Jurnal Teknologi Industri Pertanian 35 (3): 312-323, December 2025
DOI: https://doi.org/10.24961/j.tek.ind.pert.2025.35.3.312
ISSN: 0216-3160 EISSN: 2252-3901

SIMULTANEOUS SACCHARIFICATION AND CO-FERMENTATION (SSCF) FOR BIOETHANOL PRODUCTION FROM BAMBOO SHOOTS: A SYSTEMATIC LITERATURE REVIEW

SAKARIFIKASI DAN KO-FERMENTASI SECARA SIMULTAN (SSCF) UNTUK PRODUKSI BIOETANOL DARI REBUNG BAMBU: TINJAUAN PUSTAKA SISTEMATIS

Nurul Cinthiya Nasution[1)*], Machfud[2)], and Khaswar Syamsu[2,3)]

[1)]Study Program of Agro-Industrial Engineering, Graduate School, IPB University
Dramaga Campus Bogor 16680, Indonesia
[2)]Departement of Agroindustrial Technology, Faculty of Agricultural Engineering and Technology, IPB University
[3)]Research Center for Biotechnology, IPB University. Darmaga Campus Bogor 16680, Indonesia
*E-mail: nurulcinthiyanasution@apps.ipb.ac.id

Paper: Received July 13, 2025; Revised October 22, 2025; Accepted November 25, 2025

ABSTRAK

Meningkatnya permintaan energi global dan menipisnya cadangan bahan bakar fosil telah mempercepat upaya pencarian alternatif bioenergi yang berkelanjutan. Bioetanol diakui secara luas sebagai kandidat yang menjanjikan, tetapi produksinya masih sangat bergantung pada substrat berbasis pangan seperti singkong dan molase, sehingga memunculkan dilema food vs fuel. Oleh karena itu, biomassa lignoselulosa muncul sebagai alternatif yang layak karena ketersediaannya yang melimpah serta sifatnya yang non-pangan. Di antara sumber potensial, rebung bambu merupakan bahan baku strategis yang memiliki kandungan selulosa tinggi (33–45%) dan hemiselulosa (23–30%), disertai dengan fraksi lignin yang sangat rendah (0,89%), sehingga mengurangi kebutuhan pre-treatment yang intensif dari sisi energi maupun biaya. Pertumbuhan rebung bambu yang cepat semakin memperkuat kelayakannya sebagai sumber biomassa terbarukan yang masih kurang dimanfaatkan. Studi ini melakukan systematic literature review untuk menilai potensi rebung bambu sebagai bahan baku produksi bioetanol melalui metode Simultaneous Saccharification and Co-Fermentation (SSCF). Secara khusus, penelitian ini bertujuan untuk: (i) menguraikan tren riset global mengenai SSCF melalui analisis bibliometrik, (ii) mengidentifikasi kesenjangan pengetahuan terkait pemanfaatan rebung bambu, dan (iii) mengusulkan arah penelitian masa depan guna meningkatkan efisiensi SSCF. Analisis bibliometrik menggunakan perangkat lunak VOSviewer, mencakup publikasi tahun 2006 hingga 2025, menunjukkan adanya peningkatan fokus ilmiah terhadap SSCF, terutama yang berkaitan dengan fermentasi, hidrolisis enzimatis, dan pemanfaatan biomassa lignoselulosa. Menariknya, ketiadaan kata kunci "rebung bambu" pada keseluruhan dataset menandakan adanya kesenjangan penelitian yang signifikan. Temuan ini menegaskan perlunya investigasi eksperimental yang lebih mendalam serta pengembangan model simulasi prediktif dalam pemanfaatan rebung bambu pada SSCF, dengan tujuan mengoptimalkan hasil etanol, memperjelas dinamika proses, dan mendorong pengembangan bioetanol berkelanjutan.

Kata kunci : bioethanol, rebung, simulasi, simultaneous saccharification and co-fermentation (SSCF

ABSTRACT

The escalating global energy demand and the depletion of fossil fuel reserves have accelerated the pursuit of sustainable bioenergy alternatives. Bioethanol is widely recognized as a promising candidate; however, its production continues to depend predominantly on food-based substrates such as cassava and molasses, thereby exacerbating food vs fuel dilemmas. Consequently, lignocellulosic biomass has emerged as a viable alternative owing to its abundance and non-food nature. Among potential resources, bamboo shoots constitute a particularly strategic feedstock, characterized by high cellulose (33–45%) and hemicellulose (23–30%) contents, coupled with an exceptionally low lignin fraction (0.89%), which minimizes the requirement for energy- and cost-intensive pretreatment. Their rapid growth further reinforces their suitability as a renewable and underexploited biomass source. The present study undertakes a systematic literature review to assess the potential of bamboo shoots for bioethanol production via Simultaneous Saccharification and Co-Fermentation (SSCF). Specifically, it seeks to: (i) elucidate global research trends in SSCF through bibliometric analysis, (ii) identify knowledge gaps concerning the utilization of bamboo shoots, and (iii) propose future research directions to enhance SSCF efficiency. Bibliometric analysis conducted with VOSviewer, encompassing publications from 2006 to 2025, reveals growing scholarly focus on SSCF, particularly in relation to fermentation, enzymatic hydrolysis, and lignocellulosic feedstocks. Notably, the complete absence of "bamboo shoot" as a keyword across the dataset signifies a critical research gap. This gap underscores the necessity for rigorous experimental investigations and the development of predictive simulation models employing bamboo shoots in SSCF, with the aim of optimizing ethanol yields, elucidating key process dynamics, and advancing sustainable bioethanol production.

Keywords: bamboo shoot, bioethanol, simulation, simultaneous saccharification and co-fermentation (SSCF)

Coressponding Author

INTRODUCTION

Energy is a fundamental necessity for human civilization, with global demand continuing to rise. According to the 2023 International Energy Agency (IEA) report, global energy consumption is projected to keep increasing beyond 2030. However, reliance on fossil fuels remains excessively high, making it challenging to achieve the commitments set in the 2015 Paris Agreement, which aims to limit global temperature rise to 1.5°C above pre-industrial levels (IEA, 2023). Human activities that rely on conventional energy sources have significantly contributed to global climate change, leading to rising temperatures, extreme weather conditions, and ecosystem disruptions (Irma and Gusmira, 2024).

