

Advancing Process Intensification in Petrochemical and Specialty Chemical Manufacturing – A Mini Review



F. S. Olorunnaiye^{1*}, S. A. Akolo², E. O. Babatunde^{3, 4*}

¹Fluor Corporation, Houston, Texas, USA.

²Ardova Plc 41B, Oba Akinjobi Way, Ikeja, GRA, Lagos, Nigeria.

³Department of Chemical Engineering, University of Ilorin, Ilorin, Nigeria.

⁴Department of Chemical Engineering Technology, Faculty of Engineering and Built Environment, Doornfontein Campus, University of Johannesburg, South Africa.

ABSTRACT: The chemical process industries face increasing pressure to improve efficiency and reduce negative environmental impact. Process intensification (PI) has emerged as a top strategy to achieve step-change improvements in performance and sustainability by fundamentally reimagining process design. PI involves radically redesigning processes and equipment to integrate functions, boost transfer rates, and eliminate inefficiencies, thereby shrinking the footprint of operations while improving energy and material utilization. Researchers have touted PI as “the most promising way to achieve sustainable development” in sectors like oil and gas. This approach promises cleaner, smaller, and more efficient processes that meet economic and environmental objectives simultaneously. However, despite many novel PI technologies reported in literature, relatively few have seen broad commercial adoption in petrochemical and chemical plants so far. Bridging this gap through practical design methodologies and demonstrated industrial successes is a critical challenge. This review discusses key process intensification strategies (integrated unit operations, advanced distillation technologies, novel reactors, membrane systems, and modular processing) and how they are transforming petrochemical and specialty chemical manufacturing. It also examines the benefits achieved through PI and the challenges that must be overcome to fully realize its potential.

KEYWORDS: Process Intensification, Petrochemical Industry, Specialty Chemicals, Modular Processes, Reactive Separation, Energy Efficiency.

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I. INTRODUCTION

Process intensification (PI) refers to the development of radically innovative process and equipment designs that achieve significantly enhanced performance compared to conventional operations (Stankiewicz & Moulijn, 2000; Harmsen, 2010). Rather than simply optimizing existing unit operations, PI seeks step-change improvements by fundamentally rethinking how processes are organized and integrated. The concept dates back to pioneering work in the 1970s and 1980s (Reay et al., 2008) but has gained renewed urgency in recent years as the chemical industry faces pressures to improve energy efficiency, reduce environmental impact, and increase flexibility. PI techniques can deliver significant benefits in terms of efficiency, cost, product quality, safety, and environmental footprint by combining or intensifying physical and chemical transformations within equipment (Van Gerven & Stankiewicz, 2009). In practical terms, this often means merging multiple unit operations into

one, using novel equipment designs, or pushing processes to operate in new regimes (Kiss, 2016).

Petrochemical and specialty chemical manufacturers are actively exploring PI to remain competitive and meet sustainability targets. Petrochemical processes (such as large-scale commodity chemicals and fuels) are highly energy-intensive. For example, steam cracking for olefins and large distillation trains consume vast amounts of energy; therefore, even incremental efficiency gains can result in significant cost savings and reduced emissions (Harmsen, 2010). At the same time, specialty chemical and pharmaceutical production is shifting toward smaller volumes of high-value products, where agility and speed to market are crucial. Traditional large continuous plants lack the flexibility needed for rapidly changing demand for specialty chemicals. PI offers an opportunity to design smaller, modular, and more agile processes that can economically produce high-grade specialty products (Baldea et al., 2018). As such, process intensification is increasingly seen as a key enabler for the next generation of chemical manufacturing, combining higher efficiency with

*Corresponding author: babatunde.eo@unilorin.edu.ng

greater flexibility and inherent safety (Kim et al., 2017). In the following sections, we discuss the need for PI in the chemical industries, review major intensification technologies and strategies, examine the benefits realized, and consider the challenges and future outlook for widespread implementation.

II. THE NEED FOR PROCESS INTENSIFICATION

The drivers for process intensification in petrochemical and specialty chemical manufacturing stem from both economic and environmental imperatives. Energy efficiency and sustainability are prime motivations. Large petrochemical processes (e.g. ethylene production, refinery separations) consume immense energy; improving energy utilization by even a few percent can translate to substantial cost savings and lower CO₂ emissions. PI methods have demonstrated the potential to cut energy usage and associated greenhouse gas emissions by 20 – 50% in various applications (Yildirim et al., 2011; Dejanović et al., 2010). For instance, the European chemical industry identified PI as a crucial strategy for sustainable manufacturing in its roadmap, targeting “smaller, cleaner, and more energy-efficient” processes (EFCE, 2015). Similarly, industry analyses have highlighted that conventional processes in petrochemicals are approaching the thermodynamic limits of efficiency, and new approaches are necessary to overcome these bottlenecks (Harmsen, 2010).

