

Enhanced isobutanol recovery from fermentation broth for sustainable biofuels production

Janković, Tamara; Straathof, Adrie J.J.; Kiss, Anton A.

DOI

[10.1016/j.ecmx.2023.100520](https://doi.org/10.1016/j.ecmx.2023.100520)

Publication date

2024

Document Version

Final published version

Published in

Energy Conversion and Management: X

Citation (APA)

Janković, T., Straathof, A. J. J., & Kiss, A. A. (2024). Enhanced isobutanol recovery from fermentation broth for sustainable biofuels production. *Energy Conversion and Management: X*, 21, Article 100520. <https://doi.org/10.1016/j.ecmx.2023.100520>

Important note

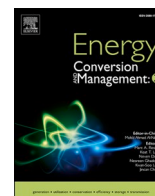
To cite this publication, please use the final published version (if applicable). Please check the document version above.

Copyright

Other than for strictly personal use, it is not permitted to download, forward or distribute the text or part of it, without the consent of the author(s) and/or copyright holder(s), unless the work is under an open content license such as Creative Commons.

Takedown policy

Please contact us and provide details if you believe this document breaches copyrights. We will remove access to the work immediately and investigate your claim.



Enhanced isobutanol recovery from fermentation broth for sustainable biofuels production

Tamara Janković, Adrie J.J. Straathof, Anton A. Kiss*

Department of Biotechnology, Delft University of Technology, van der Maasweg 9, 2629 HZ Delft, The Netherlands

ARTICLE INFO

Keywords:

Biofuels
Isobutanol
Downstream processing
Industrial biotechnology
Gas stripping with vacuum evaporation
Dividing-wall column

ABSTRACT

Isobutanol is a highly attractive renewable alternative to conventional fossil fuels, with superior fuel properties as compared to ethanol and 1-butanol. Even though the isobutanol production by fermentation has significant potential, complex downstream processing is limiting the wide-spreading of this technology. Accordingly, this original research significantly contributes to the advancement in industrial biofuel production by developing two eco-efficient downstream processes for the industrial-scale recovery of isobutanol (production capacity 50 ktonne_{IBUT}/y), from a highly dilute fermentation broth (>98 wt% water). Vacuum distillation and a novel hybrid combination of gas stripping and vacuum evaporation were coupled with atmospheric azeotropic distillation to recover over 99.9 % of isobutanol as a high-purity product (100 wt%). Advanced heat pumping and heat integration techniques were further implemented to allow the complete electrification of these recovery processes. Furthermore, implementation of these techniques significantly decreased total annual costs (0.131–0.161 \$/kg_{IBUT}), reduced energy requirements (0.488–0.807 kWh/kg_{IBUT}) and lowered CO₂ emissions (0.303–0.449 kg_{CO2}/kg_{IBUT}), resulting in highly competitive purification processes. In addition to efficiently recovering isobutanol, the designed downstream processes provide the potential to enhance the fermentation process by recycling all present microorganisms and reducing water demand. Therefore, the results of this original research substantially contribute to the advancement in industrial biotechnology and the wide-spreading of biofuel production.

1. Introduction

Swiftly growing energy demands have led to extensive fossil fuel consumption, resulting in significant environmental pollution and climate change. Additionally, rapidly depleting sources of fossil fuels are raising concerns about energy security. In order to minimize the negative impacts of climate change on the environment, a greener alternative for most oil, gas and coal, currently used for providing energy and producing different chemicals and materials, needs to be sought. Biofuels and biochemicals potentially present renewable substitutes for conventional fossil fuel-derived sources. Production of various biochemicals has already been established using fermentation. The advantages of these production pathways are relatively mild fermentation conditions, a wide range of substrates (e.g. lignocellulosic biomass, municipal waste, organic waste biomass, industrial off-gases, etc.) that can be used by microorganisms to produce valuable biochemicals and lower environmental impact compared to conventional fossil fuel-based processes [1]. Additionally, biochemicals are beneficial for energy

security, sustainability and socioeconomics of rural sectors [2]. However, the major drawback of large-scale fermentative production is the low product concentrations that can be obtained due to inhibitory effects on the microorganisms. Consequently, high water throughput is needed, which results in rather complex and expensive downstream processing [3].

The most mature fermentation technology is the production of bioethanol from either lignocellulosic biomass or syngas. Even though methods for using ethanol as a renewable fuel are well-established [2], higher alcohols are potentially better replacements for conventional fuels due to higher energy density [4]. The main limitations of using ethanol as biofuel are significantly lower energy density compared to gasoline (about 19.6 and 32 MJ/kg for ethanol and gasoline, respectively), high hygroscopicity and higher vapor pressure that complicate ethanol storage and transport [1]. Alternatively, 1-butanol has been gaining significance as a superior sustainable fuel alternative [5]. Its large-scale production is commonly based on acetone–butanol–ethanol fermentation (ABE). The main advantage of 1-butanol compared to

* Corresponding author.

E-mail address: A.A.Kiss@tudelft.nl (A.A. Kiss).

ethanol is higher energy content (27–29.2 MJ/kg), being close to the one of gasoline. Furthermore, there is practically no need to modify automobile engines due to a higher mixing ratio and better compatibility with gasoline. Additionally, 1-butanol is more suitable for transport and storage using existing systems due to low corrosivity [1]. However, biofuels can be upgraded even further by using isobutanol. Compared to 1-butanol, isobutanol has a higher octane number [6] and can be more easily converted to biojet fuel [1]. Furthermore, isobutanol is less toxic to the microorganisms, potentially resulting in higher achievable concentrations and less complex downstream processing [7]. Therefore, isobutanol may be a very attractive renewable alternative to fossil carbon-based fuels [1] and has already been studied as a potential biofuel [8–10].

Isobutanol is an important platform chemical with an estimated industrial production of about 500 ktonne/y [11]. It is commonly produced in fossil fuel-based processes, whereby there are three main approaches. Firstly, isobutanol is traditionally synthesized by hydrogenation of isobutylaldehyde, which is obtained from propylene in carbonylation reaction with syngas. The main drawbacks of this pathway are extreme process conditions (temperature of about 150–200 °C and pressure about 200–400 bar), low catalyst stability and relatively low yield [1]. Secondly, isobutanol can be produced from syngas in the presence of different catalysts [12]. However, intermediate steps in this pathway are production of methanol, ethanol and propanol, whereby high productivity and selectivity of isobutanol are dependent on high temperature (up to 420 °C) and pressures (up to 250 bar) [1]. Lastly, Guerbet reaction was proposed for synthesis of isobutanol from methanol and 1-propanol. This production pathway consists of several steps: oxidative dehydrogenation to produce aldehydes from alcohols, aldol condensation of formed aldehydes to produce alcohol-aldehydes, dehydration of alcohol-aldehydes to form olefine aldehydes and finally, hydrogenation of olefine aldehydes to produce isobutanol [13]. However, this reaction still requires usage of expensive catalysts and relatively severe process conditions (temperature of about 200 °C). All these described processes are dependent on fossil fuels, require extreme process conditions and expensive catalysts, and are very energy-intensive [1]. Therefore, a more environmentally friendly alternative for the production of isobutanol is an important step towards sustainable development.

Isobutanol synthesis by fermentation presents an attractive renewable alternative to conventional fossil fuel-based production processes. The major advantages of this production pathway are mild process conditions, minimized environmental impact and usage of biomass that does not compete with food production (e.g. lignocellulosic or waste biomass). However, isobutanol is not naturally synthesized in significant amounts by any microorganisms [7]. Nevertheless, as natural production pathways exist, considerable focus of research has been put on engineering different microorganisms [11]. Genetical engineering on different types of bacteria is mainly focused on introducing isobutanol production pathways into bacterial cells [14,15]. A typically used metabolic pathway is a modification of the pathway to L-valine [11]. Unlike synthesis of 1-butanol, metabolic pathway of isobutanol synthesis is less complex and not dependent on acetyl-CoA, resulting in lower possibility of side-product formation [6]. Combination of different gene manipulations resulted in an isobutanol titer of 22 g/L [16]. Alternatively, engineering strategies on yeasts imply overexpression of specific genes, blocking competitive pathways and localizing isobutanol production pathway in a certain part of the cell [17,18]. Thus, all of these genetic engineering approaches strive to overcome the major problem of product toxicity by developing tolerant strains. In that sense, adaptive evolution methods may lead to more efficient isobutanol production in the future [19]. Alternatively, continuous concurrent alcohol recovery and fermentation (CARAF) can overcome product toxicity limitations [20]. Recent advances in fermentation technology have significantly contributed to the industrial production of isobutanol. Company Gevo established the first bioisobutanol production plant in

2010 with a production capacity of about 750,000–1,000,000 gallons/y [1,21]. Furthermore, BP and DuPont combined expertise in 2016 to form Butamax, a joint venture for producing bioisobutanol [22].