Many countries are therefore accelerating the transition toward renewable energy. The European Union, United States, China, India, and Brazil have implemented large-scale biofuel programs to reduce dependence on fossil fuels while ensuring energy security (Iglinski *et al.,* 2024). Bioethanol, in particular, is one of the most widely adopted biofuels globally because it can be blended with gasoline, lowering greenhouse gas emissions and improving air quality. Bioethanol is an ethanol-based biofuel derived from biomass containing fermentable sugars, starch, or cellulose, commonly sourced from feed stocks such as cassava and sugarcane molasses (Hendrawati *et al.,* 2018). Other common feed stocks include corn and sorghum (Khabibulloh *et al.,* 2024). However, first-generation bioethanol, which relies on food-based feedstocks such as corn, sugarcane, and cassava, has triggered the well-known food vs. fuel debate, creating concerns about food security and land-use competition. This makes the exploration of non-food lingo cellulosic feed stocks critical not only for Indonesia but also for many other countries seeking sustainable pathways for bioethanol production.

Indonesia, with its vast biodiversity and abundant biomass resources, holds strong potential for lingo cellulosic bioethanol production. Similar to other biomass-rich nations such as Brazil, India, and China, Indonesia faces the dual challenge of reducing carbon emissions while diversifying its energy sources. According to the Ministry of Transportation (Kementerian Perhubungan, 2024), the country emitted approximately 1.3 gigatons of CO_2 in 2022, with 50.6% of these emissions originating from the energy sector. More than 80% of the sector's emissions come from transportation, primarily due to fossil fuel dependence (Mingshen *et al.,* 2022). The government has therefore set ambitious targets of achieving a 23% renewable energy share by 2025, which requires investment and innovation in sustainable fuels (Kementerian ESDM, 2024).

One promising lingo cellulosic feedstock is bamboo shoots, which are abundant, fast-growing, and rich in carbohydrates with relatively low lignin content (Ramadhani *et al.,* 2024). Compared to conventional feed stocks, bamboo shoots contain higher proportions of cellulose and hemicellulose, making them suitable for bioethanol production. Their lingo cellulosic structure can be efficiently processed using Simultaneous Saccharification and Co-Fermentation (SSCF), a technique that integrates enzymatic hydrolysis and fermentation in a single step, improving ethanol yield and reducing operational costs. While SSCF has been studied for other lingo cellulosic materials, its application to bamboo shoots remains underexplored and could provide broader insights for sustainable bioethanol production globally.

Accordingly, this study aims to review existing research on SSCF for lingo cellulosic biomass with an emphasis on its applicability to bamboo shoots, to identify and analyze critical parameters influencing ethanol yield such as fungi, yeast, glucose, and xylose dynamics, and to conduct a bibliometric analysis using VOS viewer to evaluate global research trends, highlight research gaps, and provide recommendations for future directions. The findings are expected to not only support Indonesia's renewable energy roadmap but also contribute insights that are relevant to other countries pursuing sustainable and non-food-based bioethanol development.

MATERIAL AND METHODS

This study employed a two-step approach consisting of a systematic literature review and bibliometric analysis. The systematic review was conducted to collect, screen, and synthesize relevant studies, while bibliometric analysis was applied to visualize research patterns and trends. First, a systematic search was carried out in the Scopus database, which is recognized for its comprehensive indexing of peer-reviewed publications. The search strategy used the following query: "Bioethanol" AND "Simultaneous AND Saccharification AND Co-Fermentation" OR "Bamboo AND Shoot". The search was limited to publications from 2006 to 2025 to capture both the foundational and most recent developments in the field. The retrieved records were screened in several stages. Titles and abstracts were examined to exclude irrelevant studies, while duplicates and non-English articles were removed. The inclusion criteria were: (i) studies focusing on bioethanol production, particularly through SSCF, (ii) articles that discuss lingo cellulosic feed stocks, and (iii) publications that provide experimental results, reviews, or modelling relevant to the topic. After screening, the final dataset consisted of both empirical and review papers directly addressing SSCF for lingo cellulosic bioethanol production, with a particular focus on bamboo shoots as an emerging feedstock.

Second, the bibliometric method was applied to map research trends and thematic clusters. VOS viewer software was used exclusively for keyword co-occurrence analysis, enabling the identification of research hotspots, emerging themes, and potential gaps. VO Sviewer is particularly effective in constructing and presenting text-based visual maps, which makes it a powerful tool for uncovering topic structures within a given field (Xu *et al.,* 2020). Figure 1 presents a simplified flowchart describing the implementation of VO Sviewer for this study (Bukar *et al.,* 2023).

The metadata extracted from Scopus, including article titles, authors, affiliations, keywords, and publication years, was exported in CSV format and processed with VOSviewer. The software generated three types of visualization network, overlay, and density, that were used to examine the evolution of SSCF research, identify thematic clusters, and highlight underexplored areas. By combining systematic literature review with bibliometric analysis, this study not only identifies global research trends but also provides in-depth insights into the technological challenges, opportunities, and research gaps in SSCF-based bioethanol production from lignocellulosic biomass. This dual approach strengthens the validity of the findings and ensures a comprehensive overview of the field.

RESULT AND DISCUSSION

Justification of Using Bamboo Shoots as a Bioethanol Feedstock

Bioethanol is an organic biofuel that has been widely recognized and utilized as an alternative energy source to reduce dependence on fossil fuels (Garcia *et al.,* 2018). It is considered one of the most promising biofuels due to its environmentally friendly characteristics and its potential to lower greenhouse gas emissions (Tse *et al.,* 2021). The process of producing bioethanol involves several unit operations aimed at obtaining high-purity ethanol from lignocellulosic biomass. This type of biomass, which serves as a renewable raw material, plays a significant role in promoting environmental sustainability. It can be derived from agricultural residues, which are typically inexpensive and readily available, and it primarily consists of cellulose, hemicellulose, and lignin. According to Sembada (2022), the demand for bioethanol can be met by utilizing biomass that contains cellulose and hemicellulose. Tan *et al.,* (2008) further stated that bioethanol is an environmentally friendly alternative fuel that can be used as a substitute for gasoline. Its key advantages include affordability, low environmental impact, and compatibility with existing gasoline-powered engines. Moreover, bioethanol is a clean fuel that does not contribute to carbon dioxide accumulation in the atmosphere.