Another driver is cost reduction and competitiveness. The petrochemical sector is capital-intensive, and PI can reduce both capital and operating costs by simplifying process schemes. Merging multiple unit operations into a single piece of equipment can dramatically reduce plant footprints and decrease the number of vessels, piping, and controls required. This not only lowers capital expenditure but also often reduces maintenance costs and improves reliability. For example, integrating reaction and separation in a single unit can eliminate entire downstream separation trains. Harmsen (2010) noted that in certain cases, a well-implemented PI solution, such as reactive distillation, led to 20–80% reductions in capital cost and energy usage, resulting in a transformative economic benefit. In specialty chemicals, the need is for flexible, agile production rather than sheer scale. Manufacturers of high-value, low-volume products seek production facilities that can be rapidly reconfigured for new products and scaled out incrementally. Conventional large plants built for economies of scale are often uneconomical for these purposes. Distributed modular production enabled by intensified, small-footprint technologies allows companies to seize high-margin specialty opportunities without the risk of building large, dedicated plants (Baldea et al., 2018). Small, intensified processing units can be deployed near feedstock sources or markets, thereby reducing transportation and logistics costs for specialty and fine chemicals (Mascia et al., 2013).

Finally, safety and environmental compliance provide additional impetus for PI. Smaller volumes and equipment sizes inherent in many PI technologies (e.g. microreactors, compact heat exchangers) mean smaller inventories of hazardous chemicals, which lowers the risk of major accidents and makes containment easier (Reay et al., 2008). Intensified

processes often produce less waste and fewer byproducts due to improved selectivity and integration of waste-recovery operations. Overall, the need for process intensification arises from the convergence of these drivers: the pursuit of step-change improvements in efficiency and cost, coupled with the demand for more sustainable, safe, and flexible production methods in the chemical process industries.

III. KEY INTENSIFICATION TECHNOLOGIES AND STRATEGIES

Process intensification encompasses a broad “toolbox” of technologies and design strategies. In the context of petrochemicals and specialty chemicals, several key PI approaches have emerged as especially impactful. These include integrated and multifunctional unit operations (combining multiple functions in a single piece of equipment), advanced distillation technologies such as dividing-wall columns, reactive distillation, and other reactive-separation schemes, membrane-based and hybrid separation systems, microreactors and micro-structured process devices, and modular processing concepts. We outline each of these below:

A. INTEGRATED UNIT OPERATIONS AND MULTIFUNCTIONAL REACTORS

A core theme of PI is combining separate steps into a single unit to intensify mass and heat transfer and even invoke synergy between processes. Traditional chemical plants are built around the unit operation principle (“one unit, one function”), but intensified designs aim to break this paradigm by executing multiple functions in the same physical space (Baldea et al., 2018). Examples include reactive separations (simultaneous reaction and separation), coupled reaction-extraction, reactive filtration, and other multifunctional reactors. By bringing different process phenomena into direct contact, such integrated units can drive reactions to completion (by immediately removing products) or significantly enhance yield and selectivity. Reactive distillation is a prime example, as discussed below, but other integrated operations also exist. For instance, reactive absorption (absorption combined with reaction in the same column) for gas treatment, or separative reactors for simultaneous reaction and product removal (Kiss, 2016). The design of such units often requires careful balancing of reaction kinetics and separation thermodynamics, but when successful, the payoff is a simpler flowsheet with fewer pieces of equipment. Integrated units intensify processes at the phenomenon level, ensuring that every volume of the equipment is used efficiently for multiple tasks (Stankiewicz & Moulijn, 2000). This approach maximizes the effectiveness of molecular-scale events by closely coupling those (Van Gerven & Stankiewicz, 2009). Many multifunctional reactor concepts remain areas of active research, but some have seen industrial adoption, as described below.

B. DIVIDING-WALL DISTILLATION COLUMN (DWCs).

Distillation is ubiquitous in petrochemical and chemical manufacturing, but conventional distillation sequences often involve multiple columns in series or parallel for multi-component separations. A dividing-wall column is an intensified distillation column that can perform a complex separation (for example, splitting a ternary mixture into three

products) within a single shell. It features a vertical partition (dividing wall) in part of the column, creating two parallel sections that allow feed and internal flows to be arranged such that a single column can replace two or more columns (Asprion & Kaibel, 2010). By integrating what would normally be separate distillation steps, DWCs eliminate redundant reboilers and condensers and reduce remixing inefficiencies, leading to significant energy and capital savings. Studies report that DWCs can achieve energy savings on the order of 20 – 40% compared to conventional multi-column arrangements, along with lower investment cost and footprint (Yildirim et al., 2011; Dejanović et al., 2010). For example, a case study on a DWC retrofit for a separation in a petrochemical plant showed about 30% energy reduction and 25% lower total annual cost relative to the baseline process (Dejanović et al., 2010). These benefits arise from the heat integration within the column and the avoidance of duplicated equipment.

Industrial acceptance of dividing-wall columns has grown steadily over the past two decades. Early implementations in the 1980s and 1990s (Kaibel's pioneering work) proved the concept, and by the 2000s, companies like BASF, Dow, and others began widely using DWCs for processes such as benzene-toluene-xylene (BTX) separation and various refining and chemical separations (Schultz et al., 2002; Parkinson, 2007). By 2010, dozens of commercial DWCs were in operation, and that number has only increased as confidence in the technology has grown (Yildirim et al., 2011). Modern designs include not only simple three-product DWCs but also extractive and reactive dividing-wall columns that layer on additional functionality. A notable example is a DWC implemented to separate a quaternary mixture of xylene isomers and ethylbenzene in one shell, significantly debottlenecking an aromatics processing unit (Slade et al., 2006). Overall, dividing-wall distillation is a proven PI technology in the separation domain, delivering compact, energy-efficient separations with a single-column solution.

