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# Process Intensification and its Applications - A Critical Review

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**Abstract :** The problems faced by the various industries are high energy consumption which further increases the cost of production followed by reduced productivity and conversion, longer residence time, and pollution caused by industrial waste. Many researchers have found various alternative pathways to overcome these drawbacks. The same products were obtained in a better way by process intensification. Any process can be intensified either by introducing entirely a new process or by combing two or more conventional methods to form a new hybrid process e.g- reactive distillation, micro-reactors, etc. Due to an increase in population and less availability of land, reducing the chemical plant footprints is highly appreciable which is possible by process intensification. In this paper, we have reviewed the majority of the processes that have been intensified into a new process such as bioprocesses, extraction, distillation, leaching, Biofuels production, Desalination, etc.
**Key words :** Intensification, cost-optimization, sustainability, energy-efficient processes..

## Introduction

Process intensification, a promising pathway in the development of sustainable and cost-effective chemical process systems is defined by Ramshaw, as a methodology for making a remarkable reduction in equipment size, energy consumption, or waste generation while achieving a given production goal. Process Intensification



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has become a topic of increased interest with its main goal to coordinate different unit operations, unit processes effectively and to activate synergistic effects during process development [1,2,3]. Currently, the world is facing major issues related to energy requirements, waste generation, and environmental concerns. Hence process intensification is a major topic of research. Chemical Industries are continuously finding out new solutions to meet the ever-increasing demand for products. These solutions are directly linked with process intensification techniques opted for maximizing the production and purity of the product, by minimizing the cost, energy requirements, and environmental footprints caused by the traditional methods. Process Intensification has witnessed exponentially increasing growth in the past two decades and is one of the major fields that is under constant research. Methods for Process Intensification depend upon mathematical optimization in order to employ an objective function either to minimize or maximize. This objective function is constrained by the feasible region of the system performance, defined by particular process specifications and physical relations with respect to these system variables. Mathematical modelling is utilized for optimization, based methods for overall flowsheet synthesis. These methods forced to generate a superstructure for required flowsheet which is translated into an MINLP optimization problem with a focus on process economics and subject to constraints for the operating condition. The heuristic approach is another method for process intensification. It is based on experience and process insights obtained from unit operations and verified through simulation or experimentation. Heuristic Method possesses three main categories methods viz. data models, data mining models, and application models. Hybrid methods are a combination of the advantages of both heuristic as well as mathematical optimization methods. They tend to use a simple structure of the heuristic approach while replacing the fixed rules with thermodynamic insights and thus narrowing the search space by removing physically impossible or improbable solutions[4].

This paper focuses on providing deep insights into the applications of Process Intensification on various processes and unit operations. It briefly explains the need for intensifying a particular process or a unit operation and also concretely focuses on the experimentation carried out for intensification. Results obtained from traditional methods and developed methods are also compared. This paper reviews the process intensification techniques opted for operations such as distillation, extraction, leaching, membrane separation, and processes such as Biofuel manufacturing, catalysis, oil recovery, etc. It also reviews the application of process intensification in the production of pharmaceutical products and process equipment's such as batch reactors, continuous reactors, and microreactors.

## Literature Review

### 1. Process Intensification in Distillation:

Zheyu Jiang et al.; intensified multicomponent distillation using 'Heat mass Integration strategy' (HMI) and also provided methods for intensification in 'Divided wall columns (DWC)[5]. They performed HMI on thermally coupled distillation columns which largely reduced the number of columns required and also reduced heat requirements. This strategy reduced the number of condensers and reboilers used for multicomponent multiple distillation towers and thus minimized heat duty for both the exchangers. They tried HMI on 6 component distillation which yielded several configurations for distillation columns. They found that heat exchangers were reduced from 10 (in conventional distillation) to 6 when sub mixture heat exchangers were replaced by side streams after combining two columns. Further, when sub mixture streams were replaced by thermal coupling, heat exchangers were reduced to 4 thus providing a highly energy-efficient model. When conventional distillation was replaced by DWC capital cost was reduced by 30%. Operable configurations for DWC were obtained when Thermal coupling converted to "Liquid Transfer" only was used in DWC. This strategy reduced the issues such as desire vapor split in DWC, which hindered its implementation on a large scale. Anton A. Kiss and Megan Jobson, carried out process intensification on Reactive Distillation (RD) by combining it with other intensive distillation technologies such as DWC, Heat integrated distillation, and cyclic distillation[6]. Reactive divided wall columns increased production yield to a great extent by simultaneously saving 15-70% of energy usage and decreasing capital costs by 20% when compared to classical DWC techniques. They added solid catalysts on trays bringing in the new technique of catalytic cyclic distillation (CCD). Helium catalysts helped in controlling the liquid flow rate and reaction time. This technique increased the quality of the product and reduced the energy requirements