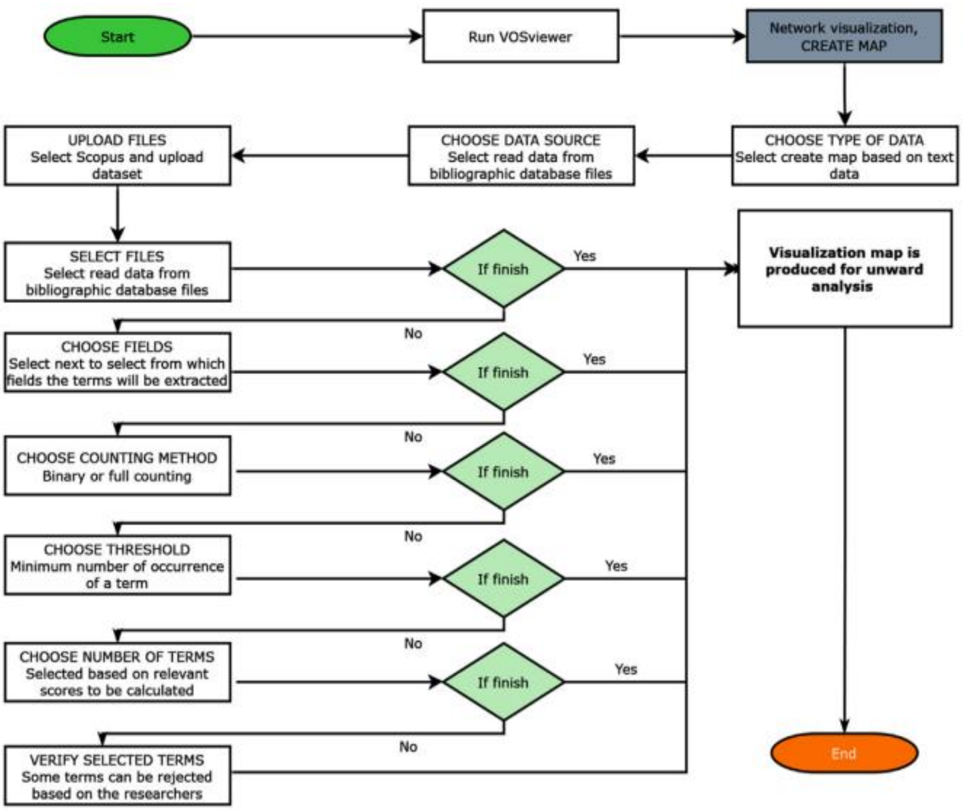

Figure 1. Seamless execution of VOS viewer for text analysis with dataset (Bukar *et al.,* 2023)

Second-generation bioethanol, which is produced from lignocellulosic materials, includes waste products from agriculture and forestry. Lignocellulosic biomass has a complex three-dimensional structure composed of cellulose, hemicellulose, and lignin (Faizal *et al.,* 2021). Its widespread availability makes it a highly potential energy source through conversion processes involving physical, chemical, or biological methods. Among these, the conversion of lignocellulose into bioethanol has been extensively studied for its potential to replace gasoline in transportation applications (Houfani *et al.,* 2020). One of the main advantages of producing bioethanol from lignocellulosic biomass is that it uses non-edible feedstock, thereby avoiding competition with the food industry (Broda *et al.,* 2022; Mutjaba *et al.,* 2023). However, the use of lignocellulosic biomass is associated with higher production costs, primarily due to the need for pretreatment steps, which may include enzymatic hydrolysis before fermentation. Additionally, the entire process of converting lignocellulosic biomass into bioethanol requires careful attention to environmental impact, energy consumption, and operational maintenance. These factors are evaluated through a life cycle assessment, which provides a comprehensive view of the sustainability of second-generation bioethanol production (Aron *et al.,* 2020).

Bioethanol is a form of ethanol (alcohol) produced through microbial fermentation of plant- or algae-based carbohydrates, including those found in corn, sugarcane, wheat, and lignocellulosic biomass. While many lignocellulosic feedstocks such as rice straw, sugarcane bagasse, corn stover, and mature bamboo have been extensively used in bioethanol production, bamboo shoots offer unique advantages that position them as a promising and underexplored alternative raw material.

The chemical composition of various lignocellulosic feedstocks can significantly influence their efficiency and cost-effectiveness in the conversion process. Table 1 compares the hemicellulose, cellulose, and lignin content across different feedstocks commonly used in bioethanol production. For example, rice straw contains 19–27% hemicellulose, 32–47% cellulose, and 5–24% lignin (Belal, 2013), whereas bamboo shoots contain 23–30% hemicellulose, 33–45% cellulose, and only 0.89% lignin (Ramdhani *et al.,* 2024), making them attractive due to their low lignin content and sufficient cellulose levels.

Cellulose is a linear polymer composed of over 1,000 glucose subunits linked by β-1,4-glycosidic bonds. It is a carbon-rich compound, and the carbon content can be utilized in microbial fermentation processes (Roni, 2015). In fibrous material processing, cellulose serves as the dominant polymer (Lestari *et al.,* 2017). According to Muryanto *et al.* (2016), high cellulose content in a feedstock can be converted into energy in the form of liquid biofuels such as bioethanol. As shown in Table 1, bamboo, corn stover, and bamboo shoots have among the highest cellulose contents, suggesting their strong potential as bioethanol feedstocks.

Hemicelluloses are a diverse group of polymers that generally constitute 15–35% of plant biomass. They may include pentose sugars (such as β-D-xylose and α-L-arabinose), hexose sugars (such as β-D-mannose, β-D-glucose, and α-D-galactose), and uronic acids (such as α-D-glucuronic, α-D-4-O-methylgalacturonic, and α-D-galacturonic acids). Among these, xylans and glucomannans are the most relevant, with xylans being the most abundant hemicellulose components in the secondary cell walls of hardwoods and herbaceous plants. In some parts of grasses and cereals, xylans can represent up to 50% of the biomass (Girio *et al.,* 2010). Nabil *et al.,* (2024) emphasized that both hemicellulose and cellulose are rich in fermentable sugars and are thus highly valuable for biofuel production. This is further supported by Caroline *et al.,* (2023), who noted that high levels of cellulose and hemicellulose can be effectively converted into ethanol and xylitol, respectively. Based on Table 1, feedstocks with high hemicellulose and cellulose content include sugarcane bagasse, corn stover, bamboo, and bamboo shoots. In addition to cellulose and hemicellulose, lignin content is an important factor to consider when selecting feedstocks for bioethanol production. Lignin forms a strong and rigid structure in plant cell walls, which can hinder the bioconversion of cellulose into ethanol. It is the most robust component in biomass and is highly resistant to biological, enzymatic, and chemical degradation (Roni, 2015). Therefore, feedstocks with low lignin content, such as bamboo shoots, are more favorable for bioethanol production due to their easier digestibility and improved conversion efficiency. Bamboo shoots are known to have significantly lower lignin content compared to other lignocellulosic biomass. While mature bamboo contains around 20–30% lignin, bamboo shoots typically have only 0.89 lignin (Ramdhani *et al.,* 2024)

Table 1. Comparative analysis of key chemical components among different feedstocks

Feedstock	Hemicellulose (%)	Cellulose (%)	Lignin (%)	References
Rice straw	19-27	32-47	5-24	Belal, 2013
Sugarcane Bagasse	25-35	32-44	14-20	Nasution *et al.,* 2022
Corn Stover	20-30	35-45	15-20	Zhao *et al.,* 2018
Bamboo	20-25	40-50	20-30	Hossain *et al.,* 2024
Bamboo Shoots	23-30	33-45	0.89	Ramdhani *et al.,* 2024

This characteristic reduces or even eliminates the need for a delignification step, which is often required to break down the lignin barrier that impedes enzymatic hydrolysis. Consequently, this simplification leads to faster processing times, lower chemical usage, and reduced environmental pollution resulting from delignification waste.

