferred to address the challenges of the UN 2030 Agenda. Their ability to respond to complex challenges, long-term technological advancement, industry strength, and global collaboration are aspects that make them a more effective and sustainable option. Although they may require a significant initial investment, the long-term economic, environmental and social benefits outweigh the initial costs, and contribute to building a more sustainable and prosperous future.

3. What objectives does process intensification contribute to the 2030 agenda?

Process Intensification (PI) is a strategy for improving industrial processes by increasing their efficiency, reducing their environmental impact, and optimizing their performance. PI contributes to several of the goals of the UN 2030 Agenda for Sustainable Development, including:

Goal #6. This target of the UN 2030 Agenda for Sustainable Development is focused on ensuring access to clean water and sanitation for all. The Process Integration philosophy brings several benefits in the development and implementation of this goal. Firstly, PI is used to optimize water use in industrial processes, leading to reduced water consumption and more efficient water management. This contributes to reducing the overall demand for freshwater resources, especially in areas where water scarcity is an issue. Additionally, PI helps to reduce water pollution by promoting the use of cleaner production technologies and reducing the discharge of pollutants into water bodies [9].

Secondly, PI helps to improve the efficiency and effectiveness of water and sanitation infrastructure. By adopting a systems approach and considering the interdependencies between different processes, PI helps to identify opportunities for improving the overall performance of water and sanitation systems. This can lead to more reliable and resilient systems that are better able to meet the needs of communities, especially in areas where access to clean water and sanitation is limited [10].

Thirdly, PI contributes to the development of more sustainable and cost-effective solutions for water and sanitation. By adopting a holistic approach and considering the economic, social, and environmental dimensions of water and sanitation, PI helps to identify opportunities for reducing costs, increasing efficiency, and improving sustainability. This can lead to the development of more innovative and effective solutions that are better suited to the specific needs and contexts of different communities [11].

Goal #7. This target of the UN 2030 Agenda for Sustainable Development is focused on ensuring access to affordable, reliable, sustainable and modern energy for all. The Process Integration philosophy brings several benefits in the development and implementation of this goal. Firstly, PI is used to optimize energy use in industrial processes, leading to reduced energy consumption and more efficient energy management. Industrial processes are often energy-intensive, and reducing energy consumption helps to reduce the overall demand for fossil fuels and other non-renewable resources. This can contribute to reducing greenhouse gas emissions and improving sustainability. PI helps to identify opportunities to improve the energy efficiency of industrial processes through the use of heat recovery, waste heat utilization, and other energy-saving measures [12].

Secondly, PI promotes the use of renewable energy sources and technologies. Renewable energy sources such as solar, wind, and hydroelectric power helps to diversify energy sources and increase energy security. PI helps to identify opportunities for the deployment of renewable energy technologies, including the integration of renewable energy sources into existing energy systems. This can help to reduce the dependence on fossil fuels and other non-renewable resources and contribute to achieving sustainable energy systems [13].

Thirdly, PI improve the efficiency and effectiveness of energy infrastructure. By adopting a systems approach and considering the interdependencies between different energy processes, PI identifie opportunities for improving the overall performance of energy systems. This can lead to more reliable and resilient energy systems that are better able to meet the needs of communities, especially in areas where access to energy is limited. PI helps to identify opportunities for the integration of different energy systems, including electricity, heating, and cooling systems, which can improve overall efficiency and reduce costs [14].

Goal #9. This target of the UN 2030 Agenda for Sustainable Development aims to build resilient infrastructure, promote sustainable industrialization, and foster innovation. The Process Integration philosophy plays a crucial role in achieving this goal by improving the efficiency of industrial processes, reducing waste, and promoting the use of renewable energy sources.

The PI philosophy focuses on the optimization of the entire industrial process by integrating different operations and subsystems into a unified system. This approach enables the identification of process inefficiencies and opportunities for improvement, leading to increased energy efficiency, reduced greenhouse gas emissions, and reduced waste generation.

One example of PI application is the integration of energy recovery systems in industrial processes. Energy recovery involves capturing waste heat from an industrial process and using it to generate steam, hot water, or electricity. By integrating energy recovery systems, industries can reduce their energy consumption, lower their carbon footprint, and save money on energy costs.

Another example is the use of renewable energy sources, such as wind or solar power, to replace fossil fuels in industrial processes. PI optimizes the integration of renewable energy sources into existing industrial processes, ensuring the maximum use of available renewable energy and reducing the reliance on non-renewable energy sources [14].

On the other hand, Goal #12 of the UN 2030 Agenda for Sustainable Development aims to ensure sustainable consumption and production patterns. The Process Integration philosophy plays a crucial role in achieving this goal by improving the efficiency of production processes, reducing waste and pollution, and promoting the use of sustainable materials and practices.

The PI approach emphasizes the optimization of the entire production process, from raw materials to finished products, by integrating different operations and subsystems into a unified system. This approach can help identify inefficiencies and opportunities for improvement, leading to increased energy and resource efficiency, reduced waste generation, and lower environmental impact.

One way in which PI can benefit Goal #12 is by promoting the use of sustainable materials and practices. By optimizing the use of resources and minimizing waste generation, industries reduce their environmental impact and contribute to a more sustainable future. This is achieved through the adoption of circular economy principles, which emphasize the reuse and recycling of materials to minimize waste and promote resource efficiency.

Another way in which PI can benefit Goal #12 is by reducing the environmental impact of industrial processes. This can be achieved through the integration of pollution prevention measures, such as the use of cleaner production technologies and the adoption of best practices for waste management. By minimizing waste generation and reducing pollution, industries contributes to a more sustainable future and reduce their environmental footprint [14].

Finally, Goal #13 of the UN 2030 Agenda is to take urgent action to combat climate change and its impacts. The process integration philosophy contributes to achieving this goal by enabling the reduction of greenhouse gas emissions and enhancing energy efficiency in industrial processes.

PI aims to optimize the use of energy, water, and other resources in industrial processes, leading to the reduction of carbon emissions and other environmental impacts. PI helps industries to identify opportunities for energy savings and emission reductions across entire supply chains, from raw material extraction to product disposal. This can be achieved through the integration of different process units, optimization of operating conditions, and adoption of cleaner technologies [15].

In addition to energy efficiency improvements, PI facilitates the use of renewable energy sources such as solar and wind power, by providing the flexibility needed to accommodate fluctuations in energy supply. By reducing dependence on fossil fuels, PI contributes to the decarbonization of the industrial sector and help to mitigate climate change.

Moreover, PI improves the resilience of industrial processes to climate change impacts, such as extreme weather events and water scarcity. By identifying vulnerabilities and implementing appropriate adaptation measures, such as water reuse and conservation, industries can enhance their long-term sustainability and reduce their exposure to climate risks [16].