Even though isobutanol production by fermentation has significant potential, there are several challenges that are limiting wide-spreading of this technology. The major one is the relatively low isobutanol concentration that can be obtained despite a significant effort to increase the tolerance of various microorganisms [1]. Consequently, purifying isobutanol from highly dilute fermentation broth up to a high-purity final product is complex and may be very cost- and energy-intensive [23]. Furthermore, due to the large water throughput that is needed, equipment cost can be significant [1]. Additionally, the presence of viable microorganisms limits operating conditions for the initial separation steps (moderate temperatures, short residence times and absence of any additional chemicals that can be toxic to cells). Lastly, thermodynamic constraints due to isobutanol – water azeotrope formation further complicate the purification process. Accordingly, developing separation techniques that can recover isobutanol in cost-effective and energy-efficient way is of crucial importance for improving the feasibility of bioisobutanol production processes [24]. Thus, this original research significantly contributes to the advancement in industrial biofuel production by developing an efficient large-scale downstream process for recovering isobutanol from a highly dilute fermentation broth. The main novelty in the proposed process design is a hybrid combination of gas stripping and heat pump assisted vacuum evaporation that ensures complete recovery of isobutanol while maintaining operating conditions appropriate for the present microorganism. Additionally, apart from enhancing the process with heat pump systems, a dividing-wall column is proposed as an additional process intensification opportunity. Therefore, the highly competitive recovery process proposed here may substantially improve attractiveness of the overall fermentative production of isobutanol.

2. Problem approach

2.1. Recovery methods

One of the major limitations in industrial fermentation of bioalcohols is the end-product inhibition that occurs due to the end-product toxicity. This phenomenon decreases productivity and determines maximum achievable product concentration in the fermentation broth. However, these constraints may be effectively mitigated by continuously removing products while fermentation is on-going. Therefore, an efficient separation method, compatible with present microorganisms, is needed for the concurrent alcohol recovery and fermentation (CARAF) [20]. Several different separation techniques have been studied for in-situ separation of isobutanol from dilute aqueous solution [1,25]. The first potential recovery option is adsorption using activated carbon and polystyrene-divinylbenzene [26]. However, these adsorbents have not been employed to the real fermentation broth so far and desorption process has not been investigated [1]. Additionally, microorganisms can easily cause adsorbent fouling. Furthermore, simple pervaporation or hybrid hydrophobic-hydrophilic pervaporation processes [27] can also be used for in-situ recovery of isobutanol from dilute solutions. However, selectivity of membrane materials needs to be improved to increase overall energy efficiency [25]. Moreover, finding membrane suitable for industrial-scale process is challenging [1]. Solvent extraction is another option for isobutanol separation from an aqueous solution. This method does not require high temperatures, resulting in low energy requirements [25]. However, common extractants are usually toxic to the microorganisms. Additionally, further purification is needed as isobutanol still has to be removed from the extractant, while different impurities that are present in the fermentation broth can significantly complicate this process [1]. Another method for isobutanol purification is salting-out, during which isobutanol ends up in organic phase, while all salt remains in aqueous phase after liquid–liquid phase splitting [28].

Following recovery of salt from dilute solution is the common drawback of this method due to energy intensity. Salting-out extraction is a novel type of purification method that improves separation of valuable products. However, the efficiency of the separation process highly depends on the used combination and amounts of organic solvent and salting-out agent. In inappropriate combinations, some salt may end up in the organic phase, resulting in reduced separation efficiency [1]. Another option for in-situ recovery is gas stripping which implies removing isobutanol from dilute broth using different gases. Isobutanol is obtained in gaseous stream that needs to be condensed for further treatment [4,29,30]. This method can conveniently use gases already produced in the fermentation process, such as carbon-dioxide. However, amount of present gases might not be enough to completely separate products, and additional gas source may be needed [1]. The nature of used gases for isobutanol stripping will determine complexity of the following condensation step. Lastly, vacuum evaporation has been proposed and already used method of isobutanol recovery from fermentation broth. Company GEVO is using GIFT (Gevo Integrated Fermentation Technology) system to separate isobutanol from the fermentation broth. In this system, a side stream is taken from the fermenter and partially evaporated under reduced pressure [31]. Formed vapor, containing significantly increased isobutanol content compared to the fermentation broth [21], is condensed and further purified. However, the remaining liquid broth that is being recycled to the fermenter still contains significant amount of isobutanol product [31]. Furthermore, even though vacuum evaporation can use low-temperature heat source, this process can be very energy demanding. Thus, this original research presents a step forward towards more efficient CARAF processes by proposing two highly advanced processes for bioisobutanol recovery on large-scale (production capacity 50 ktonne/y). The first recovery process implies heat pump assisted vacuum distillation and atmospheric azeotropic distillation (later referred as VD configuration, see Fig. 1).

Heat pump assisted vacuum distillation was chosen for the initial separation of isobutanol from the rest of the fermentation broth, as this method is the most mature and most easily applied on an industrial-scale from all proposed [1], does not require usage of additional chemicals that would risk viability of present microorganisms and can be designed in a way to ensure high product recovery. The second proposed recovery design is a novel hybrid process that merges gas stripping and heat pump assisted vacuum evaporation method for the initial separation step (this process configuration is later referred to as GS-VE, see Fig. 2). This novel

combinational technology results in complete separation of isobutanol from very dilute fermentation broth in energy-efficient way, thus allowing isobutanol-free recycle to the fermentation. Furthermore, azeotropic distillation is used to obtain a high-purity product, while heat integration opportunities are considered to enhance energy efficiency.

2.2. Process design and simulation

The recovery process was designed for high-capacity industrial plant producing about 50 ktonne of isobutanol per year [32]. The feed stream for this process (stream 1 in Table 2 and Table 3) is taken from the fermenter and is at atmospheric pressure (1 bar) and fermentation temperature (30 °C) [4,6]. Due to the inhibitory effects isobutanol has on microorganisms, its concentration in the fermentation broth is about 16 g/L [6]. As a product of microbial metabolism, some CO₂ is dissolved in this stream (about 0.13 wt%) [33]. Some microorganisms and inert components are also present but can be neglected in simulations as they are removed in the first steps without evaporation. Nonetheless, the fermentation broth contains more than 98 wt% water, while the concentration of the main product is less than 2 wt%. Apart from the highly dilute feed stream, the closeness of boiling points and thermodynamic limitations due to azeotrope formation (Table 1) complicate the recovery process even more.

Besides the low product concentration and thermodynamic constraints, the presence of living microorganisms is a limiting factor that determines operating conditions for the first separation step. This initial separation of isobutanol from most of the fermentation broth should be performed without toxic chemicals, at moderate temperatures and with short residence times so that microorganisms can survive the lack of nutrients. Two methods are proposed for the first separation step: vacuum distillation (VD process configuration, see Fig. 1) and novel hybrid separation combining gas stripping and vacuum evaporation (GS-VE process configuration, see Fig. 2). In both cases, the usage of additional chemicals that might harm present cells is avoided, and moderate temperatures are maintained by applying reduced pressure. Even though exposing fermentation broth to vacuum might require additional experimental validation, it has already been proven that reduced pressure does not jeopardize microbial viability [34–36]. Microorganisms, other non-volatile inert components and most of the present water will flow directly to the bottom stream in the initial separation step. After isobutanol is removed, this aqueous stream may be recycled to the