The high productivity and rapid regrowth of bamboo shoots offer an abundant and sustainable biomass source. An export demand of merely 1% globally would require approximately 1,125 hectares of bamboo plantations, a feasible target for Indonesia due to its suitable climatic and soil conditions. Currently, most bamboo cultivation in Indonesia is still performed through traditional intercropping systems, which contributes to relatively low productivity. However, with improved cultivation techniques, Indonesia could potentially match or even exceed the productivity levels of leading producers such as China and India (Widiarti *et al.,* 2013). Bamboo shoots in particular are capable of growing up to 60 cm in just 2 weeks (Shimokawa *et al.,* 2009), ensuring a steady and renewable supply of biomass.

This rapid turnover supports year-round biomass availability and offers a cost-effective supply chain, especially in bamboo-rich regions such as Indonesia, which hosts more than 170 bamboo species, with nearly 50% being endemic. Despite these advantages, bamboo shoots remain underutilized in Indonesia. Their use is mostly limited to food consumption, and the idea of using them as a source of renewable energy such as bioethanol is not yet widely known. Promoting bamboo shoots as a bioethanol feedstock would not only contribute to energy diversification but also improve the livelihoods of rural farmers. Since bamboo shoots are not a staple food or a major starch source in Indonesia or globally, their utilization for bioethanol production is unlikely to trigger food-versus-fuel conflicts now or in the future. These factors collectively support the feasibility and strategic importance of using bamboo shoots as an alternative bioethanol feedstock, combining rapid biomass regeneration, minimal food competition, economic potential, and alignment with Indonesia's agroecological conditions.

The chemical composition of bamboo shoots shows a balanced proportion of cellulose (33–45%) and hemicellulose (23–30%), making them particularly suitable for Simultaneous Saccharification and Co-Fermentation (SSCF) processes. SSCF is a single-reactor fermentation process that eliminates the need for separate hydrolysis and fermentation steps, thereby reducing overall production costs and minimizing feedback inhibition (Ojeda *et al.,* 2011). This method enables the simultaneous utilization of glucose and xylose through the application of specialized microorganisms, such as the fungi *Trichoderma cerevisiae* and yeasts *Saccharomyces cerevisiae* and *Scheffersomyces stipitis* (Naggar *et al.,* 2014). Several studies have reported that SSCF lowers capital costs while achieving higher ethanol yields and productivity compared to separate hydrolysis and fermentation processes (Koppram *et al.,* 2013). The flexibility of SSCF makes it a promising approach for bioethanol production from lignocellulosic biomass, particularly at an industrial scale.

A previous study by Ramadhani *et al.,* (2024) reported that SSCF (Simultaneous Saccharification and Co-Fermentation) could be conducted without a pretreatment step, as it simultaneously utilizes two carbon sources, cellulose and hemicellulose. The co-culture approach in SSCF enhances bioethanol yield by utilizing both cellulose and hemicellulose as carbon sources and employing a microbial consortium for efficient fermentation. Furthermore, according to Jacqueline and Velvizhi (2024), a high xylose-to-glucose ratio can be maintained throughout the process because of the rapid consumption of glucose. This enhances xylose fermentation by reducing competitive inhibition by glucose on sugar uptake. As a result, Simultaneous Saccharification and Co-Fermentation offers favorable conditions for efficient bioethanol stripping.

To enhance process efficiency, researchers have explored SSCF as an alternative. SSCF eliminates the need for pretreatment by utilizing bamboo shoots with lower lignin content, thereby reducing processing time, labor, and costs. Unlike SSF, which primarily uses cellulose as a carbon source, SSCF simultaneously hydrolyzes cellulose and hemicellulose, enabling the co-fermentation of both glucose and xylose into ethanol. This results in higher ethanol yields, shorter processing times, and lower contamination risks. Syamsu *et al.* (2020) reported that SSF using *Trichoderma reesei* for hydrolysis and *Saccharomyces cerevisiae* as a monoculture fermenting microorganism yielded only 6.6 g/L ethanol. In contrast, Suriyachai *et al.,* (2013) achieved a significantly higher ethanol concentration of 15.9 g/L using SSCF with a *S. cerevisiae* and *P. stipitis* co-culture, compared to just 12.1 g/L for SSF. Furthermore, a study conducted by Ghazali and Mustafa (2025) formulated a table summarizing various strategies of bioconversion processes for bioethanol production, which is presented in Table 2.

Simultaneous Saccharification and Fermentation (SSCF) is frequently applied in bioethanol production from lignocellulosic biomass because it avoids end-product inhibition, minimizes enzyme requirements, shortens processing durations, and lowers operational costs. High ethanol concentrations can be achieved using this method, particularly with high solid loadings (Huang *et al.,* 2022). However, in many cases, the liquid hydrolysate resulting from pretreatment is not utilized because it contains numerous inhibitors derived from lignocellulosic biomass. Xylose, which is a major sugar component of the hydrolysate, is often not used either.

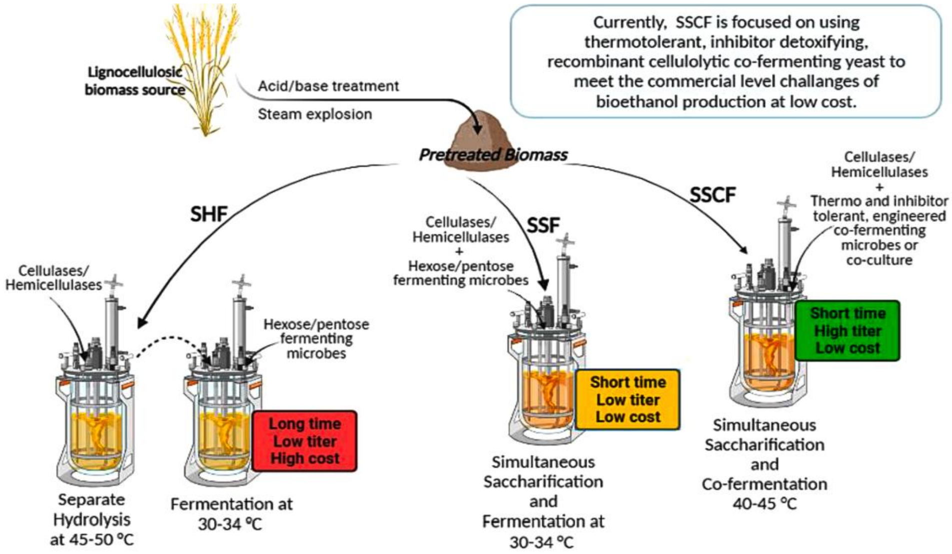

Figure 2. Process flow of SHF, SSF, and SSCF (Sharma *et al.,* 2021)