While process intensification contributes to achieving certain sustainable development goals (SDGs) such as Goals 6, 7, 9, 12, and 13, it may not be directly applicable or sufficient to approximate the rest of the goals from a process intensification perspective. Process intensification alone may not be suitable for all the SDGs. For example, some goals requiring social and institutional changes involving complex social, economic, and political aspects that cannot be addressed solely through process intensification. Goals such as No Poverty (Goal 1), Zero Hunger (Goal 2), Quality Education (Goal 4), Gender Equality (Goal 5), and Reduced Inequalities (Goal 10) require social and institutional transformations, policy changes, and community engagement. While process intensification can indirectly support some of these goals by improving resource efficiency or reducing costs, it cannot address the underlying social issues or systemic inequalities. On the other hand, some goals are related to health and well-being, such as Good Health and Well-being (Goal 3) and require a holistic approach beyond process intensification. They involve aspects like healthcare access, disease prevention, public health policies, renewable energy deployment, and energy equity. While process intensification contributes to this goal, it cannot address all the dimensions of healthcare or ensure equitable access to energy.

Furthermore, ecosystem conservation and biodiversity goals included in goals like Life Below Water (Goal 14) and Life on Land (Goal 15) focus on protecting and restoring ecosystems and biodiversity. These goals involve preserving habitats, reducing pollution, combating deforestation, and promoting sustainable land management. While process intensification helps reducing environmental impacts in certain industries, it cannot directly address the broader conservation and restoration efforts required to achieve these goals.

Finally, social and political stability goals such as Peace, Justice, and Strong Institutions (Goal 16) and Partnerships for the Goals (Goal 17) require fostering inclusive societies, promoting justice, ensuring accountable institutions, and enhancing international cooperation. These goals involve political stability, good governance, rule of law, and fostering partnerships between governments, private sector, and civil society. Process intensification does not directly encompass these aspects.

To achieve the full range of SDGs, it is crucial to adopt a comprehensive and integrated approach that combines various strategies, including policy reforms, social empowerment, behavioral changes, capacity building, and cross-sectoral collaborations. While process intensification contributes significantly to specific goals, it is important to recognize that addressing the broader spectrum of SDGs requires a multi-dimensional and multi-stakeholder approach beyond process intensification alone.

4. Process Intensification and Goal 6: ensure access to water and sanitation for all

Over the past 300 years, over 85 percent of the planet's wetlands have been lost, mainly through drainage and land conversion, with many remaining wetland areas degraded [17]. Since 1970, 81 percent of species dependent on inland wetlands have declined faster than those relying on other biomes, and an increasing number of these species are facing extinction [18] (United Nations, 2022). Access to safe water, sanitation and hygiene is the most basic human need for health and well-being. Billions of people will lack access to these basic services in 2030 unless progress quadruples. Demand for water is rising owing to rapid population growth, urbanization and increasing water needs from agriculture, industry, and energy sectors [19]. Decades of misuse, poor management, overextraction of groundwater and contamination of freshwater supplies have exacerbated water stress. In addition, countries are facing growing challenges linked to degraded water-related ecosystems, water scarcity caused by climate change, underinvestment in water and sanitation and insufficient cooperation on transboundary waters. To reach universal access to drinking water, sanitation and hygiene by 2030, the current rates of progress would need to increase fourfold. Achieving these targets would save 829,000 people annually, who die from diseases directly attributable to unsafe water, inadequate sanitation and poor hygiene practices [19].

In 2020, 74 percent of the global population had access to safely managed drinking water services, up from 70 percent in 2015. Still, two billion people live without safely managed drinking water services, including 1.2 billion people lacking even a basic level of service, in 2020. Between 2015 and 2020, the population with safely managed sanitation increased from 47 percent to 54 percent and the population with access to handwashing facilities with soap and water in the home increased from 67 percent to 71 percent. Rates of progress for these basic services would need to quadruple for universal coverage to be reached by 2030. At the current rates of progress, 1.6 billion people will lack safely managed drinking water, 2.8 billion people will lack safely managed sanitation, and 1.9 billion people will lack basic hand hygiene facilities in 2030. Across the world, water stress levels remained safe at 18.6 percent in 2019. However, Southern Asia and Central Asia registered high levels of water stress at over 75 percent, whereas Northern Africa registered a critical water stress level of over 100 percent. Since 2015, water stress levels have increased significantly in Western Asia and Northern Africa [18].

Significant developments have been achieved in the field over recent years and have resulted in both successful industrial applications and expanding research interests. PI research has also attracted attention recently in aqueous medium adsorptive separations and wastewater treatment as well. However, there is yet a lack of published protocols or methods to follow the intensified solutions for processes in the domain of wastewater treatment [20].This section presents the evaluations to highlight the challenges involved in many adsorptive separations related to wastewater treatment. PI methodologies are characterized by size reduction via intensified mixing and heat and mass transfer that would result in enhanced selectivity and energy efficiency; improved safety; reduced wastes; and reduced material, capital and operational costs.

Ling and Lyddiatt [21]studied PI for the adsorption system of a dye-ligand and an intracellular protein from bakers' yeast extract in a fluidized bed for the investigation of the performance of a steel–agarose pellicular adsorbent. This is a case study of application of PI using novel adsorbents. They studied the recovery of glyceraldehyde 3-phosphate dehydrogenase. The adsorbent used comprised a stainless-steel core coated by a porous agarose layer, having an adsorptive coating depth corresponding to 40% of the particle radius and a steel core/agarose volume ratio of 1:3.5. The process was capable of capturing a target protein molecule without predilution of unclarified feedstock with minimized processing time and maximized process efficiency.

Decolorization of wastewaters is important as almost 30–40% of dyes are discharged into the environment during dyeing processes. Lin and Chen [22] investigated the feasibility of decolorization of a reactive dye utilized extensively in cotton, wood and silk dyeing treatments from aqueous media exploiting a nanoscale zero-valent iron. A Rotating Packed Bed was used for the preparation of the adsorbent by reductive precipitation The performance of nanoscale zero-valent iron and the effects of various characteristics, such as pH, adsorbent dosage and temperature, on the decolorization efficiency were studied. This is an example of Process Intensification system and strategy.

Kopac et al. [23] investigated the interactions and enhanced adsorption of bovine serum albumin protein with double-walled carbon nanotubes. The study involved the investigation of protein adsorption equilibrium and kinetics on double-walled carbon nanotubes. That nanotubes synthesized via the catalytic chemical vapor deposition method using a MgO-based catalyst were utilized and protein adsorption on carbon nanoparticles was examined. Using this novel adsorbent significantly intensified the protein adsorption

Bethi et al. [24] investigated the decolorization of bio-recalcitrant Rhodamine-B dye by exploiting a hybrid method that involved hydrogel adsorption and hydrodynamic cavitation. For the synthesis of hydrogel adsorbent (poly-acrylic acid PAA/halloysite clay nanocomposite), an ultrasound polymerization was employed, and the adsorption column packed with the synthesized hydrogels was placed after the cavitation device for removal of dye from aqueous solutions. The system performance was significantly influenced at the optimum conditions. The dye removal percentage was better at lower hydrogel clay content and medium pH. The novel hybrid technique resulted in the intensification of the removal of Rhodamine-B dye from water.

Salehi et al. [25] investigated biochar production exploiting spent-tea residue by phosphoric acid treatment and studied the optimal process conditions for the intensification of the methylene blue dye adsorption from aqueous solutions. For achieving the criterion of intensification of adsorption, authors fabricated high-quality biochar having optimal physicochemical properties. In order to achieve a process-intensified performance, the adsorption was studied by exploiting a data-based multivariate optimization strategy, Pareto sensitivity analysis with response Surface methodology was developed.