by 20-35%. When Heat Integrated distillation and RD were combined, a new reactive system called as "Reactive heat integrated distillation column" was formed. They found that this method can reduce energy usage by 22% compared to traditional reactive distillation.

Hui ding et al.; found an effective process intensification technique by combining microwaves with classical reactive distillation [7]. This technique not only improved reaction time but also improved the product purity. They experimented with microwave-assisted reactive distillation (MRD) for esterification reaction between acetic acid and ethanol in the presence of sulfuric acid as a catalyst. Their main agenda of using microwaves were its property to increase the relative volatility of mixture components. They studied the effects of reflux ratio, ethanol to acetic acid mole ratio, reboiler duty, microwave power on conversion, and purity of the product. With an increase in the reflux ratio, they found the purity of the product to be increased for RR = 2 to 4 and then decreased for RR = 4 to 5. At RR =6 purity of the product was again increased which was because of an increase in residence time of ethanol. They also discovered the rapid increase in conversion and product purity with an increase in reboiler duty, which was because of the high vaporization of ethanol in the liquid phase of the reaction zone. The conversion of ethanol and product purity was found to decrease with an increase in microwave power. They simulated all the results and verified it using Aspen Plus. Matthais Wierschem et al; experimented with one of the most efficient process intensification techniques on Reactive Distillation[8]. They focused on utilization of ultrasound on enzymatic reactive distillation (ERD). ERD is a bioreactive process in which enzymes are immobilized on the internal surface of the column to overcome chemical reaction and phase equilibrium conditions. Ultrasound was used to activate these enzymes. This method was tested for the synthesis of ethyl butyrate (EtBu) by transesterification reaction with BuOH yielding BuBu as the main product. The enzymatic catalyst, lipase B from yeast candida Antarctica were immobilized in a thin film on the surface of structured packing used for conventional distillation. When Ultrasound was used, the conversion of reactants was 1.6% more than the conventional ERD method. Also, the purity of BuBu obtained was approximately 99%. They justified the cost of Ultrasound-ERD column with 12% less reactive section height and 7% lower total height of the column compared to the conventional ERD column. Gregorius Rionugroho Harviantoa et al.; studied hybrid process combining thermally coupled reactive distillation with membrane-based pervaporation[9]. They used the process for enhancing the production of n-Butyl acetate from n-Butanol and methyl acetate. They found that this hybrid technique improved the energy efficiency of RD process by preventing remixing effect and nullifying the azeotropic nature of methanol (product) and methyl acetate in the recycle stream. This method reduced reboiler duty by 63% and annual cost by 43% when compared to conventional Reactive Distillation. This method proved to be advantageous in cases of low feed rate, high methanol concentration in the liquid split stream, low methanol concentration in rectifying stages, and high conversion in Reactive Distillation. MomciloDj. Spasojevic et al.; intensified the distillation process by providing a new approach to minimize entropy production across the column. In traditional approach, adiabatic columns were used which require condensers and reboilers for heat exchange[10]. However, they used the technique of diabatic distillation in which heat is introduced in stripping and removed from the rectifying section. Heat exchange is independent for each tray and does not require heat exchangers. In conventional method, heat to be exchanged on trays depend upon was based on temperature on trays. Rather than temperature, they used the quantity of heat to be exchanged as control variables for minimizing the entropy production. This procedure was tested for the separation process of benzene and toluene feed mixture each consisting of 0.5 mole fraction. The minimum value for produced entropy in the diabatic column was 1.056 J/s K, while for the adiabatic column, the entropy produced was 2.998 J/s K. By this method, they saved around 64.77% of energy requirements.