Table 2. Strategies of the bioconversion process for bioethanol production

Strategies	**Process Involved**	**Advantages**	**Disadvantages**	**Maximum Ethanol Yield (g/L)**	**References**
Separate Hydrolysis and Fermentation (SHF)	Enzymatic hydrolysis and fermentation are conducted sequentially	Requires fewer cellulolytic enzymes compared to Simultaneous Saccharification and Fermentation. Lower risk of contamination because the saccharified solution containing fermentable sugars can be sterilized	Accumulation of glucose and cellobiose can cause partial inhibition and affect the conversion of biomass into glucose	44.7	Istrate *et al.,* 2023; Alhadeff *et al.,* 2019; Istrate *et al.,* 2021; Alvarado *et al.,* 2021.
Simultaneous Saccharification and Fermentation (SSF)	Enzymatic hydrolysis and fermentation are conducted simultaneously in the same vessel	Minimizes feedstock inhibition and production costs. Enables immediate sugar utilization, reduces processing time, and improves productivity. Can produce higher ethanol concentrations than Separate Hydrolysis and Fermentation	The optimal temperature for enzymatic hydrolysis is higher than that for fermentation, requiring a careful balance to ensure efficient operation	77	Thorman 2020; Jeong *et al.,* 2023; Li *et al.,* 2024.
Simultaneous Saccharification and Co-Fermentation (SSCF)	Concurrent enzymatic hydrolysis and co-fermentation of glucose and xylose in a single reactor	Lower production cost. Constantly mitigates end-product inhibition, thereby maintaining enzymatic activity. Shorter processing time, high productivity, and reduced contamination risks	Temperature poses a challenge, as saccharification occurs optimally at 50°C while fermentation is optimal between 30–37°C	68.7	Brasil *et al.,* 2020; Sha *et al.,* 2022; Albaseer and Doren 2022.

Therefore, the SSCF process, which utilizes both glucose and xylose, is essential for improving economic viability. Nevertheless, inhibitors present in the hydrolysate derived from lignocellulosic biomass continue to pose obstacles to the successful implementation of this method (Zhang *et al.,* 2024).

In conclusion, although SHF allows for the independent optimization of hydrolysis and fermentation conditions, it is prone to enzymatic inhibition and contamination. Simultaneous Saccharification and Fermentation (SSF) addresses some of these challenges but remains limited in its utilization of hemicellulose. Simultaneous Saccharification and Co-Fermentation (SSCF) emerges as the most effective and promising method, as it maximizes the use of carbon sources, enhances ethanol yield, and increases overall process efficiency. Considering these advantages, Simultaneous Saccharification and Co-Fermentation is regarded as the most appropriate strategy for optimizing bioethanol production from lignocellulosic feedstocks such as bamboo shoots.

Future Research Directions Based on Bibliometric Analysis

Future research recommendations were formulated through bibliometric analysis using VOSviewer software. This analysis utilized co-occurrence mapping by examining the keywords found in each study to identify frequently appearing terms, highlighting key research trends and gaps. According to Prasetyani *et al.,* (2024), VOSviewer generated a color-coded visualization, where dark blue nodes indicate topics that have been extensively researched. Green nodes represent topics that have been explored by a moderate number of researchers. Meanwhile, yellow nodes suggest research areas that remain relatively underexplored. The visualization of keyword occurrences was generated with a minimum occurrence threshold of 5, resulting in a total of 136 keywords. Among these, "bioethanol" was the most frequently used keyword, appearing 120 times. As shown in Figure 3, the larger the circle, the more frequently the keyword appears in research related to bioethanol production and lignocellulosic biomass conversion.

The identified keywords were classified into four distinct clusters, each represented by a different color. Cluster 1 (Red) includes the main keywords "simultaneous saccharification", "bioethanol production", and "enzymatic hydrolysis", which are strongly related to enzymatic breakdown and sugar conversion processes in bioethanol production. Cluster 2 (Green) contains the keywords "bioethanol", "ethanol", and "fermentation", which are linked to microbial fermentation processes, particularly yeast metabolism and ethanol yield optimization. Cluster 3 (Blue) is characterized by keywords such as "yeast", "hydrolysis", and "article", indicating a strong connection to studies on microbial selection, enzymatic efficiency, and fermentation kinetics. Lastly, Cluster 4 (Yellow) consists of "enzymatic hydrolysis", "bioethanol", and "enzymolysis", which focus on enzyme-assisted biomass breakdown and its role in improving bioethanol production efficiency. Beyond describing clusters, these bibliometric results provide insight into how research in this field has evolved. The dominance of clusters related to enzymatic hydrolysis and fermentation reflects the centrality of microbial and enzymatic pathways in bioethanol production.

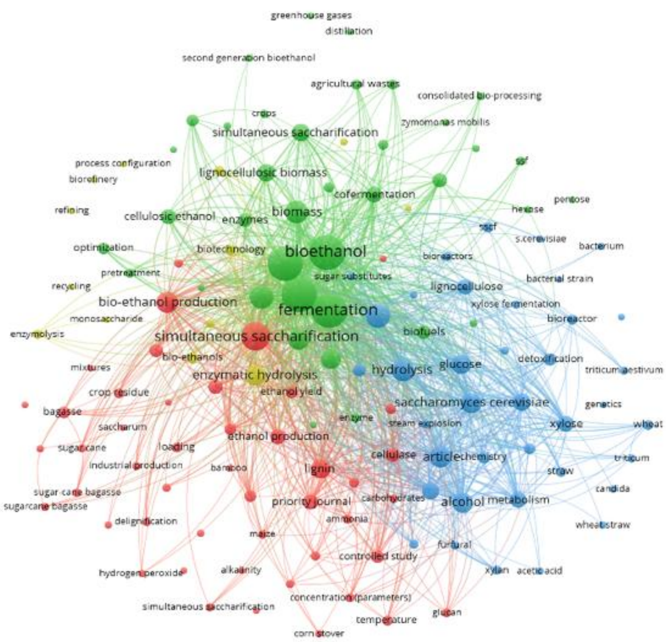

Figure 3. Research themes network visualizaiton

However, the limited presence of keywords related to feedstock innovation highlights a knowledge gap. For example, while terms such as “simultaneous saccharification,” “co-fermentation,” and “xylose” repeatedly appear, the keyword “bamboo shoot” is completely absent. This absence demonstrates that bamboo shoots as a feedstock for bioethanol remain underexplored, despite their favorable chemical composition described earlier in this paper. Furthermore, Figure 4 illustrates the frequency of keyword usage by year, showing that after 2018, research emphasis shifted toward SSCF processes and xylose utilization, underscoring the growing importance of maximizing both glucose and pentose sugar fermentation. This aligns directly with the objectives of this study, which seek to analyze SSCF as a cost-effective and efficient strategy for bioethanol production. Meanwhile, the density visualization (Figure 5) reinforces that although SSCF and lignocellulosic bioethanol are trending topics, their specific integration with bamboo-based feedstocks remains largely unaddressed.