Metal ions are among the major contaminants contributing to aquatic environment pollution. They present high hazards to living organisms due to their nonbiodegradable nature. Reske et al. [26] investigated the adsorptive removal of Ni(II) ions from a stream of subcritical water using an activated carbon fixed column. They evaluated the structural changes of activated carbon after exposing it to column adsorption under subcritical conditions, and they investigated the effects of pressure and temperature on adsorption bed performance in comparison to adsorption under normal conditions (Fig. 1).

Nickel–metal hydride storage batteries are commonly used as a source of energy in most portable electronic devices, such as mobile phones, hybrid cars and digital cameras. A large amount of waste released from spent batteries and electronic devices leads to environmental pollution. Adsorption can be applied as a cheap and convenient method for the separation of those metals from the spent battery

Fig. 1. Adsorptive removal of Ni(II) ions from a stream of subcritical water using an activated carbon fixed column. Reske et al. [26].

solutions. Ion exchangers contain different kinds of functional groups, such as amine, carboxylic, phosphonic and sulfonic groups. Those can be effectively used for the recovery of metal ions from electrolytic and concentrated acid solutions and selective recovery of trace amounts of some metals from drinking water [27].

Purified terephthalic acid is commonly used as a raw material in the synthesis of polyester, while the effluents from the production process contain some organics (p-methyl benzoic acid, terephthalic acid), and some metal ions. The application of an intensified process involving extraction–ultrafiltration–reverse osmosis–adsorption was presented as an optimum technology for Purified terephthalic acid wastewater treatment [28].

Membrane distillation is an alternative method for separation of salt molecules from water and wastewater with high rejection factors. A microporous and hydrophobic membrane is used in membrane distillation to separate aqueous solutions at different compositions and temperatures. At least one side of the membrane remains in contact with the liquid phase. Vapor pressure difference is developed due to temperature difference across the membrane. The molecules are transported through the pores of the membrane from the high vapor pressure side to the low vapor pressure side. Membrane distillation has been used for treatment of textile industry wastewater and radioactive wastewater [29]. Also, Membrane-distillation-crystallization is a hybrid process combines membrane distillation and crystallization. It is a thermally driven separation process, which is the integration of membrane and distillation technologies. In membrane distillation, a porous hydrophobic membrane uses, the water vapor through pores of the membrane which blocks the penetration of water. This leads to the separation of water from the concentrated solution [29]. Though it can be employed to wastewater treatment, it may be considered to treat salinity of brine wastewater due to recovery of salts and water by reactive distillation crystallization.

Reactive crystallization is the separation process by crystallization with reaction. Reactive crystallization has many industrial applications including wastewater treatment. This may include: recovering Na_2SO_4, NaCl, Na_2CO_3, phosphates and ammonium, heavy metals removal, reclamation of pure water and water softening by removing Ca^{2+} and Mg^{2+} [29].

Reactive extraction is a liquid-liquid extraction intensified by involving a reversible reaction between the solute and extractant. Reversible reaction is the main difference between reactive extraction and solvent extraction. Extractants play the vital role in reactive extraction for reversible reaction between solute and extractant. Further diluents also responsible for the salvation of the complex in the organic phase to attain certain level of extraction. It may be alternative for the separation of waste products or removal of waste from effluent. Reactive extraction has been successfully employed for separation of toxic heavy metals from wastewater [29].

Hijab et al. [30] applied microwave and thermal (Fig. 2) treatment approaches in the production of activated carbons utilizing wastes of date stones/pits obtained from a date syrup processing plant and investigated the assessment of their adsorption capacity for malachite green dye, which is applied generally in plastics and textile industry. Authors developed a two-stage batch adsorber model for the optimization of the adsorption process and correspondingly obtaining minimized adsorbent amounts and costs. It was reported that the adsorbent requirements were reduced considerably in the two-stage process in comparison to a single-stage one, providing a basis for the design of an industrial-scale two-stage batch adsorber unit for the removal of dyes from wastewater PI concerning the effective design of novel equipment and production methodologies has been one of the most promising and important progress fields for wastewater treatment. Despite the significant progress accomplished so far, there is still a considerable need for further study to increase the economic and technical feasibility of the related technologies. In wastewater treatment, the intensification of adsorber volume and the development and application of novel sorbents

Fig. 2. Microwave and thermal treatment approaches in the production of activated carbon. Hijab et al. [30].

and novel energy technologies for the reduction in energy requirements deserve further research work and progress [17].

Finally, process intensification is relevant to meeting this objective because it helps improve the efficiency and effectiveness of water and sanitation treatment systems. Intensified processes allows a greater amount of water and waste to be treated in less time and with fewer resources, which increases the availability and quality of drinking water and basic sanitation. Additionally, process intensification helps address the challenges faced by many communities around the world in terms of access to safe drinking water and basic sanitation. For example, process intensification may allow treatment of contaminated water in areas where access to clean water is limited or non-existent. In this way, process intensification reduces the spread of waterborne diseases and improve the health of communities. In summary, process intensification is relevant for the fulfillment of Goal 6 of the United Nations because it can improve the efficiency and effectiveness of water treatment and sanitation systems, which increases the availability and quality of drinking water and basic sanitation and help address the challenges faced by many communities around the world in terms of access to safe drinking water and basic sanitation. Table 1 shows some works that have contribute to UN Goal #6

Table 1
Some proposals that contribute to UN goal # 6.

Knowledge approach	Proposed intensified technology	Reported results/ conclusions	Refs.
Elimination of proteins in wastewater	Implement catalytic chemical vapor deposition with Double Walled Carbon Nanotubes	maximizes the absorption of Bovine Serum Albumin in wastewater	[23]
Elimination of recalcitrant dyes from aqueous solutions	Implement high-quality biochar in intensified absorption	maximizes the absorption of Methylene blue dye in wastewater	[25]
Elimination of Metal ions from aqueous solutions	Implement an activated carbon fixed intensified absorption	maximizes the absorption of Ni(II) ions in wastewater	[26]
Recovery of metal ions from electrolytic and concentrated acid solutions and selective recovery of trace amounts of some metals from drinking water	Implement of ion exchangers contain different kinds of functional groups, such as amine, carboxylic, phosphonic and sulfonic groups in intensified absorption	maximizes the absorption of Nickel–metal hydride	[27]
Elimination of recalcitrant dyes from aqueous solutions	Implement of activated carbons utilizing wastes of date stones/ pits obtained from a date syrup processing plant in intensified absorption	maximizes the absorption of malachite green dye in wastewater	[30]

5. Process Intensification and Goal 7: affordable and clean energy

The United Nations' Sustainable Development Goal (SDG) #7 is to ensure access to affordable, reliable, sustainable, and modern energy for all. Achieving this goal requires a significant shift from fossil fuel-based energy systems towards renewable and sustainable energy sources. Process intensification (PI) plays a crucial role in achieving this goal by promoting energy efficiency and reducing the environmental impact of energy production. The following is a description of several relevant works where process integration techniques were used for the generation of affordable and clean energy.

The article by Panwar et al. [31] reviews the role of renewable energy sources in environmental protection. The article highlights the environmental benefits of using renewable energy sources, such as reduced greenhouse gas emissions and air pollution, as well as the potential to create new employment opportunities. The authors also discuss the challenges of integrating renewable energy sources into the grid, including the intermittency of some sources, the need for energy storage, and the lack of infrastructure (Fig. 3).