C. REACTIVE DISTILLATION

Reactive distillation (RD) is often hailed as one of the most successful examples of process intensification in practice (Harmsen, 2007). In a reactive distillation column, chemical reaction and distillative separation occur simultaneously within one apparatus. The column is typically configured with a section that contains catalyst (for reaction) and other sections with trays or packing to facilitate fractional distillation. As reactants flow through, they react to form products, and the volatile components are continuously separated by distillation within the same column. This coupling can drive equilibrium-limited reactions to higher conversion by constantly removing one of the products (shifting the equilibrium); it also inherently separates the product mixture, often delivering the desired product as a high-purity distillate or bottoms stream.

The Eastman Chemical methyl acetate process is a classical success story of RD: Eastman replaced a complex process (which involved a reactor and a series of eight distillation columns for an esterification reaction and purification) with a single reactive distillation column, achieving the same conversion and purity with drastically lower energy usage and equipment count (Agrega et al., 1990).

This innovation, implemented in the 1980s, demonstrated that reactive distillation could reduce capital and energy costs enormously in this case by eliminating multiple separation steps and their reboilers. Since then, reactive distillation has been applied commercially to many systems, especially in the production of fuels and bulk chemicals such as MTBE, ETBE, methyl acetate, and various esters and ethers (Harmsen, 2007). In recent years, RD has also been explored for biofuel production and specialty chemical synthesis. For example, biodiesel (fatty acid methyl ester) production by transesterification can be intensified in a reactive distillation column to integrate reaction and separation of glycerol byproducts, leading to energy savings and a simpler process with easier product purification (Ali et al., 2021). Ali et al. (2021) demonstrated optimized operation and control of a biodiesel RD process, achieving a 34% reduction in energy consumption via heat integration and effective column control. Reactive distillation's advantages include improved conversion and higher selectivity (since immediate removal of products can suppress side reactions) and significant capital savings from unit integration. It is not a panacea; RD is feasible only for certain reaction/separation combinations (for instance, the reaction must occur in a temperature/pressure range suitable for distillation, and component volatilities must be favorable), but when applicable, it is often the most economically attractive option. Indeed, RD is frequently referred to as the "front-runner of industrial process intensification" due to its early and successful adoption in industry (Harmsen, 2007). Ongoing research continues to extend RD to new chemistries (e.g., equilibrium-limited reversible reactions and heterogeneous catalysis in RD) and to improve design and control methodologies for these coupled systems (Qiu et al., 2010). Variants such as reactive absorption and reactive extraction are also being investigated, applying the same integration principle to other types of separation processes (Górak & Stankiewicz, 2011).

D. MEMBRANE AND HYBRID SEPERATION SYSTEMS

Another major strategy in PI is the use of membrane-based technologies and hybrid separation processes to intensify separations that are energy-intensive or otherwise difficult with conventional methods. Membrane processes (such as gas permeation, pervaporation, membrane reactors, etc.) can offer lower-energy alternatives to traditional distillation or absorption by leveraging selective permeation. In practice, a hybrid system might combine a distillation column with a membrane unit to achieve a separation more efficiently than distillation alone. For example, a distillation column could be used for bulk separation while a membrane "polishes" the remaining difficult separation (or vice versa), allowing overall energy savings by avoiding very high reflux or deep separation in distillation (Reay et al., 2008). Membranes are especially useful for breaking azeotropes or separating close-boiling components when distillation becomes impractical. An intensified process will often integrate the membrane unit directly in the recycle loop of a column or reactor so that the two units work in synergy – this

coupling reduces equipment and improves driving forces (Liu et al., 2011, as cited in Qiu et al., 2010).

Membrane reactors are another powerful PI concept wherein a membrane is incorporated into a reactor to selectively remove one product (or introduce a reactant), thereby shifting the reaction equilibrium and increasing conversion. For instance, in hydrogen-producing reactions like dehydrogenation or reforming, a hydrogen-selective membrane can continuously extract H_2 from the reaction zone, achieving higher yields than the equilibrium would normally allow. A striking demonstration is a catalytic membrane reactor developed for the direct conversion of methane to aromatics: by using an oxygen-ion-conducting membrane to remove hydrogen (as water) from the reacting methane, researchers drove the equilibrium toward aromatic products and achieved higher single-step yields of benzene and naphthalene, essentially coupling oxidative dehydrogenation with separation in one unit (Morejudo et al., 2016). This process would normally require multiple steps (methane conversion, hydrogen separation, aromatics separation), but the membrane reactor intensifies it into a single step, offering a cleaner and potentially more efficient route to valuable products from natural gas (Morejudo et al., 2016). In petrochemicals, membrane systems are also being explored for hybrid distillation–membrane schemes in refining and gas processing, such as combining a membrane unit with a distillation column for C_3/C_4 separations or for enhanced CO_2 removal in natural gas treatment (Kim et al., 2017). While membranes alone might not achieve ultra-high purities, their integration with conventional units can dramatically cut energy usage by handling the “difficult” part of the separation with less energy. From an intensification viewpoint, membranes allow separation without a phase change (avoiding boiling and condensing), which is a huge energy saver. They also often operate in compact, modular units, aligning with the trend toward small-scale, distributed processing. Dang et al. (2014) employed a membrane-assisted micro-structured fluidized bed to investigate the distribution of solids holdup and solid circulation patterns. This micro-structured fluidized bed enhanced solid circulation relative to the findings of De Jong et al. (2014) who utilized a larger-scale fluidized bed and emphasized precise control of extraction velocity. Dead zones within the reactor can impair solid mixing as well as heat and mass transfer. Unlike the stationary dead zones near the membrane wall in the larger reactor reported by De Jong et al. (2011), those in the micro-structured reactor remained dynamic and mobile. The challenges with membranes include sensitivity to fouling, limited chemical compatibility under harsh conditions, and sometimes lower throughput for very large-scale applications hence the popularity of hybrid processes that leverage the strengths of both membranes and traditional separation methods. Overall, membrane-assisted intensification has shown great promise in reducing the energy and carbon footprint of separations and in enabling novel process routes (Li & Chen, 2018; Morejudo et al., 2016).