The absence of the keyword “bamboo shoot” in the VOSviewer analysis suggests that the use of bamboo shoots as a raw material for bioethanol production remains relatively unexplored. While topics such as bioethanol production and Simultaneous Saccharification and Co-Fermentation (SSCF) have been extensively researched, their specific application to bamboo shoots has not received significant attention in the existing literature.

To validate this observation, an additional bibliometric screening was carried out using the Scopus database. This screening identified a total of 146 documents published between 2006 and 2025, retrieved using the query: “Bioethanol” AND “Simultaneous AND Saccharification AND Co-Fermentation” OR “Bamboo AND Shoot.” Interestingly, the keyword “bamboo shoot” was absent from all selected documents, reinforcing the notion that its potential as a feedstock for bioethanol is largely underexplored. This finding reveals a clear research gap and underscores a promising opportunity for future studies. The frequent appearance of keywords such as “bioethanol,” “simultaneous saccharification,” “co-fermentation,” and “xylose” indicates that most prior research has focused on general lignocellulosic biomass, without specifically addressing bamboo shoots.

By linking these bibliometric findings with the objectives of this review, it becomes evident that the main research frontier lies not only in refining SSCF processes but also in expanding their application to novel, non-food biomass such as bamboo shoots. This provides two clear conclusions: (1) SSCF is validated as a globally relevant strategy in bioethanol research, and (2) bamboo shoots represent a significant opportunity to extend current knowledge and address energy diversification in Indonesia while contributing to global renewable energy goals.

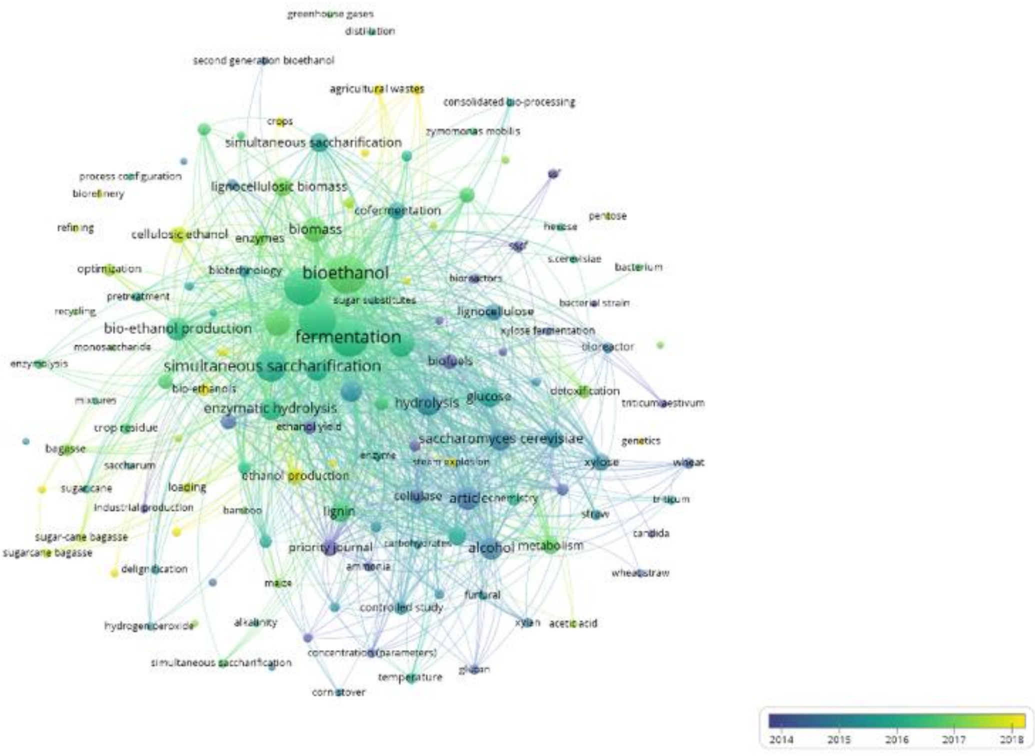

Figure 4. Overlay visualization and its relation to the year of publication

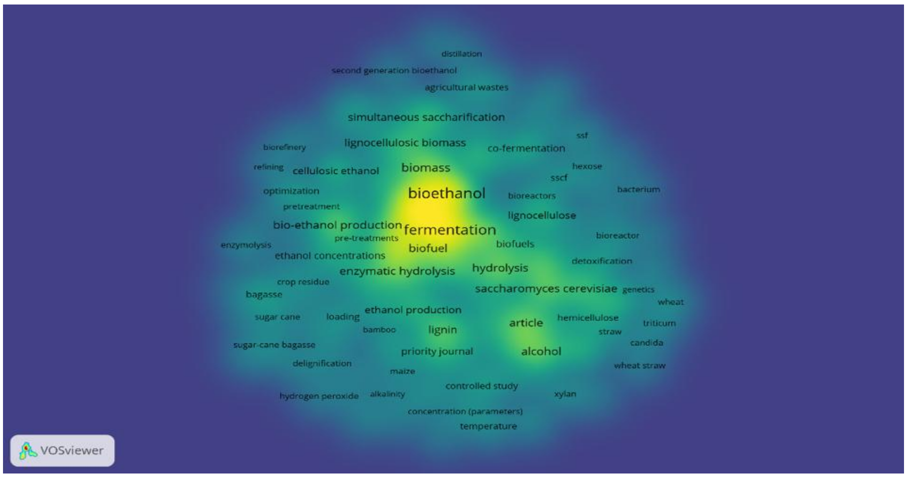

Figure 5. Research density visualization

CONCLUSIONS AND RECOMMENDATIONS

Conclusions

This review aimed to systematically map global research trends on Simultaneous Saccharification and Co-Fermentation (SSCF), assess the extent to which bamboo shoots have been investigated as a potential lignocellulosic feedstock, and identify critical research gaps. The bibliometric analysis of publications between 2006 and 2025 indicates a consistent growth of scholarly interest in SSCF, with distinct clusters centered on enzymatic hydrolysis, microbial fermentation, and lignocellulosic biomass conversion. Beyond describing these clusters, the visualization provides interpretive insights into how research trajectories have evolved, revealing both areas of consolidation and neglected domains.