From a process intensification perspective, the integration of renewable energy sources requires a holistic approach that considers the entire energy system. PI techniques optimizes the use of renewable

Fig. 3. Renewable energy sources, such as solar thermal and geothermal, in the operation of district heating and cooling systems Panwar et al. [31].

energy sources by improving the efficiency of energy conversion processes and reducing energy losses. For example, the use of microreactors and process intensification techniques in the production of biofuels increases the yield and reduce the energy required for production, making biofuels more competitive with fossil fuels.

Thermal energy storage (TES) is another area where process intensification plays a significant role in achieving SDG #7. The book by Dincer and Rosen [32] provides a comprehensive overview of TES systems and applications. TES systems improves the efficiency of energy production by storing excess energy generated during times of low demand and releasing it during peak demand periods. This reduces the need for additional energy generation capacity and helps ensure a stable and reliable energy supply.

From a process intensification perspective, TES systems are optimized using PI techniques to improve their efficiency and reduce their environmental impact. For example, the use of phase change materials

(PCMs) in latent TES systems improves the thermal conductivity and heat transfer rates of the system, reducing energy losses [33]. PI techniques are also used to design TES systems that are compatible with renewable energy sources, such as solar thermal energy, which can be used to heat the PCM and store thermal energy for later use [34].

The review article by Jouhara et al. [33] focuses specifically on latent TES technologies and their applications. The authors discuss the advantages of latent TES systems over sensible TES systems, including higher energy storage density, reduced thermal losses, and a more compact design. The article also highlights the challenges of implementing latent TES systems, such as the need for high-performance PCMs and the potential for material degradation over time.

Sameti and Haghighat [35] discuss optimization approaches in district heating and cooling thermal networks. The paper provides a comprehensive review of the different optimization techniques used in the design and operation of district heating and cooling systems. The authors highlight the importance of energy-efficient design and control strategies to reduce energy consumption and emissions, and to enhance the overall system performance. The paper emphasizes the importance of using renewable energy sources, such as solar thermal and geothermal, in the operation of district heating and cooling systems to achieve sustainable energy production. The optimization techniques discussed in the paper include mathematical modeling, simulation, and artificial intelligence-based methods. These techniques can be used to improve the system's efficiency, reduce operating costs, and enhance its overall sustainability.

Kumar et al. [36] provide a review of thermoelectric cooling technologies, which offer a sustainable alternative to conventional cooling systems that use refrigerants with high global warming potential. The paper discusses the materials used in thermoelectric cooling, including semiconductors, oxides, and chalcogenides, and the different modeling approaches used to optimize their performance. The authors highlight the importance of developing high-performance thermoelectric materials to achieve efficient and sustainable cooling. They also discuss the potential applications of thermoelectric cooling in various industries, such as electronics, automotive, and aerospace. The paper highlights the need for further research and development in this field to make thermoelectric cooling a viable option for sustainable cooling.

Pintaldi et al. [37] review the different thermal energy storage (TES) technologies and control approaches used in solar cooling systems. TES technologies offer a sustainable solution to store thermal energy from renewable sources such as solar thermal energy. The paper discusses the various TES technologies used in solar cooling, including sensible, latent, and thermochemical energy storage. The authors highlight the importance of integrating TES with solar cooling systems to improve their efficiency, reliability, and sustainability. The paper also discusses the different control approaches used to optimize the operation of solar cooling systems with TES. These include classical control, adaptive control, and predictive control methods. The paper emphasizes the need for further research and development in TES technologies to make them more cost-effective and scalable for widespread adoption.

Process intensification techniques addresses these challenges by improving the performance and durability of latent TES systems. For example, the use of microencapsulated PCMs improves the thermal stability and prevent PCM leakage, reducing the risk of material degradation (Jouhara et al., 2020). PI techniques optimizes the design of TES systems, such as the use of multi-stage TES systems that combine sensible and latent TES to improve overall system efficiency [32]. The Table 2 shows a summarized list of some proposals already presented.

Overall, all the works highlight the potential of renewable energy sources, such as solar, wind, and geothermal, to replace traditional fossil fuels and reduce greenhouse gas emissions. They also discuss the challenges of integrating renewable energy into existing power systems and the need for innovative solutions, such as district heating and cooling networks, smart energy control systems, and thermal energy storage.

Table 2
Proposals that contribute to UN goal # 7.

Knowledge approach	Proposed intensified technology	Reported results/ conclusions	Refs.
Energy efficient buildings	Implement Thermal energy storage to reduce energy consumption in heating ventilation and air conditioning	TES systems can be regarded as a green solution to confront the higher consumption of fossil-based energy sources, since it utilizes the electrical energy available at off-peak periods for charging	[34]
Heating and cooling systems	Adsorption heat pump technology	The article concludes that AHPs have significant potential by improving the efficiency and sustainability of heating and cooling systems, particularly in areas with limited access to conventional energy sources.	[38]
Thermal energy store in buldings	Phase change materials (PCM) for thermal energy storage (TES)	PCM do serve as thermal buffers that prevails load shifting and consequently reduces indoor temperature swings resulting in residential thermal comfort in heating applications while it needed more research effort regarding hybrid applications	[39]
Sustainability of public transport systems	Public Transport System Sustainability Monitoring Tool	Sustainability must be measurable. Transport system sustainability is in close connection with environmental sustainability and with related areas to complete common sustainability	[40]
Smart energy control systems in buildings	Building energy management systems (BEMS) and home energy management systems (HEMS)	The authors presented case studies that demonstrate the effectiveness of smart energy control systems in reducing energy consumption, improving indoor comfort, and lowering carbon emissions.	[41]
Renewable energy sources	Renewable energy technologies in the context of smart grids (including solar, wind, hydro, and geothermal, and their potential applications in different regions and sectors)	Geothermal resources have shown potential for both district heating purposes and for electricity generation purposes. Photovoltaic systems are showing improving performance, with research results showing e.g. a large economic potential for island systems	[42]

6. Process Intensification and Goal 9: infrastructure and industrialization

This target seeks to build resilient infrastructure, promote inclusive and sustainable industrialization and foster innovation. This goal encompasses three important aspects of sustainable development: infrastructure, industrialization and innovation. Infrastructure provides the basic physical systems and structures essential to the operation of a society or enterprise. Industrialization drives economic growth, creates job opportunities and thereby reduces income poverty. Innovation

Fig. 5. Microwave reactor for the production of biodiesel from palm oil [83].

advances the technological capabilities of industrial sectors and prompts the development of new skills. Inclusive and sustainable industrial development is the primary source of income generation, allows for rapid and sustained increases in living standards for all people, and provides the technological solutions needed for environmentally sound industrialization. In order to have a successful community, a functioning and strong infrastructure has to be in place as its basic requirement [43].

Goal 9 is all about promoting innovative and sustainable technologies and ensuring equal and universal access to information and financial markets. The key emphasis is on developing reliable and sustainable infrastructural solutions that support economic development as well as human well-being, while also ensuring financial affordability [43]. This goal aims at ensuring every society in the world possess good infrastructure. Achieving target 9 will require significant financing and political will. Key challenges include improving internet access in developing countries, inadequate transport, (particularly in land-locked developing countries) and the disparity of Research and Development investment and the number of researchers in developing countries when compared to developed countries.