## 2. Process Intensification in Biodiesel Production:

Prashant Danke et al. intensified the production of Biodiesel using "Ultrasonic cavitation reactors" [11]. They experimented the process for the esterification reaction between cottonseed and Methanol. They studied the effects of parameters such as reaction time, reaction temperature, catalyst concentration, and oil to alcohol mole ratio on biodiesel production. They experimented various runs by varying the parameters like oil to alcohol mole ratio from 1:6 to 1:15, catalyst concentration (NaOH) from 0.5-2 wt%, reaction temperature from 30-60 degrees Celsius, and reaction time from 10-40 min. They observed optimum conditions for biodiesel production is at 1:9 mole ratio, 1 wt% catalysts concentration at 50 degrees Celsius for 30 minutes reaction time which yielded lowest kinematic viscosity of 4 cST, which is within high-quality biodiesel range as per ASTM standards. However, they observed the formation of

undesired side products which is a short drawback for the process. Tran Hai Ung et al.; carried out process intensification in Biodiesel manufacturing by using "Hydrodynamic Cavitation Reactor"(HCR)[12]. This reactor was tested for a reaction between methanol and Basa Fish fat at 60 °C using a homogeneous catalyst (NaOH in methanol, 1 wt% of fish oil). They performed this in CSTR for comparing the results. They observed that 92% of conversion required 90 min in CSTR, whereas the same conversion was obtained in just 1 min when the hydrodynamic cavitation reactor was used. They observed that the reduction in reaction time was due to increase mass transfer rate induced by an increase in the interfacial area between methanol and fat due to cavitation phenomena. They also used HCR for the same reaction but in presence of solid metal oxide catalysts such as CaO. Time required to obtain 93% conversion using Cao catalyst in conventional reactor was 90 mins and in HCR was just 20 mins. Kasim and Harvey; synthesized Biodiesel using the technique of reactive extraction [13]. They studied the reaction between Jatropharcuras L. seeds and methanol in presence of NaOH as catalyst having a concentration of 0.1-0.3 N. They experimented various runs by varying seeds particle size of 0.5 -4 mm, reaction temperature 30-60°C, mixing speed of 100- 400 rpm, reaction time 10-60 min and solvent to oil ratio of 200:1 to 600:1. 96% of Biodiesel was yielded through the process. Noshadi et al., produced Biodiesel in reactive distillation columns using waste cooking oil, methanol, and solid heteropolyacid as catalyst [14]. Runs were conducted by varying feed flow rate from 115 to150 mol/h, methanol to oil ratio as 30:1 to 70:1, reboiler duty 1 to 1.5 kW, and inlet temperature of 20 to 30°C and. The maximum biodiesel yield of 92.79% was obtained from the experiments. Both the experiments intensified the production by increasing conversion and selectivity in reaction. They found the production and equipment cost was reduced by a huge margin. However, reactive distillation had high energy requirements which proved to be a drawback for the process.

A. Samniang et al.; employed a Supercritical method for intensification of Biodiesel production by reacting Jatropha Oil, Krating oil, and methanol without any presence of catalyst [15]. By maintaining reaction pressure about 8-18 MPa, methanol to oil ratio of 30:1 and reaction time about 5-15 min, 90% pure biodiesel was yielded. Jiang and Tan, used the supercritical technique on coconut oil for biodiesel production in the presence of various co-solvents[16]. These co-solvents helped in increasing the biodiesel yield to 72% compared to 41% without using any co-solvents. They found this method to be environmentally friendly with negligible formation of by-products and yielded high-quality product. Khemthong et al.; produced biodiesel from palm oil and methanol in the presence of CaO as a catalyst and intensified the production by using Microwaves [17]. They studied the effect on product yield when microwave power was varied in the range of 450 to 900 W, microwave irradiation time from 1 to 4 min, solvent to oil ratio in the range of 12:1 to 24:1 and catalyst loading 5 to 15 (wt%). The use of microwaves rapidly increased the production yield to 96.7%. Microwaves helped to attain the reaction temperature quickly by minimizing energy requirements. They also reduced the heating costs to about 2/3rd of the conventional process. They found that microwaves not only increased the reaction rate but also reduced the formation of byproducts. N.P. Patil et al.; researched an energy-efficient process for the production of Biofuels particularly Bioethanol [18]. Production of Bioethanol from molasses is consists of a two-step process i.e fermentation followed by distillation. The distillation section for production has high energy requirements and thus increases the production cost of ethanol. They used Vapor decompression systems (DVR) to achieve energy savings within a single distillation column. DVR systems ate the one in which vapors from top of the column are compressed to desire pressure and temperature and are allowed to condense in the reboiler of the same column. Heat is directly transferred from the rectifying section to the stripping section leading to continuous evaporation of bottom liquid. They observed that the technique reduced the compression ratio as well as energy requirements for the operation. Traditional method used atmospheric distillation for separation and purification of ethanol which increased the number of distillation columns in order to achieve required purity. They used Multi pressure distillation technology which brought external heat integration in the system and reduced the steam consumption from 5.8 Kg/L to 3.2 Kg/L of ethanol compared to atmospheric distillation. Arne Hommes et al.; synthesized and intensified biodiesel production by using enzymatic Biphasic esterification reaction between oleic acid and 1-butanol in microreactor [19]. They performed the reaction in aqueous organic system in a capillary microreactor consisting of Rhizomucormiehei lipase in an aqueous phase and n-Heptane as an organic solvent. They obtained a 100% yield of Butyl oleate within 30 mins of residence time at 30°C. A greener way for biodiesel synthesis was provided by using this enzyme. The enzyme performance was improved by intensive stirring in the reactor which increased the interfacial area promoting more conversion of reactants. The use of microreactors enhanced heat