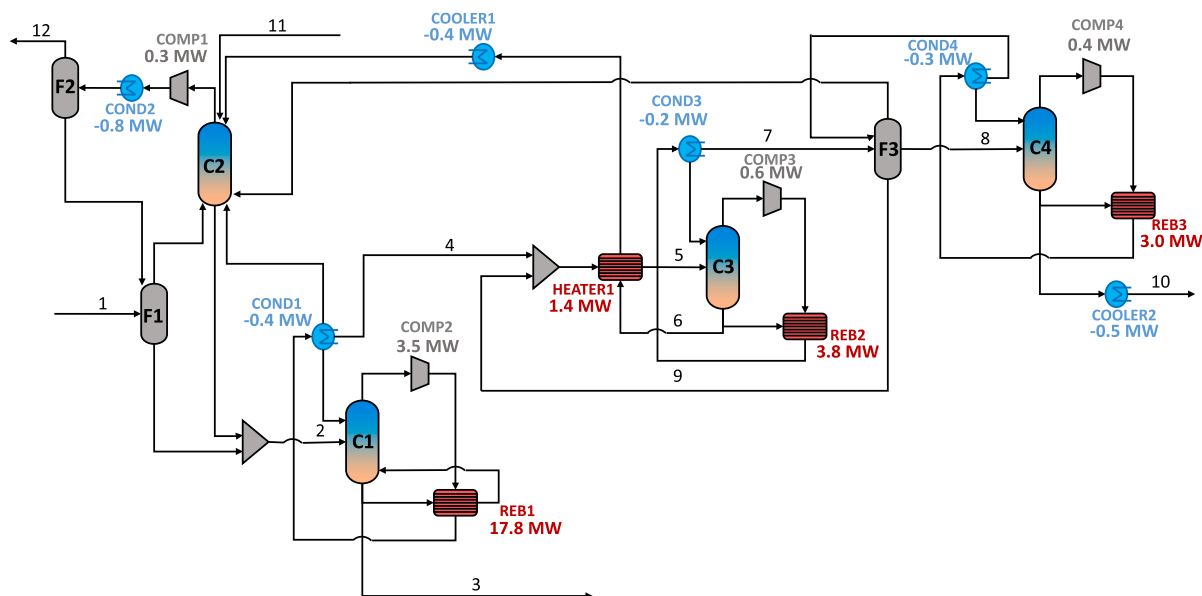


Fig. 1. Isobutanol recovery by VD process (initial separation from the fermentation broth and following azeotropic distillation), stream compositions and conditions are given in Table 2.

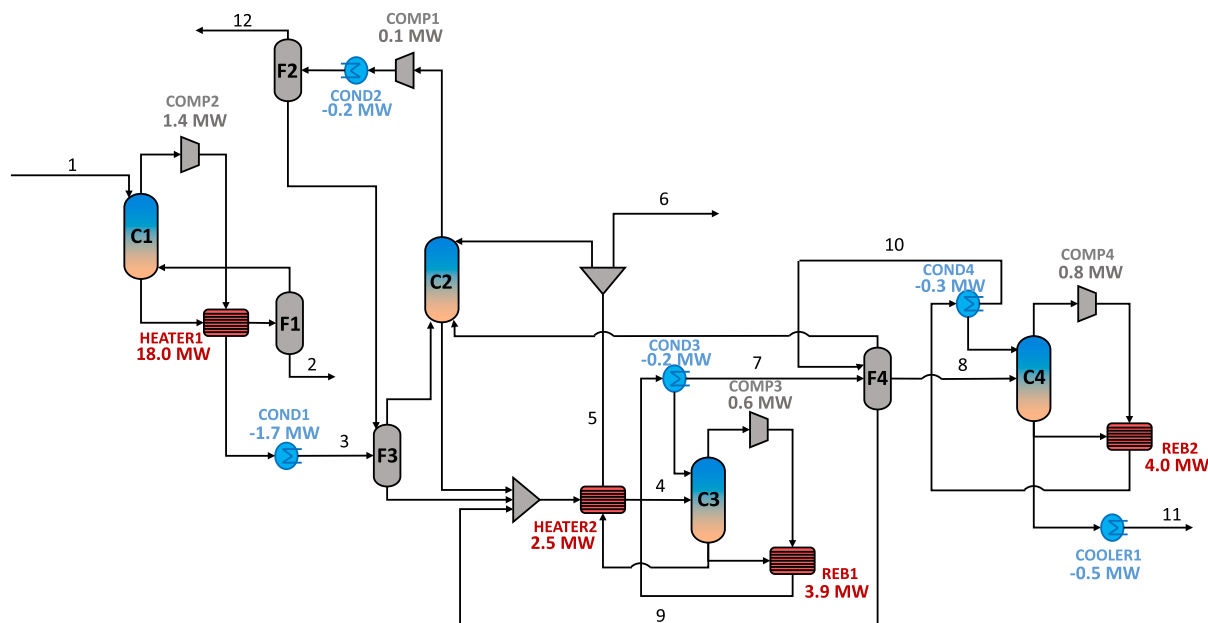


Fig. 2. Isobutanol recovery by GS-VE process (initial separation from the fermentation broth and following azeotropic distillation), stream compositions and conditions are given in Table 3.

Table 1
Boiling points of pure components and azeotrope formation at 1 bar.

Pure components	Azeotrope			
	Component	Mass fraction	T (°C)	Type
Water	100.00	0.3473	90.28	heterogeneous
Isobutanol	107.68	0.6527		

Table 2
Condition and composition of process streams – VD process configuration, see Fig. 1.

Stream	1	2	3	4	5	6
Temperature (C)	30.0	28.2	35.7	21.9	81.0	103.6
Pressure (bar)	1.000	0.055	0.059	0.050	1.200	1.152
Flowrate (kg/h)	387,500	437,825	411,555	25,765	29,788	19,452
Mass fractions						
Water	0.9826	0.9848	1.0000	0.7546	0.7716	1.0000
Isobutanol	0.0161	0.0148	0.0000	0.2439	0.2260	0.0000
CO ₂	0.0013	0.0004	0.0000	0.0015	0.0024	0.0000
Stream	7	8	9	10	11	12
Temperature (C)	84.7	83.0	82.9	30.0	25.0	11.7
Pressure (bar)	1.000	1.200	1.000	1.152	1.000	1.200
Flowrate (kg/h)	10,337	13,862	3,965	6,238	30,800	507
Mass fractions						
Water	0.3419	0.2004	0.8826	0.0000	1.0000	0.0046
Isobutanol	0.6513	0.7943	0.1092	1.0000	0.0000	0.0019
CO ₂	0.0069	0.0053	0.0082	0.0000	0.0000	0.9935

fermentation to avoid loss of biomass, enable a closed-loop upstream process and reduce fresh water requirements [37]. Additional testing of microorganisms that are recycled might be needed to avoid any infection possibilities. Furthermore, continuous removal of isobutanol from the fermenter decreases inhibitory effects and increases fermentation productivity. Following this initial separation step, performed either by vacuum distillation or combination of vacuum flashing and gas

Table 3
Condition and composition of process streams – GS-VE process configuration, see Fig. 2.

Stream	1	2	3	4	5	6
Temperature (C)	30.0	29.7	24.8	84.9	32.2	32.2
Pressure (bar)	1.000	0.042	0.095	1.200	1.152	1.152
Flowrate (kg/h)	387,500	355,203	32,297	41,065	30,553	25,553
Mass fractions						
Water	0.9826	1.0000	0.7912	0.8314	1.0000	1.0000
Isobutanol	0.0161	0.0000	0.1932	0.1616	0.0000	0.0000
CO ₂	0.0013	0.0000	0.0156	0.0070	0.0000	0.0000
Stream	7	8	9	10	11	12
Temperature (C)	63.4	61.0	61.0	58.1	30.0	9.0
Pressure (bar)	1.000	1.200	1.000	1.000	1.152	1.200
Flowrate (kg/h)	10,513	17,088	4,058	10,851	6,237	507
Mass fractions						
Water	0.3413	0.2022	0.8795	0.3183	0.0000	0.0038
Isobutanol	0.6314	0.7784	0.0910	0.6511	1.0000	0.0026
CO ₂	0.0273	0.0194	0.0295	0.0306	0.0000	0.9935

stripping, the obtained isobutanol – water mixture is more concentrated as compared to the fermentation broth. However, further purification is needed to obtain a high-purity final product. Due to the azeotrope formation, the separated mixture needs to be concentrated close to the azeotropic composition using conventional atmospheric distillation. The nearly azeotropic mixture formed is heterogeneous, and simple phase separation can be used to obtain most of the isobutanol in the organic phase. Lastly, to recover high-purity isobutanol product, an additional distillation step is necessary. Rigorous simulations for every step in the designed recovery process were developed in Aspen Plus. Operating conditions for the initial separation steps were chosen not to threaten microbial viability but to ensure complete isobutanol recovery from the fermentation broth. The presence of microorganisms in the feed stream can be neglected in the simulations as they are removed in these first separation steps without evaporation. The following distillation steps were designed to recover high-purity isobutanol product while minimizing energy requirements. By convention in Aspen Plus, number of stages, position of the feed stage and operating pressure are design specifications, while distillate-to-feed ratio and reflux ratio were chosen

for operating specifications. Heat exchangers were designed with a logarithmic mean temperature difference of about 10 °C.