The use of Artificial Intelligence (AI) techniques, particularly Machine Learning for the acceleration of equipment design, process optimization, and streamlining, is presented by the novel concept Process intensification 4.0. Under this concept, Process Intensification uses data-driven algorithms to understand other physical and chemical processes that improve equipment design, predictive control, and optimization [44].

This novel definition discusses the emerging framework of the integration between Circular economy Industry 4.0, and Process Intensification and how the data obtained from this integration is at the core of the next generation of Process Intensification strategies and thus contribute to the fulfillment of goal 9.

Food production is responsible for a large amount of greenhouse gas emissions, mainly due to meat and dairy production. The food industry must find ways to reduce its carbon footprint and promote more sustainable farming practices. It is estimated that one third of the food produced in the world is wasted each year. The food industry must work together to reduce food waste and improve efficiencies throughout the supply chain. Additionally, food production requires large amounts of water and other natural resources. The food industry must find ways to reduce its use of natural resources and promote more sustainable farming practices. Knoerzer et al. [45] review how Process Intensification improves food production and reduce waste to contribute to the fulfillment of the sustainability objectives of the United Nations.

Process intensification is an important strategy to achieve sustainable processes in the food industry and other sectors. Process intensification involves optimizing existing processes to achieve greater efficiency, reduced waste, lower energy consumption, and a smaller environmental footprint. For example, the use of advanced technologies, such as automation and process control, improves energy efficiency and reduce greenhouse gas emissions. Boodhoo and Harvey [46] reviews the application of chemical intensification in sustainable chemical production and highlights how this technique improves energy efficiency and reduce waste. Along the same lines, Esteban-Lustres et al. [47] review how chemical intensification can help convert waste to resources and improve sustainability.

The sustainable production of biofuels is important for several reasons: sustainably produced biofuels reduces greenhouse gas emissions compared to fossil fuels. This is especially important for climate change mitigation. Also, the production of sustainable biofuels diversifies energy sources and reduce dependence on fossil fuels. This improves energy security and reduce price volatility. Furthermore, the production of biofuels generates employment in rural areas and improve the local economy. The paper by Lam et al. [48] describes how chemical intensification improves biofuel production and reduce production costs.

The work by Stankiewicz and Yan [49] highlights how chemical intensification improves the production of advanced materials and reduce environmental impact. This is a relevant point that has an impact on other areas where the generation of new materials in a sustainable way is relevant, such as medicine, the plastics and biopolymers industry, among others.

The paper by Keil [50] reviews how chemical intensification produces sustainable cleaning products and reduce environmental impact. This topic is relevant given that one of the objectives is the design of processes that generate products with low environmental impact, which will be decisive in the development of clean industries and cities.

In 2019, Palys et al. [51] highlight how chemical process intensification improves sustainable fertilizer production and reduce production costs. Sustainability is very important in the fertilizer industry for several reasons. The production and use of fertilizers have a significant environmental impact, including the emission of greenhouse gasses, water pollution, and soil degradation. Sustainability in the fertilizer industry seeks to reduce this environmental footprint through more responsible practices. Also, the production of fertilizers requires large amounts of energy and raw materials, including natural gas and phosphates. Sustainability in the fertilizer industry seeks to use these resources more efficiently and reduce waste. An important point is that fertilizers have a significant impact on the quality of the food produced. Sustainability in the fertilizer industry seeks to improve the quality of food produced through more responsible practices and the use of high-quality fertilizers. In this sense, the use of process intensification has an impact on the development of a sustainable industry in the area of fertilizers.

Machine Learning (ML) and Artificial Intelligence (AI) play an important role in sustainability in various fields. Some examples include:

a) Energy efficiency: Machine Learning identifies patterns and trends in energy use, allowing businesses and households to take steps to reduce energy consumption and therefore reduce their environmental impact.
b) Sustainable agriculture: AI makes farmers more informed decisions about managing their crops, for example, by providing information on how much water or fertilizers are needed in each area.
c) Reduction of greenhouse gas emissions: Machine Learning identifies patterns in emissions data and provide recommendations on how to reduce emissions.
d) Waste management: Machine Learning classifies and separate waste for recycling more efficiently, reducing the amount of waste sent to landfills and decreasing the associated carbon footprint.

In summary, Machine Learning and AI can be powerful tools to address environmental challenges and promote sustainability in various industries [52,53].

The paper by López-Guajardo et al. [44] describes how machine learning improves efficiency in chemical intensification and reduce production costs. Seidenberg et al. [54] reviews applications of artificial intelligence in chemical intensification, including process optimization, outcome prediction, and anomaly detection. The use of artificial intelligence in chemical intensification for pharmaceutical production is described in the book by Subramanian [55]. This study describes how AI improves efficiency and quality in pharmaceutical production through chemical intensification.

Chemical Process Intensification Technologies in the Circular Economy is analyzed in the work of Beltrami et al. [56]. This study describes how chemical process intensification helps the circular economy by improving efficiency and reducing environmental impact. In the same line, Kong et al. [57] highlight how chemical process intensification improves efficiency and reduce production costs in Industry 4.0.

The work of Ding [58] describes how chemical process intensification improves efficiency and reduce production costs in pharmaceutical production in an industry 4.0 environment. In 2019, Venkatasubramanian [59] reviews how AI improves efficiency and sustainability in chemical intensification, as well as its application in the production of sustainable chemicals.

Chemical Intensification and artificial intelligence in Food Production is analyzed in detail in the work of Kakani et al. [61]. This article reviews how artificial intelligence improves food production and reduce waste through process intensification. AI can help farmers make more informed decisions about managing their crops, for example, by providing information on how much water or fertilizers are needed in each area of intensified process. The Table 3 shows a summarized list of some intensified proposals presented.

The process intensification is relevant for the fulfillment of this objective because it promote to a greater efficiency and profitability of the industries, while reducing its environmental impact. By intensifying production processes, companies might reduce production costs and increase their productivity while reducing their consumption of energy and raw materials, as well as the generation of waste and emissions. In addition, process intensification promotes innovation by fostering the development of new technologies and practices that are more sustainable and efficient in the use of resources. The implementation of these technologies and practices might also improve the resilience of infrastructures and reduce their environmental impact. In summary, process intensification is relevant for the fulfillment of Goal 9 of the United Nations because it promotes to greater efficiency and profitability of industries, while reducing their environmental impact and promoting innovation. In addition, the implementation of more sustainable and efficient technologies and practices can also improve the resilience of infrastructures.

Table 3
Some proposals that contribute to UN goal # 9.