transfer causing precise temperature control and reduced residence time distribution for continuous flow. Adam Harvey et al.; intensified biodiesel production by using an oscillatory flow reactor (OFR) [20]. They used OFR as they are a novel type of continuous reactor, consisting of tubes containing equally spaced orifice plate baffles which has ability to superimposed oscillatory motion upon the net flow of the process fluid and creating flow patterns conducive to efficient heat and mass transfer, whilst maintaining plug flow. They experimented OFR technique on the reaction between rapeseed oil and methanol having a mole ratio of 1.5 in the presence of 32.3 g of NaOH as a catalyst. The viscosity of Biodiesel products ranged between 3.5 - 5.01 mm2/s, which satisfied DIN 51606, the German standard for biodiesel, and all other standards. The use of OFR increased the reaction rate and reduced reaction time.

## 3. Process Intensification in extraction:

E. Vialkova and E. Malyshkina; intensified the extraction process of petroleum products from aqueous solutions by sorbents [21]. Sorption is one of the processes used to treat water pollution caused by oil spills and it was found to give 99% accuracy. To prevent difficulties such as high cost and high toxicity of inorganic and synthetic sorbents, natural sorbent made from plant and wastes such as activated carbon, pine sawdust, polyurethane foam loading, etc. were used. They found only the disadvantage of natural sorbent which was insufficient sorption properties of plant materials. Various options were proposed for this study: a) ozone treatment of sorbent b) microwave treatment of sorbent c) preheating of a solution with microwave radiation. The results depicted that the sorption capacity of pine sawdust was increased by 10% when heated with microwave up to 40°C. Sorption capacity was increased by 1.5 times by ozone treatment, 2-5 times by microwave heating, and 1.5 times by microwave heating of solution for low concentration of petroleum products. They found experimentally that pine sawdust had capacity 18-20% less than that of activated carbon. Zhigang Tang et al.; intensified the extraction process of (CAS No.-1953-02-2) tiopronin (TPN) which is a free thio containing glycine derivative [22]. TPN is used for the treatment of linear tissue, ethanol-induced linear injury repair, and treatment of linear function cells. TPN was produced as an extract phase by extracting it with ethyl acetate from its aqueous solution followed by crystallization and drying. The traditional way of production was through 3-stage cross current extraction with a 30% loss of ethyl acetate. For intensifying the production of TPN, they used counter-current extraction instead of cross current. They found that for 800-900kg of TPN aqueous solution (70-80kg TPN), ethylacetate required in each stage was 370-430. By MATLAB programming, 3-5 stage cross and counter-current extractions were simulated and calculated. The coefficient ratio of TPN between two-phase was taken as 1.77 when the concentration of TPN in feed and fed throughput were 13.5g/L and 900kg/day respectively. 3.4g/L of TPN was obtained in the final raffinate phase when 1140 kg of ethyl acetate was used in cross current extraction. Whereas in counter-current extraction, for the same concentration of TPN in feed and feed throughput, 3.4g/L of TPN was obtained in the 3rd raffinate phase using only 500kg of ethyl acetate and thereby saving more than 60% of extractant. Andrea Rathgeb et al.; reviewed the study of extractive reaction system (ERS) that was based on a biphasic liquid-liquid system where the product was formed in one phase and there was in-situ product extraction in the second phase [23]. ERS was established with an intension to optimize the reaction system by the integration of the separation process and reaction in a single unit and thereby improving the reaction performance. The in-situ process engaged by the ERS helped to overcome a few difficulties such as low production selectivity and yield due to the presence of side products. To achieve high conversion, they reduced the product concentration and increased the educt concentration. Even if ERS incorporating catalyst and side product contain small impurity then they deviate considerably from the ideal behavior of a pure system. They found this process to be cost-effective and also reduced energy consumption and footprints of chemical plants.