E. MICROREACTORS AND MICRO-STRUCTURED DEVICES.

Microreactors are millimeter- or micro-scale flow reactors that offer extreme intensification of heat and mass transfer due to their very high surface-area-to-volume ratios and small characteristic dimensions. In microreactor channels, mixing and heat transfer occur in a matter of milliseconds, enabling reactions to be run under conditions that would be unattainable or unsafe in large reactors (Hessel et al., 2013). This technology exemplifies “process intensification by miniaturization” – essentially, shrinking the equipment size to intensify transport processes. Microreactors allow reactions to be performed isothermally even if highly exothermic (since heat is removed almost instantly through the channel walls), and they enable precise control of reaction time on the order of seconds or less, which can greatly improve selectivity for fast parallel reactions. They also make it feasible to explore novel process windows such as very high reaction temperatures or pressures to speed up kinetics, since the small volume confines the risks (Hessel et al., 2013; Nandakumar et al., 2022).

In the specialty and fine chemicals sector, microreactors have become a key tool for continuous-flow chemistry, often leading to better yields and cleaner products compared to traditional batch synthesis. For example, in pharmaceutical process development, microreactor systems have been used to carry out multi-step syntheses with improved efficiency and automation by condensing what would be batch reactors and large separations into a continuous micro-scale sequence (Mascia et al., 2013; Ong et al., 2024). The safety advantages are substantial: even if a reaction is highly energetic or potentially explosive, the total volume in a microreactor is so small that the worst-case energy release is minimal, making some previously “forbidden” chemistries possible (Hessel et al., 2013).

From an industrial perspective, the throughput of a single microreactor is low due to its small size, but production can be increased by numbering-up many channels or reactor modules in parallel rather than scaling up in size. This approach aligns well with modular production concepts discussed by Patel and Pereiro (2022). The entire production systems can consist of multiple parallel microreactor units, offering linear scale-out and redundancy. One high profile industrial application of micro-structured reactors is in gas-to-liquids (GTL) synthesis: microchannel reactors have been developed for Fischer-Tropsch conversion of syngas to fuels, achieving enhanced heat removal and thus higher productivity for this highly exothermic reaction (LeViness et al., 2014). The company Velocys, for instance, commercialized a microchannel FT reactor technology that enables distributed small-scale GTL plants converting natural gas or biogas to liquid fuels; the intensified microreactor design allows these processes to be economical at much smaller scales than traditional FT reactors (LeViness et al., 2014). Likewise, microreactor technology is being explored for on-demand hydrogen peroxide production, fine chemicals manufacturing, and other processes that benefit from highly intensified mixing and heat transfer. While microreactors do introduce complexities in fabrication and potential clogging issues, advances in 3D printing and new channel designs (e.g. oscillatory flow reactors, static mixer

inserts) are helping to address some of these concerns. The use of microreactors clearly illustrates how PI can unlock new processing routes and improve safety and selectivity, outcomes that are especially valuable for specialty chemicals and pharmaceuticals where product quality and speed to market are paramount (Mascia et al., 2013).

F. MODULAR PROCESSING AND DISTRIBUTED PRODUCTION

Modular processing is not a single technology but rather a production strategy enabled by PI. It involves constructing chemical plants as compact, transportable modules (skid-mounted units) that can be replicated and distributed as needed. Intensified equipment like DWCs, microreactors, or compact heat exchangers are key enablers of modular plants because they shrink the size of the process equipment to a footprint suitable for a portable module (Baldea et al., 2018). The traditional paradigm of chemical engineering favored building ever-larger plants to exploit economies of scale, but modular production offers a different economics: the ability to add capacity in increments, manufacture standardized units in a factory setting, and locate production closer to raw materials or customers (Baldea et al., 2018). Specialty chemical manufacturing is driving this trend, with high-margin specialty products often having volatile demand and short product life cycles, making large plants risky. Instead, smaller modular plants can be rapidly deployed or redeployed, and multiples can operate in parallel for production scale-up (Kim et al., 2017).