Knowledge approach	Proposed intensified technology	Reported results/ conclusions	Refs.
Reduce waste and improve energy efficiencies	Implement micro reactors and intensified separation processes	Reduce carbon footprint and promote more sustainable farming practices in food industry	[45]
Reduce carbon footprint and improve energy efficiencies	Implement intensified separation processes	Reduce carbon footprint and energy consumption in biofuels production	[48]
Low environmental impact	Implement micro reactors and intensified separation processes	Produce sustainable cleaning products and reduce environmental impact	[50]
Low environmental impact and costs	Implement micro reactors and intensified separation processes	Improve sustainable fertilizer production and reduce production costs.	[51]
Low environmental impact, costs and inherent safety	Implement Machine Learning to identify patterns and trends in energy use in intensified processes.	Improve sustainable production of several productos	[54]
Improve efficiency and reduce production costs	Implement several ntensified processes.	Improve sustainable production in Industry 4.0	[57]
Reduction of environmental impact.	Implement Machine Learning to identify patterns and trends in energy use in intensified processes	Improve sustainable production of advanced materials	[60]

Use of machine learning in chemical process intensification for the production of advanced materials is studied in the work of Goldsmith et al. [60]. This study highlights how machine learning improves the production of advanced materials and reduce environmental impact. Chemical Intensification and artificial intelligence in Food Production is analyzed in detail in the work of Kakani et al. [61]. This article reviews how artificial intelligence improves food production and reduce waste through chemical intensification.

The process intensification is relevant for the fulfillment of this objective because it contributes to a greater efficiency and profitability of the industries, while reducing its environmental impact. By intensifying production processes, companies reduces production costs and increase their productivity while reducing their consumption of energy and raw materials, as well as the generation of waste and emissions. In addition, process intensification promotes innovation by fostering the development of new technologies and practices that are more sustainable and efficient in the use of resources. In summary, process intensification is relevant for the fulfillment of Goal 9 of the United Nations because it promotes to greater efficiency and profitability of industries, while reducing their environmental impact and promoting innovation. In addition, the implementation of more sustainable and efficient technologies and practices can also improve the resilience of infrastructures.

7. Process Intensification and Goal 12: responsible consumption and production

The United Nations Sustainable Development Goal 12 aims to ensure sustainable consumption and production patterns, which involves improving resource efficiency, reducing waste generation, and minimizing the impact of industrial processes on the environment. Process intensification (PI) is a key approach in achieving this goal, as it seeks to enhance process efficiency while reducing the use of resources and minimizing environmental impact. In this context, the next works contribute to the development of UN Sustainable Goal 12 from a process intensification point of view. In this context, process intensification has emerged as an innovative approach to optimize chemical processes and achieve more sustainable production.

One example of the application of process intensification for sustainable production is the article by Gude and Martinez-Guerra [62]. The authors present a green chemistry approach to biodiesel production using process intensification strategies. Biodiesel is a renewable fuel that has the potential to reduce greenhouse gas emissions and dependence on fossil fuels. However, its production can be energy-intensive and generate significant amounts of waste and pollution. Therefore, the authors propose the use of microscale technologies and intensified reactors to reduce the environmental impact of biodiesel production.

Another relevant contribution to sustainable development through process intensification is the article by Drioli et al. [63]. The authors discuss different process intensification strategies based on membrane engineering. Membrane technology has been widely applied to various processes, including separation, purification, and reaction engineering. Membrane-based processes offers several advantages, including high selectivity, low energy consumption, and reduced waste generation. The authors highlight the potential of membrane engineering for achieving sustainable production through intensified processes.

Microprocess engineering is another technology that significantly contributes to sustainable production through process intensification, as discussed in the article by Verdnik et al. [64] The authors present recent developments in microprocess engineering and its application in different fields, including chemical synthesis, separation, and reaction engineering. Microprocess engineering involves the use of microscale reactors and devices to intensify chemical processes, reduce energy consumption, and enhance process efficiency. The authors discuss different case studies, demonstrating the potential of microprocess engineering for achieving sustainable production through process intensification.

The book edited by El-Halwagi and Foo [65] provides an overview of process intensification and integration for sustainable design. The book discusses different aspects of process intensification, including process design, optimization, and control. The authors highlight the importance of integrating different unit operations and adopting a holistic approach to process intensification for achieving sustainable production. The book includes case studies and examples from different sectors, demonstrating the potential of process intensification for reducing environmental impacts and promoting economic benefits.

Demirel et al. [66] propose a sustainable process intensification framework that uses building blocks to enhance process efficiency and reduce environmental impact. The authors argue that traditional process intensification approaches have focused mainly on the optimization of specific process units, without considering the integration of the entire process. Their framework proposes the use of building blocks, which are modular and scalable process units that can be integrated into a larger process system. The authors demonstrate the effectiveness of this framework through case studies on the production of biodiesel and polyurethane foams. They show that the use of building blocks improves process efficiency, reduce waste generation, and lower energy consumption, thereby contributing to the achievement of UN Sustainable Goal 12. As summary, Table 4 shows some approaches where process intensification aims UN Sustainable Goal 12.

In conclusion, all articles analyzed in this article demonstrate the potential of process intensification to contribute to the achievement of UN Sustainable Goal 12. The articles highlight the potential of process intensification to improve resource efficiency, reduce waste generation, and promote sustainable production practices. The articles also suggest that process intensification enables the development of more efficient and environmentally friendly production processes, supporting the transition towards a more sustainable future.

8. Process Intensification and Goal 13: climate action

There is no country that is not experiencing the drastic effects of climate change. Greenhouse gas emissions are more than 50% higher than in 1990. Global warming is causing long-lasting changes to our climate system, which threatens irreversible consequences if we do not act. The annual average economic losses from climate-related disasters are in the hundreds of billions of dollars [74]. This is not to mention the human impact of geophysical disasters, which are 91% climate-related, and which between 1998 and 2017 killed 1.3 million people, and left 4.4 billion injured. It is still possible, with strong political will, increased investment, and using existing and novel technology, to limit the increase in global mean temperature to two degrees Celsius above pre-industrial levels, aiming at 1.5 °C, but this requires urgent and ambitious collective action [75].

Chemical process intensification refers to the use of advanced techniques and tools to increase the efficiency, speed, and selectivity of chemical processes. This trend is growing in the chemical industry due to its ability to improve productivity, reduce costs and minimize the environmental impact of operations. One of the biggest challenges facing the chemical industry is the emission of greenhouse gasses (GHG). GHGs are gasses that trap heat in the atmosphere and contribute to

Table 4
Process Intensification approaches that contribute to UN goal # 9.

Knowledge approach	Proposed intensified technology	Reported results/ conclusions	Refs.
Energy consumption and improving process efficiency	Reactive pressure swing distillation (RPSD) evaluated under sustainable criteria	Sustainable design approach can reduce waste generation, lower energy consumption, and improve process safety.	[67]
Process Intensification	microreactors, heat integration, membrane processes, and hybrid processes	Identifies specific PI metrics that help address the inherent connection to more sustainable processes.	[6]
Process intensification framework in the oil and gas industry	Technologies for the oil and gas industry, including microreactors, membrane processes, and nanotechnology	A comprehensive methodology regarding PI implementation in the petrochemical field particularly is missed. Safety constraints represent a combined driver and evaluation criteria for PI implementation.	[68]
Improving sustainability in production processes	Rotating cone reactor, Shell OMEGA process, cyclic distillation, pharmaceuticals case (Fig. 4)	Process intensification can enable sustainable development by promoting the circular economy, improving resource efficiency, and supporting the transition towards renewable energy sources	[69]
Separation and energy efficiency	Adsorptive separations, including microfluidics, reactive adsorption, and membrane-based separations	Process intensification can enable the development of more efficient and environmentally friendly adsorptive separation processes, promoting sustainable production practices	[70]
Process intensification in solids handling	Intensification techniques applied in solids handling, including mechanical, thermal, and chemical methods	Process intensification can enable sustainable production practices by promoting resource efficiency, reducing the environmental impact of solids handling processes, and improving the quality of the final product	[20]
Computer-aided process intensification	Simulation software	CAPI can improve the efficiency of the process while reducing the energy consumption and emissions	[71]
Waste-to-energy production	Thermal integration, process integration, and membrane separation, applied to waste-to-energy processes	Process intensification can increase the efficiency of waste-to-energy production while reducing the environmental impact	[72]
Process intensification and its applications in various industries	Microreactors, membrane reactors, and hybrid separation systems, applied to different industries, such as chemical, petrochemical, and pharmaceutical	Process intensification can achieving sustainable production and consumption patterns	[73]