Mustafa Kamal Abdul Aziz, et al.; intensified the extraction process of oil recovery from palm oil milling and refining process using bioethanol (obtained by the fermentation process of glucose from renewable biomass) as extraction solvent instead of the traditional hexane [24]. The process is intensified by combining 3 processes; solvent extraction-crystallization-evaporation (SECE). The spent bleaching clay (SBC) consisted of color, oxidized products, metal, residual gums, and also 30-40% oil that has to be recovered to prevent pollution hazards. SBC on crystallization gave 2 compounds: a) high-density wax oil called as gold finger (GF) b) black wax (BW); these showed suitability for food and non-food application respectively. They concluded that this intensified process provided higher efficiency because under vacuum conditions, turbulence between bioethanol and oil increased as the density of bioethanol was reduced. The yield of GF was found to be between 9 to 24.6% and that of BW was

found constant at 4.78%. They observed that the percentage of oil yield varied with changes in pressure. At 0.9 atm oil yield was 25.03% ± 2.02 and at 1 atm it was 15.27% ±1.56.

## 4. Process Intensification on Catalyst development:

Anna Lind et al.; researched on the design and manufacturing of multi-purpose structured catalysts by 3-D printing [25]. This multi-purpose structured catalyst was been found to have a low-pressure drop, fast and efficient heat, and mass transfer. The 3D printed iso reticular foam made from Al Si 10mg was designed and experimented for demonstration purposes. This catalyst was tested for oxidation of NO to NO2 reaction. Anodization procedure and catalyst impregnation were the two main steps that were followed in the manufacturing and design process. They experimented anodization process in high voltage high electrolyte concentration and low voltage low electrolyte concentration. The SiO2 content in the outer oxide layer was found to be reduced from 80wt% to 10wt% by varying anodization parameters. Wet impregnation was used for the deposition of platinum catalyst in the porous oxide layer. A net increase in surface area was observed due to the generation of alumina on the surface of 3D printed iso reticular foam structures. It was observed that the direct anodization process increased mechanical resistance and reduced high-temperature fluctuations. They found the catalyst to provide a lower pressure drop due to its higher porosity. It should be noted that keeping the catalyst in direct contact with an aluminum body enhances the heat transfer rate. By the use of a very less amount of catalyst with 8% oxygen, nearly 50% conversion was achieved. Matteo Ambrosetti et al.; intensified the nonadiabatic catalytic process in a tubular reactor by using thermally conductive packed foams [26]. Spherical pellets of different sizes and different foam samples were considered to study the packing efficiency and pressure drop across the reactor. The ratio between Foam window and pellet diameter was considered as a governing parameter. They found the efficiency to increase with Radius (R) and reached the same asymptotic value of random packing when $R > 5$. For $R < 1.3$, porosity exceeds 50%. They found the pressure drop in packed foams was comparatively lower than that in packed bed for the same pellet diameter. The pressure drops in packed foam systems was calculated by CFD simulations. They found out that pressure drop was significantly higher when foams with lower void fraction were used. Using CFD simulations, they found the porosity to increase with an increase in pellet size which eventually increased packing efficiency and pressure drop.