The absence of "bamboo shoot" as a recognized keyword within the bibliometric mapping confirms that this feedstock remains largely underrepresented in the global SSCF discourse. This finding directly addresses the study's objectives by demonstrating the maturity of SSCF research in relation to conventional substrates while simultaneously underscoring the critical gap concerning bamboo shoots and associated process parameters. Accordingly, the results highlight the necessity of advancing from bibliometric evidence to empirical validation, particularly through experimental research, process modeling, and sustainability assessments. By establishing this knowledge gap and outlining future directions, this review contributes to positioning bamboo shoots as a novel feedstock within the broader global agenda of sustainable bioethanol development, while also contextualizing Indonesia's potential contribution to energy transition and bioeconomy frameworks.

Recommendations

Building upon the identified research gap, future studies should prioritize rigorous experimental investigations to validate the feasibility of bamboo shoots as a feedstock for bioethanol production via SSCF. This entails optimization of pretreatment methods, enzymatic hydrolysis conditions, and fermentation strategies, including the use of native and genetically engineered microorganisms capable of co-fermenting glucose and xylose with high efficiency. Equally important is the systematic identification and quantification of critical process parameters such as sugar conversion kinetics, enzyme dosage, inhibitor formation, and ethanol yield to ensure that insights derived from bibliometric mapping are translated into practical and scalable outcomes. Complementary to laboratory investigations, the development of mathematical models and simulation frameworks is recommended to enable predictive optimization and sensitivity analysis of SSCF systems. Furthermore, comprehensive techno-economic and life cycle assessments are essential to ascertain the industrial feasibility and environmental sustainability of bamboo shoot–based bioethanol. In parallel, integration into local agro-industrial value chains, particularly in bamboo-abundant regions, could support circular economy practices and enhance regional energy resilience. Finally, continuous bibliometric surveillance should be employed not only as a monitoring tool for keyword frequency but as an interpretive framework for understanding the evolution of global research directions, thereby ensuring that contributions from Indonesia and other emerging economies are both timely and globally relevant.

REFERENCES

Albasser SS and Doren L. 2022. A novel, rapid and sensitive HPLC method for the determination of ethanol in non alcohol beverages with pre-column derivatization and simultaneous UV and flourescence detection. *Research Square*. 293.

Alhadeff EM, Bosco AJT, Pastusiak CF, Coreeia TA, Ramirez NIB. Development of an ethanol biosensor based on silver nanoparticles/polyniline/graphite/epoxy composite for friendly analytical application. *Biosensors for Environmental monitoring.* 121.

Alvarado RL, Rostro AM, Rodriguez RJ, Sosa HJE, Melchor MEM, Iqbal HM. 2021. Enzyme (single and multiple) and nanozyme biosensors: recent developments and their novel applications in the water of food health nexus. *Biosensors*. 11(11): 410.

Aron MNS, Khoo KS, Chew KW, Show PL, Chen W, Nguyen THP. 2020. Sustainability of the four generations of biofuels – a review. *International Journal of Energy Research*. 44: 9266-9282.

Belal EB. 2013. Bioethanol production from rice straw residues. *Brazilian Journal Microbiology.* 44(1): 225-234.

Brasil MA, Gomes LH, Kamogawa MY, Basso LC. 2020. Ethanol determination in fermented sugarcane substrates by a diffusive micro-distillation device. *Journal of Microbiological Methods*. 178: 106085.

Broda M, Yelle DJ, and Serwanska K. 2022. Bioethanol production from lignocellulosic biomass – challenges and solutions. *Moleculs*. 27: 8717.

Bukar UA Sayeed MS, Razak SFA, Yogarayan S, Amodu OA, Mahmood RAR. 2023. A method for analyzing text using VOSviewer. *MethodsX*. 11: 1-9.

Caroline V, Mardawati E, Mahardika M, Fitriana HN. 2023. Hidrolisis enzimatik dua tahap dalam produksi bioetanol dan xilitol berbasis tandan kosong kelapa sawit sebagai strategi penerapan biorefineri yang terintegrasi. *Biomass, Biorefinery, and Bioeconomy*. 1(1): 1-8.

Faizal A, Sembada AA, and Priharto N. 2021. Production of bioethanol from four species of duckweeds (*Landolita punctata, Lemna aequionctialis, Spirodela polyrrhiza, and Wolffia arrhiza*) through optimization of saccharification process and fermentation with *Saccharomyces cerevisiae*. *Saudi Journal of Biological Sciences*. 28(1): 294-301.

Garcia JCG, Correaa DM, Guerraa JCC, Rodriguezb RM. 2018. Exergy analysis of an extractive distillation column for reducing energy consumption in a bioethanol production process. *Proceedings of the 28th European Symposium on Computer Aided Process Engineering*. 513-518. doi.org/10.1016/B978-0-444-64235-6.50091-7.

Ghazali MFSM andMustafa M. 2025. Bioethanol as an alternative fuels: A review on production strategies and technique for analysis. *Energy Conversion and Management*. 26: 100933.

Girio FM, Fonseca C, Carvalheiro, Duarte LC, Marques S, Lukasik RB. 2010. Hemicelluloses for fuel ethanol: a review. *Bioresource Technology*. 101. 4775-4800.

Hossain MJ, Ghosh RK, Das AK, Maryana RC, Sudiyani YC, Nath SC. 2024. Chemical composition and solubility properties of bambusa bambos at different ages and height positions. *Advances in Bamboo Science*. 6: 1-5.

Houfani AA, Anders N, Spiess AC, Baldrian P, Benallaoua S. 2020. Insights from enzymatic degradation of cellulose and hemicellulose to fermentable sugars-a review. *Biomass and Bioenergy*. 134. 105481.

Huang XY, Fan MS, Xie J, Zhong CM, Zhang HD. 2022. High titer ethanol production from poplar by alumunium chloride catalyzed organosolv pretreatment and simultaneous saccharifiication and fermentation. *Industrial Crops and Products*. 181: 1148803.

Iglinski B, Kielkowska U, Mazurek K, Druzynski S, Pietrzak MB, Kumar G, Veeramuthu A, Skrzatek M, Zinecker M, Piechota G. 2024. Renewable energy transition in Europe in the context of renewable energy transition processes in the world: A review. *Heliyon Journal.* 10: 1-25. doi.org/10.1016/j.heliyon.2024.e40997.

Irma MF and Gusmira E. 2024. Tingginya kenaikan suhu akibat peningkatan emisi gas rumah kaca di Indonesia. *Jurnal Sains dan Sains Terapan*. 2(1): 26-32.

Istarte OM, Bala C, and Rotariu L. 2023. A new highly sensitive electrochemical biosensor for ethanol detection based on gold nanoparticles/reduced graphene oxide/polyallylamine hydrochloride nanocomposite. *Biosensors*. 13(11): 954.

Istarte OM, Rotariu L, and Bala C. 2021. A novel amperometric biosensor based on poly (allyalmine hydrocholide) for determination of ethanol in beverages. *Sensors*. 21(9): 6510.