Fig. 4. Rotating cone reactor, Shell OMEGA process with cyclic distillation for pharmaceuticals purposes [69].

climate change. Major GHGs include carbon dioxide (CO_2), methane (CH_4) and nitrous oxide (N_2O). The chemical industry is responsible for a large part of GHG emissions worldwide, which has led to growing interest in chemical process intensification as a way to reduce emissions. In this context, the objective of this section is to explore the impact of the intensification of chemical processes in the reduction of GHG emissions. To this end, the main chemical process that contributes to GHG emissions will be reviewed, the most widely used chemical process intensification techniques will be described, and recent advances in research in this field will be discussed.

The chemical processes that contribute to GHG emissions are numerous and varied. One of the most important is energy production, which is responsible for around 60% of global CO_2 emissions. The chemical industry is also responsible for a significant part of GHG emissions, in particular due to the production of ammonia, which is used as a fertilizer in agriculture and is responsible for around 1% of global CO_2 emissions [76]. Another chemical process that contributes to GHG emissions is the production of chemicals from fossil feedstocks, such as oil and natural gas. These processes release large amounts of CO_2 into the atmosphere and are responsible for a large part of the GHG emissions from the chemical industry [77]. To reduce GHG emissions in the chemical industry, a number of chemical process intensification techniques have been developed. These techniques include the use of more efficient catalysts, the improvement of separation processes, the optimization of reaction kinetics and the miniaturization of chemical processes [78].

The production of biofuels from renewable sources, through intensified processes, has been a great contribution to reduce the generation of greenhouse gasses in the chemical industry. Ding et al. [79] evaluated the use of a microwave reactor for the production of biodiesel from palm oil. Intensifying the production process reduced greenhouse gas emissions by 47% compared to conventional methods. In the same line, Athar et al. [80] studied the production of biodiesel from palm oil using a microwave reactor. Process intensification reduced greenhouse gas emissions by 42% compared to conventional methods. Sharma et al. [81] studied the production of biodiesel from cottonseed oil using a microwave reactor. Process intensification reduced greenhouse gas emissions by 28% compared to conventional methods. Tan et al. [82] evaluated the use of microwaves for the production of biodiesel from jatropha oil. The intensification of the process reduced greenhouse gas emissions by 30% compared to the traditional process. The variations in the contribution to environmental indicators should be considered during the design and process selection of intensified biorefineries in the paper by Joglekar et al. [84]. To ensure the sustainability on the purification of liquid biofuels, it is important to develop intensified separation processes with low environmental impact and reduction in greenhouse gas emissions. Segovia-Hernandez et al. [85] and Segovia-Hernandez and Sánchez-Ramírez [86] show, in an in-depth review, advances on the application of process intensification in the purification of liquid biofuels and how the use of these technologies (intensified and hybrid distillation) shows important effects in the reduction of greenhouse gasses.

The development of biobased chemicals has really taken off over the past decade. There is an existing market for biobased chemicals blocks but current production is just a fraction of the petrochemical market. The growth is impressive, and it is expected that production will increase considerably in the coming years. As observed, there is a growing market that demands biobased chemicals. Therefore, it is necessary to design intensified processes so that the production of biobased chemicals can be economical, clean and efficient and their prices are competitive in the sales market. Segovia – Hernández et al. [87] show intensification strategies in the production and purification process of various biobased chemicals blocks. The use of intensified processes reduced energy consumption and decreased greenhouse gas emissions compared to conventional arrangements,

In recent years, the carbon dioxide capture process has been relevant as a strategy to reduce the emission of greenhouse gasses. The efficiency of the capture processes, using reactive absorption (intensified process) is directly related to the CO_2 concentration in the combustion gas and the absorbent flow for CO_2 capture. Note that both the energy used and the demand for the solvent in CO_2 capture are variables that significantly affect the environmental impact of the overall process, so it is necessary to determine the effect of selecting one fuel or another in the generation stage and capture of CO_2 such as energy requirements, design parameter in the downstream process, and so on. According to the results obtained by Romero-García et al. [89], for the scenario with a constant flow, the best alternative for capture is the one that considers biogas as fuel. On the other hand, non-associated gas was the most promising alternative for the scenario with constant energy demand (Fig. 6). A novel carbon capture intensified absorption process is designed and optimized using the deep eutectic liquid ChCl/urea (1:2), under a sustainability scheme was analyzed by Martínez – Lomovskoi et al. [91]. The multiobjective optimization considering simultaneous economic and environmental objectives showed that the process for CO2 from the flue gas of a coal-fired power plant outperforms the use of all other fuels evaluated by improving all environmental indicators. The proposed process achieve a 95% recovery rate and a 95% mol purity for CO_2 captured for all case studies considered.

Garcia-Costa et al. [93] investigated the degradation of phenol by microwave-assisted catalytic wet oxidation. The use of microwaves

Fig. 6. Carbon dioxide capture process (using reactive absorption) as a strategy to reduce the emission of greenhouse gasses Romero-García et al. [89].

reduced reaction time and greenhouse gas emissions by 42.4% compared to conventional oxidation. Zhao et al. [94] demonstrated that the preparation of a microwave-assisted Ni/SiO_2 catalyst for CO methanation reduced CO_2 emissions.

The small size nature of microreactor operating in continuous regime have made it promising in intensification of thermally driven [95] and photocatalytic reactions [96], among other applications. In photocatalytic reactions, in addition to overcoming thermal and mass diffusion limitations, in applications where light distribution determines the yield, microreactors allow for uniform light distribution owing to its small size, short optical paths and large surface area to volume ratio [97]. Given the high photon density in micro-reactors, it is clear that short reaction times are needed compared to conventional large scale vessels. Energy consumption and light efficiency can be further improved using low power LED light sources, which offer a high and unidirectional radiant flux. Additionally, reaction parameters such as flow rate, temperature and pressure are easily adjusted and fine-tuned in microreactors operating in continuous regime, unlike batch reactors where some parameter are adjusted after the end of each run consuming much time [97]. All these characteristics in this class of reactors support the reduction of the emission of greenhouse gasses when compared with the operation of conventional reactors.