2.3. Economic evaluation

The competitiveness of the proposed processes was evaluated by an economic analysis using the published NREL methodology [38], which considers the total capital (CAPEX) and operating (OPEX) costs. The CAPEX accounts for direct capital costs, associated with equipment purchase and installation costs, and indirect capital costs related to home office and construction, field expenses, proratable expenses, project contingency, working capital, site development, additional piping and warehouse. The OPEX accounts for fixed operating costs, determined by cost for labor, maintenance and property insurance, and variable operating costs, determined by cost for utilities. The total annual costs (TAC), based on both CAPEX and OPEX, and minimum added selling price for the isobutanol recovery process were estimated using the same procedure [38].

2.4. Sustainability assessment

Environmental impact of proposed processes was evaluated by calculating the following sustainability metrics: energy intensity, water consumption, material intensity, greenhouse gas emissions, pollutants and toxic materials [39]. Note that lower values of these metrics indicate better process performance in terms of sustainability.

- **Energy intensity** presents the amount of heat and electrical energy required per kilogram of product [39]. Total energy requirements account for both thermal and electrical energy through electrical to thermal conversion factor (conservative value of 2.5 [40]).
- **Water consumption** is the measure of water used per kilogram of product [39]. This metrics considers cooling water requirements, with a loss assumption of 7 % [39], and inefficiencies in steam generation and usage, with 70 % steam condensate recovery [41].
- **Material intensity** is the amount of waste [39] or non-product [42,43] per kg product.
- **Greenhouse gas emission** presents the amount of carbon-dioxide (CO₂) emitted per kilogram of product [39]. Due to the significance of the source of electricity, a clear distinction was made between electricity obtained from fossil fuels (grey electricity) and electricity obtained from renewable sources (green electricity).
- **Pollutants and toxic materials** account for the amount of pollutant and toxic materials emitted per kilogram of product [39].

3. Results and discussion

3.1. Recovering isobutanol from the rest of the fermentation broth

The first step in the recovery process is separating isobutanol, with some water, from most of the fermentation broth, while keeping operating conditions appropriate for present microorganisms. Two different methods were designed for this initial separation step: conventional vacuum distillation assisted with heat pump systems (VD) and novel combination of gas stripping and heat pump assisted vacuum evaporation (GS-VE), as described in the following sections.

3.1.1. Vacuum distillation

The flowsheet of isobutanol recovery using VD process configuration is presented in Fig. 1, while the composition and condition of the main process streams are given in Table 2.

Since some CO₂ is present in the stream taken from the fermenter (stream 1 in Table 2), the first step in the purification process is its removal in a simple degasser vessel (F1 in Fig. 1) under reduced pressure. The operating pressure for this step (0.05 bar) was chosen such that more than 70 % of initially present CO₂ is removed in a vapor phase.

Some isobutanol is also evaporated in this step, but it is later captured with water in stripping column C2 and returned to the recovery process. Furthermore, in order to maintain moderate temperatures that will not harm microbial viability, vacuum distillation was applied to separate isobutanol with some water from most of the fermentation broth. The defined condenser pressure for vacuum distillation column C1 is the same as for the degassing step (0.05 bar), with a pressure drop of 0.225 mbar per theoretical stage. Structured packing type Sulzer Mellapak 250 was chosen for its internals [44]. Additionally, as some CO₂ is still present, a partial condenser with both vapor and liquid distillate was defined for column C1. Vapor distillate stream is also sent to column C2 where separated isobutanol is recovered with water and returned to the recovery process. Under these operating conditions, the temperature in column C1 varies from about 36 °C at bottom to about 22 °C at the top. Due to the low condensation temperature, chilled water needs to be used as cooling utility instead of cheaper cooling water. Furthermore, as a result of large flowrates and closeness of boiling temperatures, reboiler duty for this column is very high (about 17.7 MW). However, relatively small difference in the top and bottom column temperature can be exploited to apply mechanical vapor recompression (MVR). In this heat pump system, vapor coming from the top of distillation column is compressed and used to evaporate liquid from the bottom of the distillation column. Consequently, the need for both external heating and external cooling can be significantly reduced [45]. The coefficient of performance (COP) – a measure of the obtained energy savings – is equal to the ratio of the upgraded heat (exchanged between the compressed top vapor and bottom liquid) and required compressor duty. COP values higher than 2.5, which is conservative value of electrical to thermal conversion factor [40], prove the high energy efficiency of the MVR system. Since COP for the MVR system applied to column C1 (about 5.2) is significantly higher than electrical to thermal conversion factor, energy requirements for this separation are drastically reduced. After this initial step, isobutanol is completely separated from most of the fermentation broth in a top stream from column C1 (stream 4 in Table 2). This stream contains ~ 24 wt% isobutanol and requires processing to obtain high-purity final product. Bottom aqueous product from column C1 containing all present microorganisms and non-volatile inert components (stream 3 in Table 2) may be returned to the fermentation process.

3.1.2. Gas stripping and vacuum evaporation

Fig. 2 illustrates the flowsheet of isobutanol recovery using GS-VE process configuration, whereby Table 3 provides details about the main process streams.

A novel hybrid separation method combining gas stripping and vacuum evaporation was developed to further reduce energy requirements for the initial separation step. In this process design, the broth taken from the fermenter (stream 1 in Table 2) is firstly sent to stripping column C1 in which gas is used to separate isobutanol from the aqueous feed stream. This column operates under reduced pressure (0.04 bar) to ensure that temperature does not harm microbial viability. A pressure drop of 0.225 mbar per theoretical stage and structured packing type Sulzer Mellapak 250 was realistically considered [44]. Furthermore, a part of the remaining broth, depleted of isobutanol, is evaporated under reduced pressure and then separated in the simple flash vessel. Residual liquid broth containing most of the water, all the present microorganisms and non-volatile inert components (stream 2 in Table 2), may be recycled to the fermentation. The generated steam is sent to stripping column C1 where it is used to completely remove isobutanol from the feed stream. Since evaporating a part of the depleted broth is very energy intensive (about 18.1 MW), vapor recompression is applied to reduce the energy requirements. The top product from column C1, vapor rich in isobutanol, is compressed (COMP2 in Fig. 2) and then used to evaporate part of the depleted broth. A COP value of 13.0 indicates a significant reduction in the energy requirements for this initial separation step. Isobutanol – water vapor mixture is then

condensed (stream 3 in Table 2) and sent to the degassing unit to remove most of the CO₂. The isobutanol that is separated with CO₂ is captured with water in column C2 and returned to the recovery process. As a result of this initial separation step, the isobutanol concentration was increased from 1.6 wt% to about 19 wt% in the obtained aqueous solution. However, further purification is needed to obtain high-purity final product.

3.2. Further isobutanol purification

After the initial separation step, performed either by VD or GS-VE, additional processing is required to achieve isobutanol product of high purity. This is performed in several steps due to the azeotrope formation. Firstly, the isobutanol – water mixture is concentrated in the distillation column C3. The top product from this column is nearly azeotropic mixture (stream 7 in Table 2 and Table 3), while the bottom product is pure water (stream 6 in Table 2 and stream 5 Table 3). Since the top azeotropic mixture is heterogenous, simple decanting (in a 3-phase flash unit – F3 in Fig. 1 and F4 in Fig. 2) is used to separate two liquid phases. Water-rich phase (stream 9 in Table 2 and Table 3) still contains some isobutanol (about 9–11 wt%). To avoid loss of valuable product, this stream is recycled to column C3. Contrarily, isobutanol-rich phase (stream 8 in Table 2 and Table 3) is sent to distillation column C4 for final purification. Additionally, the gas stream containing mostly CO₂, with some water and isobutanol, is separated in this flash unit. This stream is sent to column C2 in which isobutanol is captured with water and returned to the recovery process. More than 99.9 % of isobutanol from the fermentation broth is recovered as a high-purity product (100 wt%) from the bottom of column C4 (stream 10 in Table 2 and stream 11 in Table 3). The top product from this column is nearly azeotropic isobutanol – water mixture that is recycled to the flash unit. Both columns C3 and C4 are operating at atmospheric pressure with pressure drop of 8 mbar per stage and have sieve trays for internals [46]. More details about the design of the distillation columns are presented in the Appendix A file.