PI creates processes that are compact and efficient, which can then be packaged into modular units that are easily transported and connected. For example, a modular plant for a specialty chemical might use a series of intensified operations (like a microreactor for synthesis followed by a membrane separation) all mounted in a standard shipping container. Such a plant could be located on-site at a customer's facility to produce a fresh product as needed, or at a remote resource site to minimize shipping of hazardous intermediates. There are already industrial instances of modular, intensified units; one example is small-scale GTL or biomass-to-liquids units using microchannel reactors and modular separations to convert stranded natural gas or biogas into liquids on-site (LeViness et al., 2014). Another is the use of compact, modular distillation systems for pharmaceutical solvent recovery and fine chemical purification, where a traditional large distillation column is impractical due to the low throughput. The RAPID (Rapid Advancement in Process Intensification Deployment) Institute, established by AIChE in 2017 with support from the U.S. Department of Energy, has been a major initiative to develop and demonstrate modular PI technologies (Bielenberg & Bryner, 2018). The aim is to standardize intensified process equipment and overcome the engineering challenges of modular implementation.

In summary, modular processing enabled by PI offers greater flexibility, faster deployment, and lower financial risk. By decoupling production capacity from single large facilities, it paves the way for decentralized manufacturing networks, which could transform the supply chain for both bulk and specialty chemicals (Baldea et al., 2018). Manufacturers can

start with a small, intensified plant, then replicate modules to increase capacity or relocate units as market needs change. This agility is particularly attractive for specialty chemicals and polymers, as well as for commodity chemicals in remote or distributed markets (Mascia et al., 2013).

G. ALTERNATIVE ENERGY-DRIVEN PROCESS INTENSIFICATION

A further class of process-intensification strategies is based on the use of non-traditional energy fields to drive reactions and transport phenomena in ways that are not achievable with conventional thermal heating. These approaches include microwave-assisted reactors, high-intensity ultrasound, radiofrequency and dielectric heating, and various electrochemical or plasma-based systems (Górak and Stankiewicz, 2011; Boodhoo and Harvey, 2013). The common feature among them is their ability to deliver energy directly to the reacting species, specific phases, or interfaces, rather than heating the entire process volume through jackets or fired heaters. This targeted energy input often leads to faster reaction rates, higher selectivity, and shorter residence times.

Microwave-assisted reactors are a prominent example. They operate by depositing electromagnetic energy directly into polar liquids or solids, resulting in extremely rapid heating rates that conventional equipment cannot match. Because the energy is absorbed volumetrically, heat-up times can be reduced from minutes to seconds, which shortens start-up periods, enables rapid temperature control, and can significantly reduce overall batch cycles (Boodhoo and Harvey, 2013). In certain systems, microwaves selectively interact with specific intermediates or catalytic surfaces, thereby enhancing reaction pathways or improving product selectivity. For specialty and fine chemical synthesis, microwave flow reactors have demonstrated the ability to compress multi-step reactions from hours to minutes while maintaining high yields and consistent product quality (Cravotto, 2025).

Ultrasound-based intensification relies on acoustic cavitation, which involves the formation and collapse of microscopic bubbles that generate localized, high-energy conditions within an otherwise mild bulk environment. These short-lived hot spots can accelerate slow liquid-liquid or solid-liquid reactions, improve mass transfer in heterogeneous systems, and produce highly uniform emulsions or dispersions (Górak and Stankiewicz, 2011). Sono chemical enhancement has been demonstrated to enhance conversion in liquid-phase oxidations and polymerizations, and to reduce the need for high temperatures in processes where thermal sensitivity is a concern (Boodhoo and Harvey, 2013). From a process-intensification perspective, ultrasound enables higher reaction rates without increasing vessel size or residence time, which translates to higher volumetric productivity.

Electrically driven and electrochemical processes offer another route for intensification. Techniques such as direct Joule heating of conductive streams, electrochemical reactors for selective redox chemistry, and non-thermal plasma systems for gas-phase conversions can deliver high energy densities to the reaction system with precise timing and control. Because these methods can be powered by renewable electricity, they

offer a pathway toward electrified processing and a reduced carbon footprint (Cravotto, 2025). For petrochemical and specialty chemical manufacturing, this creates opportunities for alternative process routes, for example, plasma-assisted oxidative coupling or electrochemical hydrogenation, where reaction enhancement and energy decarbonization are achieved simultaneously (Cravotto, 2025; Górak and Stankiewicz, 2011).

Although these technologies are not yet deployed at the same commercial scale as dividing wall columns or reactive distillation, they represent an important and steadily growing dimension of process intensification (Górak and Stankiewicz, 2011). Their ability to lower reaction temperatures, improve selectivity, and enable partial or full electrification aligns directly with the broader sustainability and decarbonization goals of the industry (Boodhoo and Harvey, 2013). As microwave, ultrasonic, and electrochemical reactor systems continue to mature and become available as standardized modules, their integration into specialty and eventually bulk chemical manufacturing is expected to expand significantly (Cravotto, 2025).

