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Fermentative production of gluconic acid in membrane-integrated hybrid reactor system: Analysis of process intensification

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ABSTRACT

Gluconic acid was produced through microbial conversion of hydrolyzed sugarcane juice by *Gluconobacter oxydans* in a multi-stage membrane-integrated hybrid reactor system. Provision of continuous production, withdrawal of product, separation and recycle of cells, separation and recycle of unconverted sugars to the fermentation unit in the system, resulted in high concentration (44.7 g/L), yield (0.94 g/g), productivity (6.5 g/L/h) and purity (~97%) of the product in a very simple, eco-friendly, modular and compact membrane-based process. The product could be further concentrated up to 540 g/L using an additional nanofiltration step. Integration of downstream membrane separation with conventional fermenter culminated in a highly intensified green process. This work focuses on analysis of process intensification and eco-friendliness factors like space intensification, energy intensification, capacity flexibility, economic gain, E-factor and atom efficiency to assess business sustainability of the membrane-based process.

1. Introduction

Amidst tough global competition in an era of emaciated profit margin, increased awareness and concern for greenhouse emission and global warming, this is now a matter of time for the chemical and allied process industries to switch over to green production regimes leaving the conventional energy-intensive and largely polluting production schemes. Process intensification (PI) appears to be the right strategy towards business sustainability as the same guarantees very significant process efficiency in terms of reduced material and energy consumption while generating small carbon foot print. Prospects of enhanced profit margin also brighten with compact, small and flexible new process designs [1,2]. Different approaches of PI seek to develop significantly smaller and cleaner process plants with reduction in equipment size, cost, energy, waste, unit operations and manpower. Adoption of membrane separation in downstream separation-purification is emerging as one such effective approach in production of organic and amino acids that drastically simplifies the existing multi-step, energy-intensive processes culminating in green production regime [3–6]. Several downstream production steps in conventional production scheme, such as centrifugation, acidification, neutralization, carbon adsorption, crystallization, ion-exchange and drying may be turned redundant on integration of membrane based separation with traditional fermentation system [7,8]. The high degree of fractionation of target molecules by tailor-made membranes has increased the possibility of separation and purification of high purity organic acid and other thermo-sensitive biomolecules [9]. Thus, process intensification in gluconic acid manufacturing assumes significance in the context of its huge market demand that grows annually at the rate of 4.8% due to application potential in several industries spanning over dairy, beverages, metal cleaning, metal chelating, safe food additives (sodium gluconate designated as E574), plasticizer, retarding and chelating agent, shampoo, toothpaste, dishwashing compounds, liquid shop, artificial sweeter, tanning and textile sectors [10]. Downstream purification of gluconic acid from fermentation broth is most expensive that involves many unit operations for effecting stage-wise purification exploiting the physico-chemical properties like solubility, molecular size and affinity to adsorbent and charge characteristics on solute may be utilized [11]. For example, some conventional processes use anion exchange and cation exchange coupled during electrodialysis of impure gluconic acid solution. Harsh chemicals like acids and alkalis are used in conventional processes for adjusting pH in the production medium and this generates huge amount of solid waste [12,13]. Pressure-driven membrane-based separation and purification appears to be a much better option than the traditional processes like extraction, ion-exchange, evaporation and distillation as it involves no phase change and offers opportunity of fractionation of the components of a mixture or solution with drastically reduced energy involvement [14]. Downstream purification by employing single

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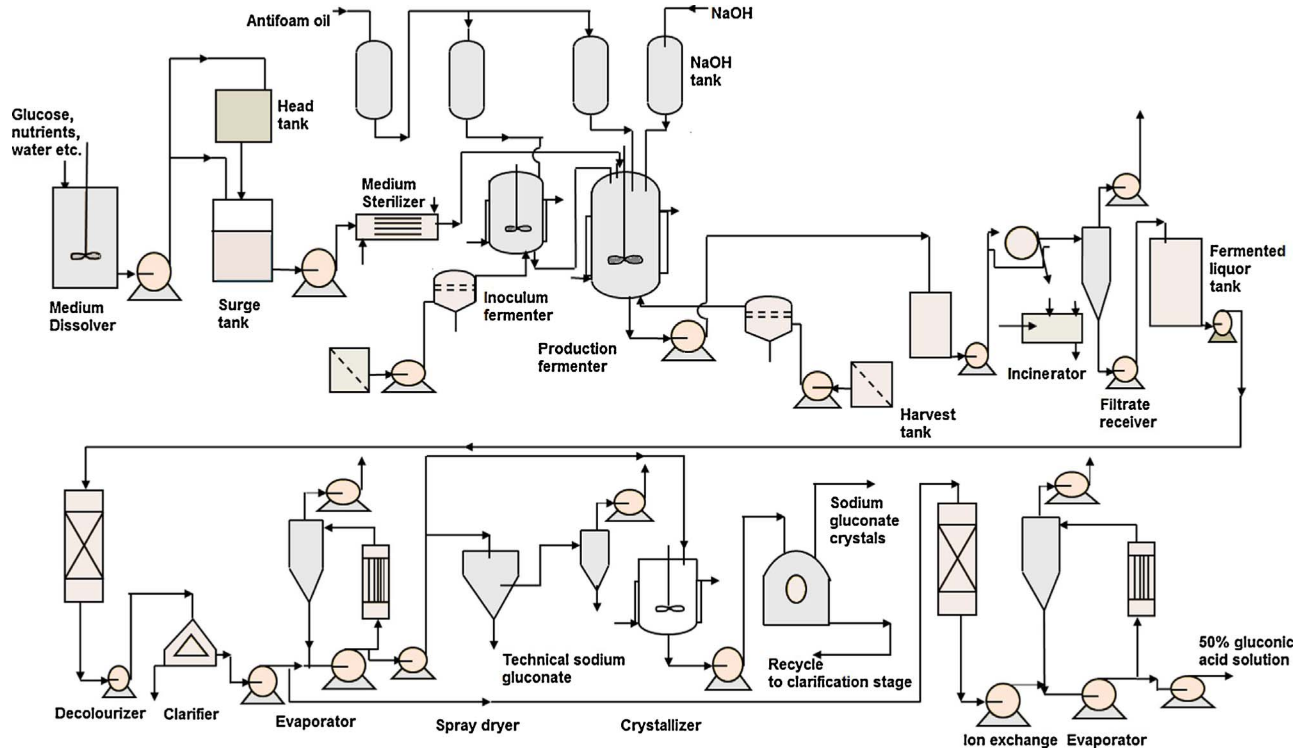