Since the required heating duties for columns C3 and C4 are relatively high, additional energy-saving opportunities were considered. Firstly, since the feed stream to column C3 is subcooled liquid, bottom water product from this column is used to preheat it to boiling state. This water stream (stream 6 in Table 2 and stream 5 Table 3) is then used in column C2 to capture the isobutanol separated in the CO₂-rich streams. The amount of water in this stream is sufficient to capture all the isobutanol from gaseous streams in process configuration GS-VE. Contrarily, in the VD process design, an additional water stream is needed to minimize loss of isobutanol. Even after preheating the feed stream, the reboiler duty for column C3 is about 3.8–3.9 MW, depending on the process configuration. Nonetheless, the temperatures at the top (about 90 °C) and bottom (about 104 °C) of this column are relatively close and MVR can be implemented. The COP for the implemented MVR systems are in range 6.2–6.3, which indicates significant energy savings that are obtained with heat pumping. Furthermore, since the temperature difference at the top and the bottom of column C4 is also rather small (about 90 °C at the top and 111 °C at the bottom), MVR can be applied to reduce heating requirements (about 3.0–4.0 MW). COP for the applied MVR systems are in the range of 5.1–7.3, indicating a noticeable reduction in the energy requirements for this column.

Lastly, dividing-wall column (DWC) technology was proposed as an alternative for sequences of two or more distillation columns [47]. A split shell column with a divided bottom section and a common overhead section system was simulated as a substitution for the distillation columns C3 and C4 (Fig. 3).

In this design, the left side of DWC replaces column C3, while the right side replaces column C4. In total, the DWC system has two reboilers and only one condenser. The bottom products from this unit are pure water (from the left side of DWC) and isobutanol product (from the right side of DWC), while the top product is nearly azeotropic

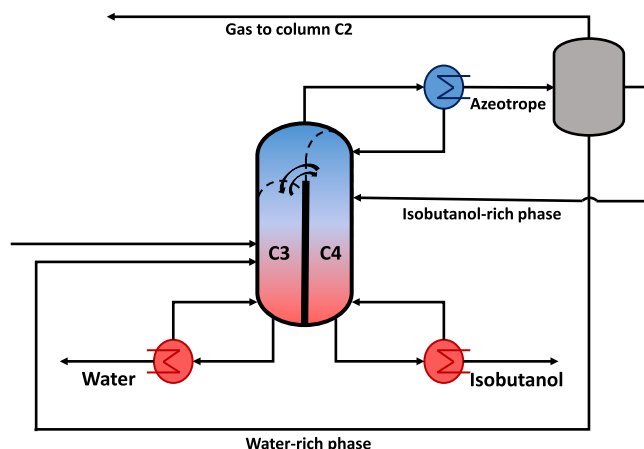


Fig. 3. Azeotropic dividing-wall column design.

isobutanol – water mixture that is sent to flash unit for phase separation. Water-rich phase containing about 11 wt% of isobutanol is recycled as a feed stream to the left part of DWC. Isobutanol-rich phase is returned to the right part of DWC. Additionally, a gas stream containing most of the remaining CO₂ with some water and isobutanol is separated from the flash vessel. This stream is recycled to column C2 to recover the separated isobutanol. This highly integrated distillation system resulted in almost identical thermal energy requirements compared to the sequence of two distillation columns (6.95 and 6.81 MW_{th}, respectively). Similarly, after applying heat pumps to both DWC and the sequence of two separate distillation columns, electrical energy requirements were almost identical (1.05 and 1.02 MW_e, respectively). Comparing the complete isobutanol recovery process when the sequence of distillation columns C3 and C4, or single DWC is used, overall performance is very similar: TAC, energy requirements and CO₂ emissions are higher by only 0.6, 1.3 and 1.1 %, respectively, in case of DWC. Nonetheless, since DWC system integrates two columns into one shell, it is a more compact design that reduces CAPEX, required footprint and minimizes the operator workload compared to the sequence of two distillation columns. Therefore, DWC remains an attractive novel opportunity for isobutanol recovery from an aqueous solution.

3.3. Economic evaluation

Results of a detailed comparison of economic performance are presented in Table 4 and Fig. 4.

The equipment installation costs are 12,028 and 9,685 k\$ for process configurations VD and GS-VE, respectively. The largest contribution to equipment installation costs is cost for compressors used in applied heat pump systems (about 57% and 50 % of the total installed equipment costs). Higher equipment expense for VD process is mainly due to the cost for installing vacuum distillation column C1 and belonging MVR system. The CAPEX for VD and GS-VE recovery process designs are 22,123 and 17,797 k\$, respectively (where about 54 % is the cost for equipment).

The OPEX for VD and GS-VE are 5,821 and 4,756 k\$/y, or expressed per kilogram of product, 0.117 and 0.095 \$/kg_{IBUT}, respectively. The

Table 4
Comparison of economic indicators.

Economic indicators	VD	GS-VE
CAPEX (k\$)	22,123	17,797
OPEX (k\$/y)	5,821	4,756
OPEX (\$/kg _{IBUT})	0.117	0.095
TAC (k\$/y)	8,033	6,536
TAC (\$/kg _{IBUT})	0.161	0.131
MASP (\$/kg _{IBUT})	0.176	0.143