IV. BENEFIT AND PROCESS OF INTENSIFICATION

The successful application of process intensification technologies yields numerous benefits, which have been documented in both industrial case studies and academic research. Although the foundational concept of process intensification (PI) centers on substantial downsizing of equipment often achieving at least a tenfold decrease in volume and the resulting cost efficiencies (Reay et al., 2013) various additional advantages spanning business, operational, and ecological domains can also be anticipated, as illustrated in Fig. 1. Even when certain of these operational gains are realized without a radical reduction in equipment scale, such approaches remain aligned with the contemporary understanding of process intensification (Boodhoo & Harvey, 2013).

Energy savings are one of the most quantifiable benefits. Intensified processes often exploit internal heat integration and improved thermodynamic efficiency, directly translating to lower energy consumption. Dividing-wall columns, for instance, typically achieve 15 – 40% energy savings versus conventional distillation sequences, as they eliminate duplicate reboilers/condensers and reduce entropy generation (Yildirim et al., 2011; Asprion & Kaibel, 2010). Reactive distillation can significantly reduce energy consumption by combining reaction and separation – the energy typically spent vaporizing reactants and products repeatedly in separate distillation columns is saved, as separation is achieved in situ. A reactive distillation column for methyl acetate not only reduced equipment counts but also required about 30% less energy than the traditional process, as a result of continuous removal of the light byproduct in the column (Agreda et al., 1990). Cost reduction naturally follows from these energy savings and from reduced equipment count. Fewer unit operations mean lower capital costs for equipment, installation, and piping, as well as lower operating and maintenance costs. For example, a single DWC replaces two or more distillation columns, thus

avoiding the cost of at least one column shell and associated auxiliaries – Schultz et al. (2002) reported that installing a dividing-wall column saved significant capital and also debottlenecked an existing unit, delaying or eliminating the need for a new column.

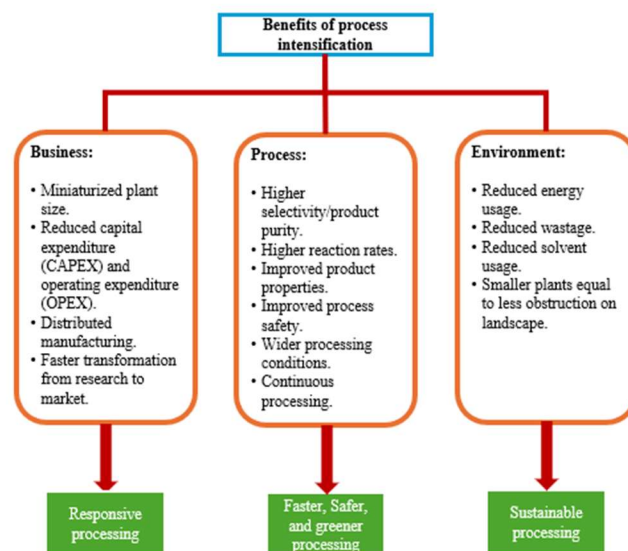


Fig. 1: Business, Process, and Environmental benefits of Process Intensification (Reay et al., 2013)

Likewise, the capital saved by using a reactive distillation column in place of separate reactors and distillation columns can be on the order of 50% in some cases (Harmsen, 2010). Harmsen (2010) analyzed several industrial PI implementations in petrochemicals and found not only energy and capital reductions, but also often improved operational expense metrics due to simpler, more efficient processes (e.g., less catalyst or solvent usage and lower waste treatment costs due to higher selectivity).

Another benefit of PI is enhanced process performance and yield. Intensified reactors like microreactors or reactive separators often improve reaction conversion and selectivity. For example, by giving all molecules a uniform processing experience (e.g., plug flow in a microreactor without back-mixing), undesired side reactions can be minimized and residence time precisely tuned (Van Gerven & Stankiewicz, 2009). Reactive distillation frequently achieves higher conversions than the equilibrium limit of the uncoupled reaction, leading to a higher overall yield of the desired product (Ali et al., 2021). Integrated processes can also improve product quality. For instance, coupling reaction and separation can immediately remove heat and avoid thermal degradation of products, or eliminate intermediate storage that could introduce impurities. In specialty chemicals, quality and purity are paramount, and intensification can provide cleaner synthesis pathways with fewer side products and purification steps (Mascia et al., 2013).

Safety and environmental benefits are also significant. Smaller equipment and lower inventories reduce the risk of large hazardous releases. Microreactors and modular plants inherently confine processing to small volumes, which

enhances intrinsic safety (Hessel et al., 2013). Intensified processes can also lead to less waste generation: for example, a process that integrates reaction and separation might obviate the need for extraction solvents or additional purification chemicals, thereby reducing effluent streams. Some PI technologies enable greener chemistry, such as using alternate energy forms (microwave, ultrasound, or electric fields) to drive reactions more selectively (Górak & Stankiewicz, 2011) as discussed in Section III.G on alternate energy-driven process intensification. From a sustainability perspective, the compact nature of intensified processes often means a smaller plant footprint and the potential for decentralized production, which can lower transportation emissions by producing chemicals on-site where needed (Baldea et al., 2018). Kim et al. (2017) summarize that PI leads to benefits including “compactness or small footprint, energy and cost savings, enhanced safety, less waste production, and higher product quality” – a concise description of why process intensification is so appealing across the chemical industries.

Table 1 below summarizes the key benefits of PI, highlighting typical improvement levels and illustrative examples from the literature.