Fig 1. Typical traditional microbial production and downstream purification for gluconic acid [27].

Table 1
Typical performances and characteristics of membranes used in present investigation.

Characteristics	MF (PVDF)	NF2	NF1
Operating pressure (bar)	3	13	15
Filtration type	Microfiltration	Nanofiltration	Nanofiltration
Material	Polyvinylidene fluoride	Polyamide	Polyamide
Pure water flux(L/m^{2}h)	455–540	210–250	110–130
Fermentation broth flux (L/m^{2}h)	86–90	120–125	70–80
Gluconic acid rejection (%)	–	14	95
$MgSO_4$ rejection (%)	–	99	99.8
NaCl rejection (%)	–	95	92
Temperature resistance	80	50	50
Width (m)	0.3	1.02	1.02
Average MWCO	5000–100,000	150–300	150–300
Thickness (μm)	165	165	165
Average pore size	0.45 (μm)	0.55 (nm)	0.53 (nm)
Used surface area (m^2)	0.01	0.01	0.01

staged membrane system like microfiltration or ultrafiltration in tubular or hollow fiber modules were reported in the literature for different organic acid purification but the expected full benefits of membrane-integrated system still could not be reaped in such reported cases due to high turbidity of fermentation broth leading to severe fouling in the used modules [15]. Thus, an integration of fermenter with two-stage flat sheet cross flow membrane module for nanofiltration following micro and ultrafiltration has been done in the proposed system where recycling of microbial cells and unconverted carbon sources is done leading to high cell density in the fermenter and high yield [16,17]. As fouling is a major hindrance in any membrane separation process, the issue needs to be addressed with due importance. Flat sheet cross flow membrane modules have been used in the proposed process to overcome this major difficulty in sustainable operation [18–20]. Thus integration of specific membranes as well as modules with a conventional fermenter in logical sequence of operations is essential to achieve process intensification [21].

This work shows how through a membrane-integrated hybrid production system, high degree of process intensification can be achieved in gluconic acid production process. This paper analyzes such process intensification and measures the degree of process intensification along with environmental factors (E-factor) and atom economy in the backdrop of absence of a similar study in the literature.

2. Gluconic acid production in conventional technologies

Traditionally, gluconic acid has been produced by chemical, electrochemical, bio-chemical, bio-electrochemical, enzymatic and fermentative routes, however currently, fermentation process is most widely used [22,23]. In catalytic oxidation procedure, the molecular oxygen under alkaline condition reacts with glucose to produce gluconic acid in presence of palladium or platinum catalyst [24]. But fermentation is one of the most efficient methods for the production of gluconic acid where the fungus, *A. niger* or the bacteria, *G. oxydans* are widely used micro-organisms [25].

The downstream purification largely depends on types of carbon source used, production method followed and types of products targeted like gluconic acid, glucono-δ-lactone, calcium gluconate and sodium gluconate. In producing technical grade sodium gluconate (98%) or pure form of gluconic acid, a number of steps are involved such as filtration, decolorizing using granular activated-carbon, concentration by vacuum drying and ion-exchange by NaOH salt as shown in Fig. 1. The major limitations that stand in economical and green production of gluconic acid are high manpower requirement, use of energy-intensive and expensive steps, and release of huge amount of wastewater [26]. Thus, a membrane-integrated biochemical process with minimum requirement of end-of-pipe treatment in tackling environmental issues is the choice of the time [27].