## 5. Process Intensification for esterification reaction:

Chandrakant R. Khudsange and Kailas. L.Wasewar; carried out process intensification on the esterification reaction for the production of propyl butyrate by pervaporation [27]. Traditionally esters were formed by reaction between acids and alcohol in the presence of catalysts like HCl, HI, etc. They were produced in various reactors such as reactive distillation, microreactor leading to high energy consumption which depended on vapor-liquid equilibria of the system and azeotropic mixture. They intensified the process by combining pervaporation and esterification led to a decrease the energy consumption, enabled the operation beyond vapor-liquid equilibria, handled azeotrope, and made it environment friendly. The conversion of reactant was limited due to thermodynamic equilibrium. They reacted butyric acid and n-propanol in the presence of p-toluenesulfonic acid as catalyst. The membrane used for pervaporation was polyvinyl alcohol (PVA)-polyethersulphone (PES) composite membrane. The conversion of acid was found to be directly proportional to temperature and molar ratio. On increasing the catalyst concentration from 1wt% to 2.5wt% the conversion of butyric acid also increased rapidly from 71.61% to the maximum of 92.94% at 353 K. This increase in conversion was due to the removal of water. PVA and PES being hydrophilic continuously removed water from the reaction mixture. Yadagiri Maralla et al.; intensified the tetrazole reaction through tritylation of 5-[4'-(methyl) biphenyl-2-YI] using microreactors [28]. 5-(4'-methyl-[1,1'-biphenyl]-2-yl)-1-trityl-1H-tetrazole {MBPT}is the most important and useful intermediate in manufacturing of some pharmaceutical products like antagonist that belong to sartan family drug including losartan potassium, landesartan, trityl olmesartan, trityl candesartan, etc. The traditional method was to use the batch reactor for reaction. However, they used continuous flow microreactor as a process intensification technique which not only reduced the reaction time and production cost but also improved reaction rate and product purity. The experiments were carried out for MBPT reaction in stainless steel capillary coil microreactor (R=1mm and 2mm). The results showed that for a 1mm microreactor, 93.72% yield was obtained for a residence time of 271 seconds. Whereas for 2mm microreactor, 92.87% yield was obtained for a residence time of 324 seconds. They found the energy consumption to be very less compared to the batch reactor.

## 6. Process Intensification in pharmaceutical operations:

Milene A. G. Fortunato et al.; developed a method for synthesis of 6-Allyl-6-Azabicyclo[3.1.0]hex-3-en-2-ol from 1-allylpyridinium salt using continuous UV light photo flow approach [29]. The U.V photochemical reactor consisted of 12 parallel quartz tube flow reactor PQT6 and it was used toperform photochemical transformation in continuous flow under batch reactor. 1-allylpyridium chloride was irradiated for 16 hours to achieve a yield of 60% of 6-allyl-6-azabicyclo[3.1.0]hex-3-en-2-ol (say A) with productivity 39.4mg/hr. They designed the reactor for large scale production of A via photochemical irradiation. High productivity was achieved by the larger internal diameter of the photoreactor. In initial cycles, full conversion was observed in 4hr residence time in process intensification of A via photoreaction. But with the number of cycles increasing conversion started to drop due to the formation of yellow polymer on the surface of the quartz tube during irradiation. Prashant. D. Jolhe et al.; reviewed the study of sonochemical formation of peracetic acid in a batch reactor [30]. Although peracetic acid (PAA) which is a type of peroxycarboxilic acids, has wide applications as disinfecting agents with high industrial importance, less stability, slower reaction rates, and explosive nature had increased the difficulties in synthesis of PAA. Traditionally PAA was prepared by either by H2O2 or by oxidation of acetaldehyde. They developed a method to intensify PAA production by using sonochemical synthesis in a batch reactor and the effects of various parameters such as Acetic acid to H2O2 molar ratio, temperature, catalyst loading and effect of ultrasound in presence of Amberlite IR-120H catalyst were studied. It was found that, on increasing the molar ratio and the concentration, PAA formation in the presence of ultrasound (50W) also increased. They observed that the mixing of reactants was increased due to mechanical and vibrational effects. The concentration of PAA in the traditional process was found to be 3.45mol/L in presence of 707mg/cc catalyst loading at 313K at the end of 60min but in presence of ultrasound, the catalyst loading required for 3.45mol/L of PAA was only 471mg/cc in same reaction conditions. The major advantage of this method was reduction in reaction time from 30hr in regular batch reactor to 60min in batch reactor infused with ultrasound.