Table 1. Key Benefits of Process Intensification in Chemical Manufacturing.

Benefit	Improvement / Outcome	References
Energy Efficiency	15 – 40% energy savings in distillation (dividing-wall columns); Approx. 30% energy reduction via reactive distillation.	(Yildirim et al., 2011; Asprion & Kaibel, 2010; Agreda et al., 1990).
Capital and Cost	20 – 50% lower capital cost (fewer units); reduced operating costs due to energy savings and simpler flowsheets.	(Harmsen, 2010; Schultz et al., 2002).
Performance (Yield and Quality)	Higher conversion and selectivity (e.g. beyond equilibrium yields in RD); improved product purity (fewer side reactions).	(Ali et al., 2021; Van Gerven & Stankiewicz, 2009).
Safety	Smaller equipment volumes and inventories reduce accident risk; enables safer handling of highly exothermic reactions (microreactors).	(Hessel et al., 2013).
Environmental Impact	Less waste and emissions via higher efficiency & integrated recycling; smaller footprint with potential for decentralized production.	(Górak & Stankiewicz, 2011; Baldea et al., 2018; Kim et al., 2017).

The benefits of PI are not merely theoretical; many have been realized in commercial operations. For example, Shell’s implementation of a reactive absorption process for CO₂ removal in natural gas sweetening achieved 70-80% reduction in absorber size (volume/height) compared to conventional non-reactive or separate absorption units, while maintaining or improving CO₂ removal efficiency (>95-99%) and significantly lowering capital costs and footprint (as referenced in Harmsen, 2010, and related Shell process intensification case studies).

BASF reported that a complex DWC installed in one of their plants achieved a 50% reduction in energy use and a substantial cut in emissions relative to the previous setup (Parkinson, 2007). These real-world successes underscore the message that process intensification can significantly

transform manufacturing economics and environmental performance when applied effectively.

V. CHALLENGES AND FUTURE OUTLOOK

Despite its compelling advantages, process intensification is not yet the norm in the chemical industry, and several challenges have slowed its universal adoption. One major challenge is the design and scale-up complexity. Intensified processes often involve strong coupling of phenomena (reaction with separation, multiple simultaneous heat integrations, etc.), which makes them more complex to analyze and design using conventional methods. Designing a single unit that replaces several others can require advanced simulation, nonlinear optimization, and a deep understanding of underlying thermodynamics and kinetics (Lutze et al., 2010, as cited in Górak & Stankiewicz, 2011). Until recently, engineers lacked user-friendly design tools for systems like reactive distillation or dividing-wall columns. This has been a barrier, as companies tend to favor proven designs over novel configurations with uncertain behavior. However, progress is being made: systematic methods for screening and designing intensified processes are emerging (e.g., phenomena-based synthesis frameworks and superstructure optimization for DWC designs) and are increasingly reported in the literature and implemented in process simulators (Asprion & Kaibel, 2010; Rong, 2011). Computational tools and models are now better able to predict the performance of intensified units, which helps de-risk their design. Additionally, more pilot plant data and published case studies are accumulating, giving engineers reference points for how to size and operate intensified equipment.

These emerging tools directly address the design barriers. For example, superstructure-based optimization frameworks for dividing-wall columns now allow engineers to evaluate multiple internal configurations, vapor-liquid split patterns, and alternative tray or packing arrangements within a single integrated model, rather than depending on the traditional trial-and-error workflow that has historically complicated DWC design (Asprion and Kaibel, 2010; Dejanović et al., 2010). In a similar way, phenomena-based process synthesis approaches and detailed rate-based models for reactive distillation explicitly couple reaction kinetics with separation thermodynamics, enabling more accurate sizing of catalytic zones, stage requirements, and internal reflux distributions within a unified design environment (Harmsen, 2007; Górak and Stankiewicz, 2011). As these modeling capabilities continue to mature and become available in mainstream commercial simulators, the design of complex coupled units such as RD and DWCs becomes less of a specialized craft and more of a transparent, optimization-driven workflow. This shift directly reduces the complex interactions between mass transfer, chemical reaction, and hydrodynamics within the integrated units that limit the broader industrial adoption of intensified separation-reaction systems (Kiss, 2016).

Another challenge lies in operability and control of intensified systems. When multiple functions occur in one unit, the dynamics can be tightly intertwined. For instance, a disturbance in feed composition to a reactive distillation column can simultaneously affect both reaction conversion and

separation efficiency, making it trickier to control than a conventional two-step process where reaction and distillation are separate (Kiss & Bildea, 2011; Santos et al., 2023). A dividing-wall column has unique control challenges because the internal flows on either side of the wall must be balanced – traditional single-column control strategies may not apply. Researchers have developed control schemes for DWCs, including multi-point temperature and composition control strategies; however, maintaining stability under changing conditions can be non-intuitive (Hernández, 2016). Similarly, microreactor-based systems have very low residence times and limited holdup, which means disturbances propagate quickly and leave little time for corrective action. These operability issues imply that implementing PI may require advanced control techniques (like model predictive control or adaptive control) and additional sensor infrastructure to ensure smooth operation (Hernández, 2016). From an organizational standpoint, there can also be a knowledge gap because operating personnel are familiar with conventional unit operations, whereas an intensified unit may be novel and require retraining along with new operational protocols.