Jeong S, Hajba L, Guttman A, Seol J, Chung DS. 2023. In-line microextraxtion techniques to improve the sensitivity and selectivity of capillary electrophoresis using commercial instruments. *Trends in Analytical Chemistry*. 163: 11705

Khabibulloh MJM, Suhartatik N, and Mustofa A. 2024. Masa depan dan pengembangan bioetanol di Indonesia. *AGRITEKNO: Jurnal Teknologi Pertanian*. 13(2): 210-223.

Koppram, Nielsen F, Albers E, Lambert A, Wannstrom S, Welin L , Zacchi G, Olsson L. 2013. Simultaneous saccharification and co-fermentation for bioethanol production using corncobs at lab, PDU and demo scales. *Biotechnology for Biofuels*. 6: 2.

Lestari MD, Sudarmin, Harjono. 2017. Optimasi ekstraksi selulosa dari limbah pengolahan agar (*Gracilaria verrucosa*) sebagai prekursor bioetanol. *Indonesian Journal of Chemical Science*. 6(3): 209-214.

Li W, Yuan H, Liu Y, Wang B, Xu X, Xu X. 2024. Current analytical strategies for the determination of resveratrol in foods. *Food Chemistry*. 431: 137182.

Mingshen, Boediarto YM, and Sinaga SP. 2022. Perubahan iklim: tinjauan holistik sektor Batubara. *Parahyangan Economic Development Review (PEDR)*. 1(2): 116-130.

Mujtaba M, Fraceto LF, Fazeli M, Mukherjee S, Savassa SM, Medeiros GA, Pereira ADES, Mancini SD, Lipponen J, Vilaplana F. 2023. Lignocellulosc biomass from agricultural waste to the circular economu: A review with focus on biofuels, biocomposites and bioplastics. *Journal of Cleaner Production.* 402: 136815.

Muryanto Y, Sudiyani Y, and Abimanyu H. 2016. Optmasi proses perlakuan awal NaOH tandan kosong kelapa sawit untuk menjadi bioetanol. *Jurnal Kimia Terapan*. 18(1): 27-35.

Nabil NH, Handoko PSB, Destantri FW, Syahputra AB, Bahlawan ZAS. 2023. Bioethanol production from rice straw through utilization of agrobiomass waste in central java towards clean energy: a review. *Journal of Clean Technology*. 1(1): 1-8.

Naggar NEAE, Deraz S, and Khalil A. 2014. Bioethanol production from lignocellulosic feedstocks based on enzymatic hydrolysis: current status and recent developments. *Biotechnology*. 13: 1–21.

Nasution MH, Lelinasari S, and Kelana MGS. 2022. A review of sugarcane bagasse pretreatment for bioethanol production. *International Bioprocessing Association Subject Conference (IBASC 2021) IOP Conference Series: Earth and Environmental Science*. 963. doi:10.1088/1755-1315/963/1/012014.

Ojeda K, Anchez ES, El-Halwagi M, Kafarov V. 2011. Exergy analysis and process integration of bioethanol production from acid pre-treated biomass: comparison of SHF, SSF and SSCF pathways. *Chemical Engineering.* 195–201. doi.org/10.1016/j.cej.2011.06.083.

Prasetyani R, Marimin, Arkeman Y, Sugiarto. 2024. Rancang bangun rantai pasok agroindustri sorghum di Jawa Barat: kajian literatur dan agenda riset. *Jurnal Teknologi Industri Pertanian*. 34(1): 75-86.

Ramadhani GH, Syamsu K, Kartika IA, Kartawiria IS. 2024. Aplikasi sakarifikasi dan fermentasi simultan dalam produksi bioethanol dari rebung bambu. *Agrointek*. 18(2): 312-319.

Roni KA. 2015. Pembuatan bioethanol dari tanah gambut dengan proses hidrolisis asam kuat. *Berkala Teknik*. 5(1): 801-813.

Saunders M, Lewis P, and Thornhill A. 2012. Research Methods for Business Students. *Pearson*. 30.

Sembada AA. 2021. Delignification of cinnamon bark (*Cinnamomum verun*) with pre-treatment by NaOH to increase cellulose and hemicellulose recovery. *Jurnal Pendidikan dan Biologi*. 14(1): 73-76.

Sha MS, Maurya MR, Geetha M, Kumar B, Abdullah AM, Sadasivuni KK. 2022. A smart colorimetric platform for detection of methanol, ethanol and formic acid. *Sensors*. 22(2): 618.

Sharma S, Nair A, and Sarma SJ. 2021. Biorefinery concept of simultaneous saccharification and co-fermentation: challenges and improvements. *Chemical Engineering and Processing - Process Intensification*. 169.

Shimokawa T, Ishida M, Yoshida S, Nojiri M. 2009. Effects of growth stage on enzymatic saccharification and simultaneous saccharification and fermentation of bamboo shoots for bioethanol production. *Bioresource Technology*. 100(24): 6651–6654. doi:10.1016/j.biortech.2009.06.100.

Suriyachai N, Weerasaia K, Laosiripojana N, Champreda V, Unrean P. 2013. Optimized simultaneous saccharification and co-fermentation of rice straw for ethanol production by *Saccharomyces cerevisiae* and *Scheffersomyces stipitis* co-culture using design of experiments. *Bioresource Technology*. 142: 171–178. doi:10.1016/j.biortech.2013.05.003.

Syamsu K, Haditjaroko L, and Syadiah EA. 2020. Bio-ethanol production from sweet sorghum bagasse by engineered simultaneous saccharification and fermentation technology using *Trichoderma reesei* and *Saccharomyces cerevisiae*. *IOP Conference Series: Earth and Environmental Science*. 472(1): 1–8. doi:10.1088/1755-1315/472/1/012025.

Tan KT, Lee KT, and Mohamed AR. 2008. Role of energy policy in renewable energy accomplishment: the case of second-generation bioethanol. *Energy Policy*. 36(9): 3360-3365.

Thorman W. 2020. Capillary electrophoresis for the determination of drugs in biological fluids. In: Handbook of analytical separations. *Elsevier*: 7: 81-96

Tse TJ, Wiens DJ, and Reaney MJT. 2021. Review production of bioethanol—a review of factors affecting ethanol yield. *Fermentation*. 7(268): 1-18.

Xu Z, Ge Z, Wang X, and Skare M. 2021. Bibliometric analysis of technology adoption literature published from 1997 to 2020. *Technological Forecasting and Social Change*. 170: 1-15.

Zhang K, Jiang Z, Li X, Wang D, Hong J. 2024. Enhancing simultaneous saccharification and co-fermentation of corncob by *Kluyveromyces marxianus* through overexpression of putative transcription regulator. *Bioresource Technology*. 399: 130627