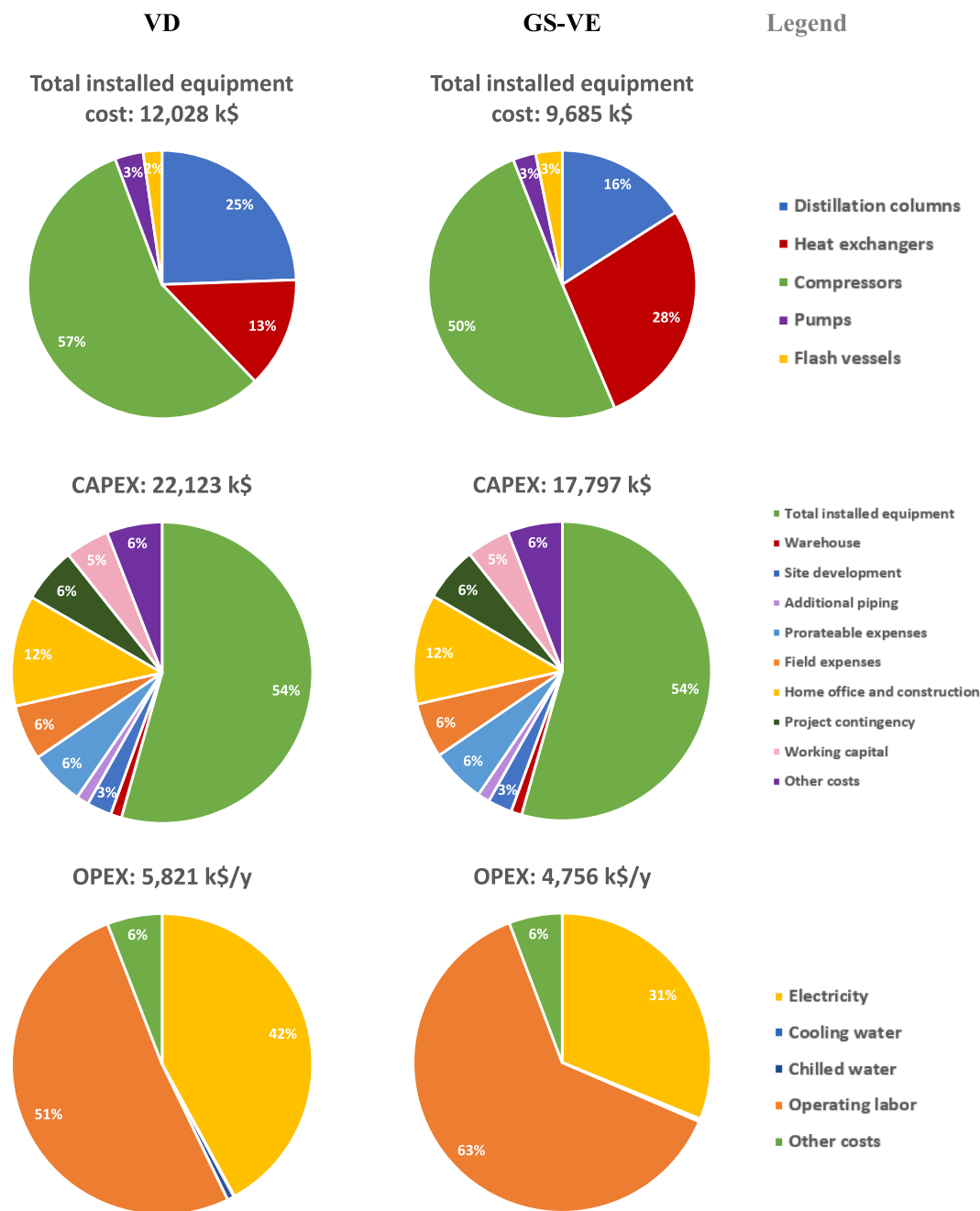


Fig. 4. Comparison of economic indicators.

highest contributions to OPEX in both cases are the cost for operating labor (about 51–63 % of the OPEX) and electricity (about 31–42 % of the OPEX).

The total annual costs, accounting for both CAPEX and OPEX, with a payback period of 10 years, are 8,033 and 6,536 k\$/y, corresponding to 0.161 and 0.131 \$/kg_{IBUT}, for VD and GS-VE, respectively. Furthermore, the added minimum selling price for recovered isobutanol is 0.176 and 0.143 \$/kg_{IBUT}, respectively. Since isobutanol market prices are assumed to be in range 1.16–1.28 \$/kg_{IBUT} [48], both designed recovery processes are highly economically competitive. However, the novel recovery process combining gas stripping and vacuum evaporation is a more suitable option in terms of both capital and operating costs.

Flexibility of performed economic evaluation was expanded by analyzing the influence of the payback period on TAC (Fig. 5).

Although TAC rises with decreasing payback period, even with a

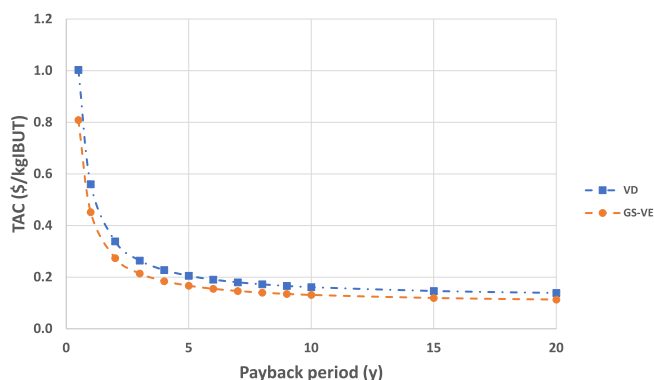


Fig. 5. Effect of payback period on isobutanol recovery costs.

payback period set to 5 years, TAC remains below 0.2 \$/kg_{IBUT} for both recovery processes. Additionally, with a payback period of 6 months, TAC is lower than 0.9 and 1.1 \$/kg_{IBUT} for VD and GS-VE, respectively. Therefore, both designed processes are highly competitive even with shorter payback periods.

3.4. Sustainability assessment

The calculated sustainability metrics, which determine environmental impact of the designed processes are summarized in Table 5.

- Energy intensity:** As a result of implemented heat pumping and additional heat integration, both designed processes are independent of external heating and can be powered by only electricity. Consequently, thermal energy requirements are equal to zero, while electrical energy requirements for VD and GS-VE recovery processes are 0.807 and 0.488 kW_eh/kg_{IBUT}, respectively. Primary energy requirements, accounting for all used sources of energy, are equal to the electrical energy requirements, corresponding to 2.018 and 1.219 kW_{th}h/kg_{IBUT}, respectively. Higher energy need in VD process is mainly due to the used compressor in MVR system applied to column C1. More details about thermal energy reduction is presented through pinch analysis in the Appendix A file. Besides improving energy efficiency, the implementation of proposed heat pump systems is a significant step toward electrification of biofuel production processes. In these systems, electricity used to power compressors replaces a much higher amount of thermal energy, thus providing renewable heat by upgrading waste heat streams. Using renewable electricity instead of fossil fuels to power process can considerably improve sustainability of biofuel production processes.
- Water consumption:** In the designed VD and GS-VE recovery processes, 0.064 and 0.082 m³_w/kg_{IBUT}, respectively, is needed. Accordingly, water losses are 0.004 and 0.005 m³_w/kg_{IBUT}, respectively. Higher requirements in GS-VE recovery process are mainly due to the water required to condense the isobutanol – water vapor used to evaporate part of the depleted broth in the vapor recompression system.
- Material intensity:** Besides the recovered isobutanol product, the output stream in both cases is depleted fermentation broth that may be recycled to the fermenter. Furthermore, in GS-VF process, there is an additional pure water outlet stream that can be recycled to the upstream process to further reduce the need for fresh water. Additionally, CO₂-rich outlet stream was taken into account in greenhouse gas emission sustainability metrics and was not considered as waste here. Therefore, the values of material intensity metrics for the designed isobutanol recovery processes are equal to zero. More detailed insight could be obtained with reliable data from the upstream fermentation process.
- Greenhouse gas emissions:** Due to higher electrical energy demand, the CO₂ emissions are higher for the VD recovery process (0.449 kgCO₂/kg_{IBUT}) than for the GS-VE recovery process (0.303 kgCO₂/kg_{IBUT}) if grey electricity has to be used. If processes can be powered with green electricity, CO₂ emissions are only a consequence of CO₂

Table 5
Comparison of sustainability metrics.

Sustainability metrics	VD	GS-VE
Thermal energy requirements (kW _{th} h/kg _{IBUT})	0.000	0.000
Electrical energy requirements (kW _e h/kg _{IBUT})	0.807	0.488
CO ₂ emission (kgCO ₂ /kg _{IBUT})*	0.449 / 0.081	0.303 / 0.081
Water consumption (m ³ _w /kg _{IBUT})	0.064	0.082
Water loss (m ³ _w /kg _{IBUT})	0.004	0.005
Pollutant emission (kg _{pollutant} /kg _{IBUT})	0.000	0.000
Toxic materials emission (kg _{toxic materials} /kg _{IBUT})	0.000	0.000

*Grey / green electricity.

present in the fermentation broth and are equal to 0.081 kgCO₂/kg_{IBUT} for both isobutanol recovery processes. Nonetheless, this outlet stream is already captured as high-purity CO₂ that may be used as feedstock for other processes, in which case it would not be emitted at all.

- Pollution and toxic materials:** Values of these sustainability metrics are equal to zero because pollutants and toxic materials, other than CO₂ that is already taken into account, are not emitted.

3.5. Sensitivity analysis

While the initial design assumed a concentration of 1.6 wt% isobutanol in the fermentation broth, the isobutanol concentration in industrial fermenters may slightly vary among different plants. To assess the effect of isobutanol concentration in the feed stream (the broth removed from the fermenter) on the designed recovery processes, a detailed sensitivity analysis was performed. Isobutanol concentration in the fermentation broth was varied, whereby the feed flowrate remained constant. The effect of the isobutanol concentration on the economic and environmental indicators is shown in Fig. 6.