## 7. Process Intensification in Desalination:

Enrico Drioli et al; studied the role of membrane engineering to achieve the objectives of process intensification in the field of desalination [31]. The membrane had features such as high selectivity and permeability for the transport of specific component, small footprints, high safety, low cost, ease of integration with other processes, etc. The disadvantage of conventional desalination was the pressure-driven process that hinder their growth. In another study, they used membrane crystallizer (MCr) in an integrated approach with RO for seawater desalination. The seawater was first treated by nanofiltration and RO followed by MCr treatment of RO concentrate on the production of NaCl. The recovery of freshwater was increased from 50%to 90% in combination with salt recovery. Unlike RO, MCr does not suffer from osmotic phenomena as a driving force was temperature gradient. 60% of desalination was occupied by reverse osmosis (RO) and by combining it with renewable energy resources like solar or wind energy gave them better performance and boost the economy of the process. The aspiring goal of "zero liquid discharge" was finally obtained. Since solar and wind energy do not allow continuous operation without storage batteries, they are integrated with a conventional energy source like diesel generator. The parameters taken into considerations while designing the process were productivity, variation in pressure, temperature, feed compositions, flexibility, modularity, etc.

## 8. Process Intensification and recovery of Biological products:

Hamideh Vaghari, et al.; reviewed the intensification of production and recovery of biological products [32]. Bioprocesses proved to be important for biological reactions that required several complicated methods and equipment to produce various compounds. Conventionally these compounds were produced by synthetic chemical reactions. Due to the high cost of equipment and the large size, these bioprocesses were limited in use at an industrial scale. In a dilute environment, the products achieve high purity. Membrane bioreactors, for instance, were used for selective in-situ separation of the reaction products which not only improved the selectivity and yield of a process but also improved mass transfer rates. They stated that Immobilized cells bioreactors were better than free cell bioreactors as immobilized cell systems allowed the use of independent growth rate bioreactors and catalytic stability was found to be greater for immobilized cells than free cells.

## 9. Intensification for Nickel Recovery:

MessaoudaGabli et al.; reported a process intensification methodology to remove Ni(II) from the water using a combined approach including electrodialysis and ion-exchange process [33]. They used Amberjet 1200 H cation exchange resin in their experiments. They observed that the applied electric field improves process efficiency. They have also overcome a drawback of ion exchange resins that they need continuous activation by employing the ED cell up to a certain extent. They increased the life of ion exchange resin which enabled it to purify the water even at very low concentrations of metal ion impurities. They also investigated the effects of various factors such as inlet Ni(II) ion concentration, current density, amount of resin incorporated, etc. Their results demonstrated that the efficiency of regenerating electrolyte was in the following order: $HNO_3$>HCl>$H_2SO_4$>NaCl. In case of ED without the resin, efficiency in terms of recovery rate and concentration factor was very low.

## 10. Process Intensification for colemanite leaching:

Ademola S. OLUFEMI et al.; intensified the colemanite (2CaO.3B2O3.5H2O) leaching for the improvement of boric acid recovery[34]. Boric acid being the most commonly used boron compound was produced by dissolving colemanite in sulfuric acid. It was a secondary mineral which occurred after the original decomposition from other minerals. Gypsum being a byproduct, was necessary to be separated. They crushed the Colemanites in jaw crusher, ground in a hammer mill, and then sieved. The largest diameter was found to be 150µm. The batch process was observed to be better than the semi-batch process. Acids were used for leaching of heavy metals for the ease of dissolution. They found out that, rate of leaching depended on parameters such as pH, time, particle size, concentration of lixiviant, and agitation speed. The reaction followed a shrinking core model which states that reaction occurs first at the outer skin of particle and then zone move toward the center of the solid particles leaving behind solid product layer called ash. Thus, dissolution of solid reactant and crystallization of product happened simultaneously. The overall reaction was:

$2CaO.3B_2O.5H_2O(s) + 2H_2SO_4$ (l) + $4H_2O$ (l)→$2CaSO_4.2H_2O$ (s) +$6H_3BO_3$(aq). Agitation significantly increased the boric acid recovery by increasing the mass transfer rate of H+ ions in the solution.