There are also economic and business hurdles. Companies may be hesitant to replace tried-and-true equipment with new technology due to perceived risks in reliability or maintenance. For example, a plant manager might wonder: will a dividing-wall column be as robust as two separate columns? Will a microreactor handle feed impurities without fouling? These concerns can make companies conservative. Harmsen (2010) pointed out that business drivers and technical hurdles must align even if PI offers cost savings, if it introduces any uncertainty in uptime or product quality, management might not approve the change. Furthermore, many existing plants represent large capital investments; retrofitting them with intensified equipment must be justified by significant benefits. In some cases, modular intensified plants break the conventional reliance on economies of scale, requiring a paradigm shift for firms used to building very large facilities. Demonstrating the economic viability of modular deployment (including practical factors like module transportation and on-site connections) is part of ongoing efforts by industry consortia and partnerships.

Looking toward the future, the outlook for process intensification is decidedly optimistic. Multiple trends suggest that PI will play a central role in the evolution of chemical manufacturing. Firstly, the drive for decarbonization and sustainability is stronger than ever; global initiatives to reduce industrial emissions align perfectly with the energy-efficiency gains offered by PI technologies. Achieving net-zero targets by mid-century will likely necessitate widespread adoption of energy-saving designs like heat-integrated distillation, reactive systems (which curb waste and reboiler duties), and alternative energy-driven processes (such as electrically heated reactors or membrane separations to avoid reboiling) (Morejudo et al., 2016). Process intensification provides some of the most effective tools to redesign processes for a lower carbon footprint, so its importance will only grow in the context of climate change mitigation.

Secondly, the advancement of digitalization and process modeling is making it easier to design and implement

intensified processes. Modern simulation software can rigorously model complex coupled operations, and computational optimization can explore innovative configurations much faster than could be done by trial-and-error. As these tools become mainstream, the design barrier for PI is reduced. Engineers can utilize software plugins for reactive distillation, or leverage AI-based optimization to identify the best dividing-wall configuration for a given separation, for example. The increasing body of literature and industrial data on PI is also lowering perceived risk, as each successful case reported builds confidence and helps establish best practices. Education and training on PI are being incorporated into chemical engineering curricula and professional workshops (Stankiewicz & Moulijn, 2000), ensuring that the next generation of engineers is fluent in these techniques. The formation of initiatives like AIChE's RAPID institute and the European Process Intensification Center (EUROPIC) is fostering collaboration between academia and industry to pilot new PI solutions and address common challenges (Bielenberg & Bryner, 2018; Gravotto, 2025).

In the realm of specialty chemicals and pharmaceuticals, the future likely holds a shift to continuous, intensified manufacturing in place of traditional batch processes. Regulators have already begun to encourage continuous manufacturing for its quality and reliability benefits in pharma, and PI technologies such as continuous flow microreactors, spinning disk reactors, and controlled crystallizers are enabling the transition (Mascia et al., 2013). Modular skid-mounted “factory in a box” concepts for on-demand production of pharmaceuticals or fine chemicals are being prototyped, which could shorten supply chains and reduce the need for large inventory stockpiles. The specialty sector will continue to serve as a testbed for PI, as the agility it provides is a competitive advantage in markets that demand rapid product changeovers and scalability.

In petrochemicals and bulk chemicals, integration of PI will likely be more gradual but is on the horizon. New grassroots plants may increasingly incorporate intensified designs from the start, for example, a next-generation olefins plant might integrate high-severity reactors with membrane separations and dividing-wall columns to minimize energy use. Retrofitting existing large plants with PI (like adding dividing-wall inserts to revamp a distillation train or replacing a section with a reactive distillation unit) is an attractive intermediate step to capture benefits without a complete rebuild (Schultz et al., 2002; John et al., 2021). Over time, as older units are retired, they may be replaced by inherently intensified systems. We also expect hybrid processes (marrying conventional and intensified units) to become common, leveraging the familiarity of established operations while still gaining some benefits of PI.

VI. CONCLUSION

Process intensification is poised to transform both petrochemical and specialty chemical manufacturing by delivering processes that are leaner, cleaner, and more flexible. While challenges in design, control, and risk perception remain, the continued efforts of the chemical engineering

community are steadily overcoming these hurdles (Kim et al., 2017). The benefits already demonstrated include energy and cost savings, improved yields, smaller and safer plants, all of which make a compelling case. As tools and knowledge advance, PI will move from being the “exception” to the new norm in process design. The future of chemical manufacturing will likely be defined by intensified processes that achieve sustainability and efficiency goals beyond what was possible with traditional approaches. In the coming decade, we can expect to see more hybrid and integrated processes, widespread use of compact modular plants, and innovative applications of PI in emerging areas like biochemical production and CO₂ conversion (Morejudo et al., 2016). The transformative potential of process intensification is immense, and its ongoing deployment will be a key factor in shaping a more sustainable and agile chemical industry for years to come.

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F. S. Olorunnaiye: Conceptualization, Literature Review, Writing – Original Draft, Writing – Review & Editing. **S. A. Akolo:** Supervision, Writing – review & editing. **E. O. Babatunde:** Review & Editing, Resources, and Supervision.

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