A more dilute feed stream leads to more cost- and energy-intensive recovery processes. Very similar trend can be noticed in change of economic and environmental indicators with changing feed composition. However, even with 1 wt% of isobutanol in the fermentation broth, the total annual costs, energy requirements, CO₂ emissions and water consumption are lower than 0.25 \$/kg_{IBUT}, 1.2 kW_eh/kg_{IBUT}, 0.66 kgCO₂/kg_{IBUT} and 0.08 m³_w/kg_{IBUT} for the VD recovery process, while these metrics are lower than 0.20 \$/kg_{IBUT}, 0.70 kW_eh/kg_{IBUT}, 0.45 kgCO₂/kg_{IBUT} and 0.11 m³_w/kg_{IBUT} for the GS-VE recovery process. Therefore, the newly designed processes are capable of efficiently recovering high-purity isobutanol product from even more diluted fermentation broth. Compared to bioethanol purification from equally dilute fermentation broth [49], isobutanol recovery is slightly less economically demanding, but with somewhat higher energy requirements, CO₂ emissions and water consumption. The better performance in terms of economic indicators is mainly due to the process electrification and the avoided need for external heating utilities. Thus, the high competitiveness of the designed isobutanol recovery processes is an important step towards the wide-spreading of isobutanol biofuel production processes.

4. Conclusion

This original study concludes that the proposed two eco-efficient processes for the recovery of isobutanol from highly dilute fermentation broth (>98 wt% water) for industrial-scale production capacity (about 50 ktonne/y) are feasible and viable. Both vacuum distillation and a novel hybrid combination of gas stripping and vacuum evaporation, coupled with regular atmospheric distillation and azeotropic distillation, are able to recover over 99.9 % of isobutanol as high-purity product (100 wt%) while providing recycle of biomass and water to enhance the fermentation process. Moreover, the implementation of heat pumping and heat integration can maximize economic and environmental performance of the designed processes by allowing complete (green) electrification. The performed sensitivity analysis showed that both of the developed recovery processes are capable of efficiently recovering isobutanol from even more dilute aqueous solutions.

The results of this work indicate that the combination of gas stripping and vacuum evaporation for continuous recovery of isobutanol from the fermentation broth is clearly superior to vacuum distillation due to lower total recovery costs (0.131 compared to 0.161 \$/kg_{IBUT}) and energy requirements (0.488 compared to 0.807 kW_eh/kg_{IBUT}). Moreover, using a dividing-wall column is recommended as an additional process intensification method. Thus, this research substantially contributes to the advancement in wide-spreading of large-scale isobutanol biofuel production.

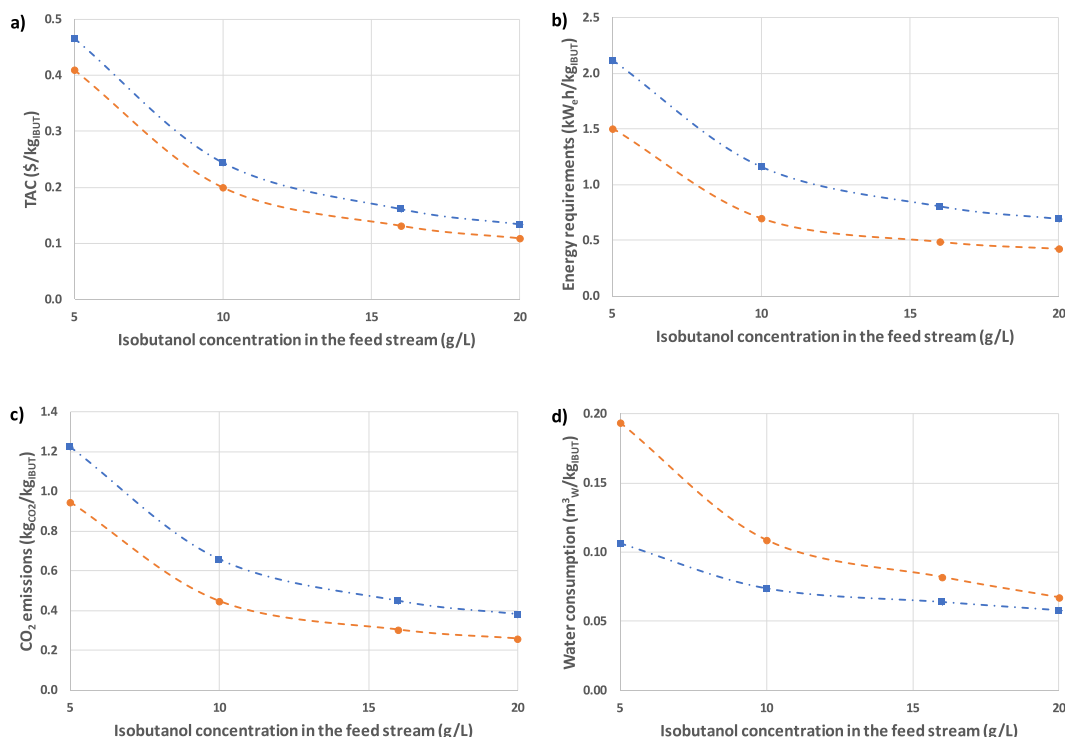


Fig. 6. Sensitivity analysis – the effect of isobutanol concentration in the fermentation broth on: a) total annual costs (TAC), b) energy requirements, c) CO₂ emissions – grey electricity usage, d) water consumption (VD – ■, GS-VE – ●).

CRediT authorship contribution statement

Tamara Janković: Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Software, Validation, Visualization, Writing – original draft, Writing – review & editing. **Adrie J.J. Straathof:** Conceptualization, Formal analysis, Methodology, Project administration, Supervision, Writing – review & editing. **Anton A. Kiss:** Conceptualization, Formal analysis, Investigation, Methodology, Resources, Supervision, Validation, Writing – original draft, Writing – review & editing.

Declaration of competing interest

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

Data availability

Data will be made available on request.

Appendix A. Supplementary data

Supplementary data to this article can be found online at <https://doi.org/10.1016/j.ecmx.2023.100520>.

References

- [1] Fu C, Li Z, Jia C, Zhang W, Zhang Y, Yi C, et al. Recent advances on bio-based isobutanol separation. *Energy Conver Manage: X* 2021;10. <https://doi.org/10.1016/j.ecmx.2020.100059>.
- [2] Demirbas A. Biofuels securing the planet's future energy needs. *Energy Conver Manage* 2009;50:2239–49. <https://doi.org/10.1016/j.enconman.2009.05.010>.
- [3] Vane LM. Separation technologies for the recovery and dehydration of alcohols from fermentation broths. *Biofuels Bioprod Biorefin* 2008;2:553–88. <https://doi.org/10.1002/bbb.108>.
- [4] Baez A, Cho KM, Liao JC. High-flux isobutanol production using engineered *Escherichia coli*: A bioreactor study with in situ product removal. *Appl Microbiol Biotechnol* 2011;90:1681–90. <https://doi.org/10.1007/s00253-011-3173-y>.
- [5] Qureshi N, Saha BC, Cotta MA, Singh V. An economic evaluation of biological conversion of wheat straw to butanol: A biofuel. *Energy Conver Manage* 2013;65:456–62. <https://doi.org/10.1016/j.enconman.2012.09.015>.
- [6] Novak K, Baar J, Freitag P, Pflügl S. Metabolic engineering of *Escherichia coli* W for isobutanol production on chemically defined medium and cheese whey as alternative raw material. *J Ind Microbiol Biotechnol* 2020;47:1117–32. <https://doi.org/10.1007/s10295-020-02319-y>.
- [7] Ofuonye E, Kutin K, Stuart DT. Engineering *Saccharomyces cerevisiae* fermentative pathways for the production of isobutanol. *Biofuels* 2013;4:185–201. <https://doi.org/10.4155/bfs.12.85>.
- [8] Kale AV, Krishnasamy A. Effects of variations in fuel properties on a homogeneous charge compression ignited light-duty diesel engine operated with gasoline-isobutanol blends. *Energy Conver Manage* 2022;258:115373. <https://doi.org/10.1016/j.enconman.2022.115373>.
- [9] Asfar KR, Hamed H. Combustion of fuel blends. *Energy Conver Manage* 1998;39(10):1081–93.
- [10] Deniz Altinkurt M, Emre Ozturk Y, Turkan A. Effects of isobutanol fraction in diesel-biodiesel blends on combustion, injection, performance and emission parameters. *Fuel* 2022;330:125554. <https://doi.org/10.1016/j.fuel.2022.125554>.
- [11] Straathof AJJ. Transformation of biomass into commodity chemicals using enzymes or cells. *Chem Rev* 2014;114:1871–908. <https://doi.org/10.1021/cr400309c>.
- [12] Gao X, Zhang T, Wu Y, Yang G, Tan M, Li X, et al. Isobutanol synthesis from syngas on Zn-Cr based catalysts: New insights into the effect of morphology and facet of ZnO nanocrystal. *Fuel* 2018;217:21–30.
- [13] Veibel S, Nielsen JI. On the mechanism of the Guerbet reaction. *Tetrahedron* 1967;23:1723–33. [https://doi.org/10.1016/S0040-4020\(01\)82571-0](https://doi.org/10.1016/S0040-4020(01)82571-0).
- [14] Boecker S, Schulze P, Klant S. Growth-coupled anaerobic production of isobutanol from glucose in minimal medium with *Escherichia coli*. *Biotechnol Biofuels Bioproducts* 2023;16:1–13. <https://doi.org/10.1186/s13068-023-02395-z>.
- [15] Gu P, Li F, Huang Z. Engineering *Escherichia coli* for Isobutanol Production from Xylose or Glucose-Xylose Mixture. *Microorganisms* 2023;11(10):2573.
- [16] Atsumi S, Hanai T, Liao JC. Non-fermentative pathways for synthesis of branched-chain higher alcohols as biofuels. *Nature* 2008;451:86–9. <https://doi.org/10.1038/nature06450>.
- [17] Morita K, Nomura Y, Ishii J, Matsuda F, Kondo A, Shimizu H. Heterologous expression of bacterial phosphoenolpyruvate carboxylase and Entner-Doudoroff pathway in *Saccharomyces cerevisiae* for improvement of isobutanol production. *J Biosci Bioeng* 2017;124:263–70. <https://doi.org/10.1016/j.jbiosc.2017.04.005>.
- [18] Lane S, Zhang Y, Yun EJ, Ziolkowski L, Zhang G, Jin Y-S, et al. Xylose assimilation enhances the production of isobutanol in engineered *Saccharomyces cerevisiae*. *Biotechnol Bioeng* 2020;117(2):372–81.