The production of specialty chemicals provides a more attractive pathway to dispose of residual biomass; however, a problem that arises in recovering products from waste is that there are currently no well-established markets that bring together all stakeholders involved (e.g., biomass production, collection, transportation, and processing). In this context, coordination is essential as all the stakeholders in the supply chain depend on the revenue generated from the derived products. In the work by Alcocer-Garcia et al. [100], they propose a market coordination framework for the production of levulinic acid and furfural (using intensified distillation technologies) from lignocellulosic biomass obtained from agricultural residues. Coordination brings a number of important economic benefits that would be difficult to achieve under existing markets (which are uncoordinated and based on peer-to-peer transactions). Results also indicate that this market would avoid the generation of 850,000 tonnes of CO_2 annually (corresponding to a 34% reduction in emissions from the combustion of agricultural residues). As such, the deployment of such a market can bring both economic and environmental benefits.

The Carbon–Hydrogen–Oxygen symbiosis networks (CHOSYNs) belong to the latest trend of sustainable process design whose main purpose is the efficient use of energy and mass resources. Processes Intensification methodologies have been used to enhance the sustainability of several chemical processes. Juárez-García et al. [101] proposes to involve intensified purification processes in the synthesis of CHOSYNs to improve the sustainability and reduction of greenhouse gas emissions of the network beyond the integration benefits. The main objective of this work is to evaluate the impact of incorporating intensified processes on the CHOSYN economic, environmental and safety performances. Due to the intensive energy use and low thermal efficiency in distillation sequences, the intensification is focused on these separation processes to improve energy efficiency and reduce operating costs. The Table 5 shows a summarized list of some proposals already presented.

Process intensification is relevant to meeting this goal because it reduces greenhouse gas emissions and energy consumption in industrial and production processes. By intensifying processes, companies use fewer resources and generate fewer emissions in the production of goods and services, which significantly reduce greenhouse gas emissions. In addition, process intensification promotes the implementation of cleaner and more efficient technologies in production, which reduces the carbon footprint of companies and contribute to the transition towards a more sustainable and low-carbon economy. In summary, process intensification is relevant to the fulfillment of United Nations Goal 13 because it reduces greenhouse gas emissions and energy consumption in industrial and production processes. This significantly contribute to the fight against climate change and its negative effects, as well as promote the implementation of cleaner and more efficient technologies in production for a more sustainable and low-carbon economy.

Table 5
Some proposals that contribute to UN goal # 13.

Knowledge approach	Proposed intensified technology	Reported results/ conclusions	Refs.
Reduction in greenhouse gas emissions	Implement microwave reactor (Fig. 5)	Sustainable production of biodiesel from soybean oil	[83]
Reduction in the energy consumption	Implement reactive absorption	Carbon capture plant to reduce heating and cooling demands, and power consumption	[88]
Reduction in greenhouse gas emissions	Implement reactive absorption	Carbon capture plant to reduce heating and cooling demands, and power consumption	[90]
Reduction in environmental impact	Implement intensified wet oxidation process	Treat wastewater from the electronics industry under sustainable criteria.	[92]
Reduction in environmental impact	Implement photocatalytic micro-reactors	Reduction of CO_2 in aqueous under sustainable criteria.	[98]
Reduction in environmental impact	Implement intensified distillation arrangements	recovery of furfural by biomass under sustainable criteria.	[99]
Reduction in environmental impact	Implement intensified extractive distillation	recovery of dichloromethane and methanol from a binary azeotropic mixture under sustainable criteria.	[102]

9. Challenges and opportunities

The development of chemistry has been fundamental in the evolution of humanity. Since the beginnings of agriculture, humans have used chemicals to improve their crops and increase production. Today, chemistry is an integral part of our daily lives, from the food and medicines we consume to the materials we use in our constructions and transportation [103]. However, the large-scale production of chemicals has also led to a number of negative impacts on the environment and human health. Therefore, one of the main objectives of the United Nations 2030 Agenda is to achieve sustainable and responsible development in the production of chemical products [104]. Chemical process intensification refers to the optimization of chemical processes to maximize efficiency and minimize resource and energy consumption. This can be achieved through the use of advanced technologies such as catalysis, microwave-assisted synthesis, and green chemistry. These technologies allow the reduction of costs and the reduction of waste and greenhouse gas emissions [105]. Below are some challenges and opportunities presented by the intensification of chemical processes in compliance with the United Nations 2030 Agenda.

Challenges:

a) Technological Barriers: Implementing process intensification technologies and techniques may require significant upfront investments and expertise. Developing and adopting these technologies at scale can pose technical challenges and require ongoing research and development.
b) Adoption Barriers: Industries often face resistance to change and may be reluctant to invest in new processes. Overcoming the inertia and convincing stakeholders about the benefits of process intensification can be a challenge.
c) Resource Constraints: Developing countries or industries with limited resources may face challenges in adopting process

intensification due to the need for advanced technologies, skilled workforce, and infrastructure upgrades.

d) Regulatory Frameworks: Existing regulations may not always align with the implementation of process intensification approaches. Adapting regulatory frameworks to accommodate and incentivize sustainable industrial practices might be a challenge.
e) Financial Constraints: Adopting process intensification may require substantial initial investments for industries with limited financial resources. Overcoming these financial constraints and ensuring access to funding is a hurdle.

Opportunities:

a) Sustainability Benefits: Process intensification offers significant opportunities for achieving sustainable development goals. It enables reduced energy consumption, resource efficiency, waste reduction, and lower emissions, contributing directly to Goals 7, 9, 12, and 13.
b) Innovation and Economic Growth: Embracing process intensification drives innovation and lead to the development of new technologies and solutions. This creates economic opportunities, stimulate growth, and foster a competitive advantage for industries and countries.
c) Collaboration and Knowledge Sharing: Implementing process intensification requires collaboration among stakeholders, including industry, academia, and governments. This collaborative approach fosters knowledge sharing, technology transfer, and capacity building, facilitating sustainable development efforts.
d) Climate Change Mitigation: Process intensification plays a crucial role in addressing climate change by reducing greenhouse gas emissions. It presents opportunities for industries to contribute to climate action targets while enhancing their environmental performance.
e) Circular Economy: Process intensification supports the transition to a circular economy by promoting the reuse, recycling, and valorization of waste streams. It enables the creation of closed-loop systems, minimizing waste and maximizing resource utilization.
f) Resource Efficiency: Process intensification offers the opportunity to optimize resource use, reduce waste generation, and enhance overall efficiency. This leads to cost savings, improved resource availability, and reduced environmental impacts.

Overall, while challenges such as technological barriers, adoption barriers, resource constraints, and regulatory frameworks exist, process intensification offers significant opportunities for achieving sustainable development goals, promoting innovation, driving economic growth, and mitigating climate change in the 21st century.

Chemical process intensification plays an important role in meeting the goals of the United Nations 2030 Agenda. The implementation of advanced production technologies and the adoption of sustainable practices reduces the environmental impacts of chemical processes and promote sustainable development throughout the world. In conclusion, while challenges such as technological barriers, adoption barriers, skills gaps, and regulatory frameworks exist, process intensification offers significant opportunities to achieve the objectives of the United Nations' 2023 Sustainability Agenda. It can drive resource efficiency, environmental benefits, innovation, competitiveness, collaboration, and contribute to climate change mitigation and the transition towards a circular economy.

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.

Data availability

No data was used for the research described in the article.

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