## 11. Process intensification for mixing operations:

SinthuranJegatheeswaran et al.; intensified mixing performance in chaotic SMX static mixer to achieve an energy-efficient mixing operation of non-newtonian fluids[35]. They worked on intensification of fluid deformation and carried out a comparative study of Electrical resistance tomography (ERT) and computational fluid dynamics (CFD) techniques. They compared various parameter result like pressure drop data, the secondary fluid concentration profile, and the mixing index of the CFD model with the experimental result. They used working fluid was 0.5 wt% xanthan gum solution and the secondary fluid water which is a Newtonian fluid possessing a constant viscosity. The dispersion of the secondary fluid into the primary fluid occurred based on mechanisms, bulk advection of the primary fluid, chaotic advection created by the SMX static mixer element, and diffusion. In SMX static mixer, the high-velocity secondary fluid was deflected in different directions allowing the secondary fluid to deform the shear-thinning primary fluid. A more uniform radial dispersion of the secondary fluid in the primary fluid was achieved through the intensification of fluid deformation at a higher secondary-to-primary velocity ratio.

## 12. General:

Hannsjorg Freund et al.; reviewed recent developments concerning the Multi-Level Reactor Design methodology and explained MLRD methodology in a combined approach with Elementary Process Function concept[36]. The EPF concept is to describe a fluid element that travels through a chemical process which is represented by a set of functional modules (e.g. contacting, activating, chemical reaction, heating/cooling, separating) instead of a series of unit operations. Each of the functional modules comprised a set of fluxes acting on the state of the fluid element. The most recent work in the field of model-based design of catalytic reactors with a special focus on the multi-level reactor design (MLRD) methodology is reviewed. The key idea of this method is to track a fluid element on its way through the reactor and to optimize the reaction conditions along its way by providing the necessary material and energy fluxes. Based on these optimal flux profiles novel reactor concepts tailored to the needs of the reaction system can be derived and analyzed. Recent advances and extensions to handle the specifics of reaction systems with different complexity are presented. The MLRD approach enables the predictive determination of the best reaction concept considering highly innovative process intensification options. Thereby, this method provides a keystone for the development of more

economical and more sustainable chemical reactors and processes of the future. MohdHizamiMohd Yusoff et al.; intensified the membrane distillation (MD) process by combining it with wet scrubber (WS)[37]. The MD+WS system simultaneously recovered water and heat through MD permeate. The scrubber achieved complete water and heat recovery as flue gas was supersaturated with steam condensed in water scrubbing unit. They used Polytetrafluoroethylene (PTFE) was used as a membrane. Artificial flue gas containing only water vapor with air was made for experimental setup and observations were made based on this. Here membrane condenser (MC) and transport membrane condenser (TMC) were used. MC made use of the hydrophobic nature of the membrane to recover water from flue gas by allowing water vapors to pass through it and condense in the permeate side. In TMC saturated flue gas flowed in the lumen side of the membrane and coolant water in the shell side. At higher flue gas temperature, they found an increase in both mass and heat flux in MD which was due to an increase in flue gas flow rates with total energy. Due to small membrane area, the conductive heat transfer was small. Excessive heat loss across the tubing of MD occurred at low flow rates.

## Conclusion:

Process Intensification of any process means its modification that makes it better than the conventional one in terms of footprints, resources used, energy consumed, economy, conversion, and productivity. The use of the new processes in combination with the traditional ones can not only resolve the problem of waste handling but can also provide the opportunity to boost the economy of the process. The application of the process intensification methods in various systems that eventually led to the betterment of the economy and various other factors. In process intensification of distillation, various methods such as Heat Mass Integration Strategy, Catalytic Cyclic Distillation were used. The microwave-assisted reactive distillation was experimented for the esterification process and enzymatic reactive distillation for bioreactive process. Process intensification was also observed in biodiesel production that employed methods such as ultrasonic cavitation reactor, hydrodynamic cavitation reactor, etc. Further, we studied that the extractive reaction system was found to be cost-effective and also reduced energy consumption and footprints of chemical plant as compared to the conventional methods. The paper also reviewed the process intensification on catalysts that concludes that use of alternative catalyst increases the efficiency of the process and make them environment friendly. Process intensification in desalination by membrane operation process obtained the aspiring goal of "zero liquid discharge". Besides these advantages, few disadvantages were also observed such as a process may become more complex and may have complex control systems, the safety of the plant has to be increased, etc. Process Intensification system requires more upfront efforts than the ready-made approaches. In short PI of any process means its modification that makes it better than the conventional one in terms of footprints, resources used, lesser byproduct formation, reduced energy requirements, cheap capital, high conversion, and productivity.

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