- [19] Lakshmi NM, Binod P, Sindhu R, Awasthi MK, Pandey A. Microbial engineering for the production of isobutanol: current status and future directions. *Bioengineered* 2021;12:12308–21. <https://doi.org/10.1080/21655979.2021.1978189>.
- [20] McGregor I, Furlong S. Concurrent Alcohol Recovery and Fermentation Using Pass-Through Distillation. *Ind Biotechnol* 2017;13:107–12. <https://doi.org/10.1089/ind.2017.29081.imc>.
- [21] Ryan Chris. an Overview of Gevo's Biobased Isobutanol Production Process Isobutanol Production Process 2023.
- [22] BP. BP and DuPont joint venture, Butamax 2017.
- [23] Kiss AA, Grievink J, Rito-Palomares M. A systems engineering perspective on process integration in industrial biotechnology. *J Chem Technol Biotechnol* 2015; 90:349–55. <https://doi.org/10.1002/jctb.4584>.
- [24] Stephanopoulos G. Challenges in engineering microbes for biofuels production. *Science* 2007;315:801–4. <https://doi.org/10.1126/science.1139612>.
- [25] Oudshoorn A, Van Der Wielen LAM, Straathof AJJ. Assessment of options for selective 1-butanol recovery from aqueous solution. *Ind Eng Chem Res* 2009;48: 7325–36. <https://doi.org/10.1021/ie900537w>.
- [26] Claessens B, De Staercke M, Verstraete E, Baron GV, Cousin-Saint-Remi J, Denayer JFM. Identifying Selective Adsorbents for the Recovery of Renewable Isobutanol. *ACS Sustain Chem Eng* 2020;8:9115–24. <https://doi.org/10.1021/acssuschemeng.0c02316>.
- [27] Omidali M, Raisi A, Aroujalian A. Separation and purification of isobutanol from dilute aqueous solutions by a hybrid hydrophobic/hydrophilic pervaporation process. *Chem Eng Process* 2014;77:22–9. <https://doi.org/10.1016/j.cep.2014.01.002>.
- [28] Fu C, Li Z, Sun Z, Xie S. A review of salting-out effect and sugaring-out effect: driving forces for novel liquid-liquid extraction of biofuels and biochemicals. *Front Chem Sci Eng* 2021;15:854–71. <https://doi.org/10.1007/s11705-020-1980-3>.
- [29] Tao L, Tan ECD, McCormick R, Zhang M, Aden A, He X, et al. Techno-economic analysis and life-cycle assessment of cellulosic isobutanol and comparison with cellulosic ethanol and n-butanol. *Biofuels Bioprod Biorefin* 2014;8(1):30–48.
- [30] Roussos A, Misailidis N, Koulouris A, Zimbardi F, Petrides D. A feasibility study of cellulosic isobutanol production-process simulation and economic analysis. *Processes* 2019;7. <https://doi.org/10.3390/pr7100667>.
- [31] Evanko W.A., Eyal A.M., Glassner D.A., Miao F., Aristidou A.A., Evans K., et al. Recovery of higher alcohols from dilute aqueous solutions. *US* 8,101,808 B2, 2012.
- [32] Lund B. *Renewable Chemicals and Advanced Biofuels Forward-Looking Statements*. 2013.
- [33] Knoche W. Chemical Reactions of CO₂ in Water. *Biophysics and Physiology of Carbon Dioxide, Proceedings. Life Sci* 1980:3–11.
- [34] Sundquist J., Blanch H.W., Wilke C.R. *Vacuum Fermentation in Extractive Bioconversions*. Boca Raton: CRC Press. p. 237–258.
- [35] Cuellar MC, Straathof AJJ. *Improving Fermentation by Product Removal in Intensification of Biobased Processes*. RSC. Green Chem. Royal Society of Chemistry. 2018.
- [36] Taylor F, Kurantz MJ, Goldberg N, Craig Jr JC. Effects of ethanol concentration and stripping temperature on continuous fermentation rate. *Appl Microbiol Biotechnol* 1997;48:311–6. <https://doi.org/10.1007/s002530051055>.
- [37] Daniell J, Köpke M, Simpson S. *Commercial Biomass Syngas Fermentation. Commercial Biomass Syngas Fermentation Energies* 2012;5(12):5372–417.
- [38] Humbird D, Davis R, Tao L, Kinchin C, Hsu D, Aden A, et al. *Process Design and Economics for Biochemical Conversion of Lignocellulosic Biomass to Ethanol*. 2011.
- [39] Schwarz J, Beloff B, Beaver E. *Use Sustainability Metrics to Guide Decision-Making*. *Chem Eng Prog* 2002;98:58–63.
- [40] BP. *Approximate Conversion Factors. Statistical Review of World. Energy* 2021.
- [41] Lieberman NP, Lieberman ET. *Steam Generation in A Working Guide to Process Equipment*. McGrawHill; 2022. p. 261–76.
- [42] Dicks AP, Hent A. *Green Chemistry Metrics, A guide to Determining and Evaluating Process Greenness*. Jiapur: Springer; 2015. 10.1007/978-3-319-10500-0 ISBN.
- [43] Sheldon RA. *Metrics of Green Chemistry and Sustainability: Past, Present, and Future*. *Sustain Chem Eng* 2018;6:32–48. <https://doi.org/10.1021/acssuschemeng.7b03505>.
- [44] Sulzer. *Structured packings* 2023.
- [45] Kiss AA, Infante Ferreira CA. *Mechanically Driven Heat Pumps in Heat Pumps in Chemical Process Industry*. Boca Raton: CRC Press; 2016. p. 189–251.
- [46] Volker E. *How to design and optimise sieve trays*. *WelChem* 2020.
- [47] Kiss AA, editor. *Advanced Distillation Technologies: Design, Control and Applications*. Wiley; 2013. p. 37–65.
- [48] Straathof AJJ, Bampouli A. Potential of commodity chemicals to become bio-based according to maximum yields and petrochemical prices. *Biofuels Bioprod Biorefin* 2017;11:798–810. <https://doi.org/10.1002/bbb.1786>.
- [49] Janković T, Straathof AJJ, Kiss AA. Advanced downstream processing of bioethanol from syngas fermentation. *Sep Purif Technol* 2023;322:124320. <https://doi.org/10.1016/j.seppur.2023.124320>.