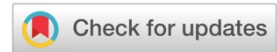


Literature Review



SIMULTANEOUS SACCHARIFICATION FERMENTATION MODEL SIMULATION OF BIOETHANOL PRODUCTION FROM BAMBOO SHOOTS: A SYSTEMATIC LITERATURE REVIEW

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ABSTRACT. Bioethanol is an alternative fuel that has the potential to replace fossil fuels because it is renewable and environmentally friendly. One of the potential raw materials for bioethanol production is bamboo shoots, which have lower lignin content than mature bamboo, making them easier to convert into simple sugars. Bioethanol production through Simultaneous Saccharification and Fermentation (SSF) has received significant attention due to its efficiency in enzymatic hydrolysis and fermentation in one step. Bamboo shoots, with lower lignin content compared to mature bamboo, are a promising raw material for bioethanol production. This Systematic Literature Review (SLR) aims to critically analyze previous studies on SSF bioethanol production from bamboo shoots, identify research gaps, and highlight areas that require further investigation. This review focuses on modeling approaches, key process parameters, and microbial interactions in SSF. Unlike previous studies that incorporated Menten kinetics, this review emphasizes Monod kinetics to describe the conversion of substrates into microbial biomass and ethanol. This analysis reveals limitations in current SSF research, including the need for optimal fermentation conditions, microbial strain selection, and better mathematical modeling for process prediction. The findings of this study provide a basis for future research in optimizing SSF for bioethanol production and contribute to the development of more efficient and sustainable bioenergy solutions.

INTRODUCTION

Bioethanol is one of the alternative energy sources to replace fossil fuels because it is a renewable energy source. The raw material for bioethanol is lignocellulose sources, such as bamboo biomass. However, this technology requires initial processing (delignification) to remove the lignin contained in bamboo. It is known that bamboo consist of 22.9% lignin substance (Ngakan *et al.*, 2017). Young bamboo, also known as bamboo shoots, contains a lower amount of lignin, specifically 0.89%. Bamboo shoots have a higher content of structural sugars compared to mature bamboo. can obtain higher bioethanol concentrations and utilize bamboo shoots, which have never been studied in Indonesia. Furthermore, the SSF method can shorten the processing time because it occurs

simultaneously (Zahroh *et al.*, 2021). This is one of the main reasons for the high sugar content in bamboo. The process of Simultaneous Saccharification and Fermentation (SSF) method has been widely applied in bioethanol production due to its ability to integrate enzymatic hydrolysis and fermentation in a single stage, making it more efficient than the Separated Hydrolysis and Fermentation (SHF) method (Jayus *et al.*, 2017). The simultaneous saccharification and fermentation process has been widely studied to produce bioethanol from materials containing cellulose and other polysaccharides (Daud *et al.*, 2012). The study of the SSF process with breadfruit starch as raw material provided a fairly high ethanol yield of up to 0.41 g ethanol/g substrate with a bioethanol concentration of 12.75 ± 0.04 g/L (Irvan *et al.*, 2017). In many previous studies, SSF has relied on external cellulase enzymes to

hydrolyze cellulose into glucose before fermentation by *Saccharomyces cerevisiae* (Zhang, 2024). This study proposes an alternative approach by directly utilizing producing microorganisms, specifically *T. reesei* is a fungus capable of producing cellulase enzymes in situ, This is because mold switches to consuming sugar, while yeast uses sugar to produce ethanol (Jasman *et al.*, 2018). enabling simultaneous substrate hydrolysis without the need for external enzyme supplementation. The optimum temperature for enzymatic hydrolysis is usually higher than the fermentation temperature in the SSF process. Therefore, it is necessary to find an equilibrium point at which the process will operate optimally (Miah *et al.*, 2022). The optimal temperature for enzymatic saccharification is 50-55°C, while for fermentation by microorganisms it is around 35°C (Sharma *et al.*, 2021)

The combination of *T. reesei* and *S. cerevisiae* in the SSF system offers significant economic and efficiency advantages, as it can substantially reduce the enzyme production costs. This study applies the Monod kinetic model, which offers a more comprehensive representation by simultaneously describing microbial growth and substrate utilization dynamics within a microorganism-based fermentation system. This approach is considered more appropriate for the simulation of bioethanol production processes, particularly when involving living cells, as it more accurately reflects biological realities. Saccharification, the process of breaking down carbohydrates into simple sugars, and fermentation, the process of converting sugars into ethanol by microorganisms, are two key steps in bioethanol production. These processes are typically carried out separately however, a simultaneous approach that integrates both can save time, reduce production costs, and improve overall efficiency. Simultaneous modeling of saccharification and fermentation can provide deeper insights into the interactions and dynamics of these processes.

Modeling of SSF involves capturing the kinetics of both enzyme-catalyzed saccharification and microbial fermentation in a unified framework. This can be complex because of factors such as varying temperature and pH optima for enzymes and microbes, substrate inhibition, and ethanol toxicity. However, in simultaneous saccharification and fermentation, glucose or other simple sugars are then used directly by the *S. cerevisiae* yeast to produce bioethanol and more cells (Syamsu *et al.*, 2016). Advanced mathematical models that incorporate reaction kinetics, mass transfer limitations, and microbial growth parameters are essential for optimizing process conditions and scaling

up industrial applications. By utilizing simulation models, we can evaluate glucose, biomass, and product formation and track changes in glucose and cellulose levels. The development of SSF processes has been recognized as a promising strategy to overcome the inherent recalcitrance of lignocellulosic biomass and improve the overall efficiency of bioethanol production using renewable resources such as bamboo shoots. Therefore, an integrated approach that combines accurate kinetic modeling with the systematic optimization of key process parameters is essential for designing more effective and sustainable SSF systems for lignocellulosic bioethanol production. Ethanol is produced from bamboo residues utilizing the SHF method with *Zymomonas mobilis*. During this process, the peak ethanol concentration attained was 4.72 g/L from bamboo shoot skin. In research conducted by Yang *et al.* (2019), the generation of bioethanol from pretreated bamboo showed that pretreatment is effective in breaking down hemicellulose and lignin. The highest bioconversion was achieved using a 0.5% NaOH solution at 170°C, yielding 4.8 g/L of ethanol. A comparable study conducted by Sindhu *et al.* (2014) also indicated that bioethanol production from bamboo utilizing the SHF method required pretreatment with various minerals and organic acids at 121°C and 15 lb pressure for a duration of 60 minutes. Fermentation took place in a sealed screw-cap vial with 20 ml of the hydrolysate at 30°C for 72 hours, following an initial inoculation with a culture of *S. cerevisiae*.

Arising problem in the fermentation process is the inhibition of the ethanol product that will damage the structure of the plasma membrane and cause protein denaturation will result in inhibited microbial growth and lower productivity. In this research, the fermentation process of glucose solution with cell immobilization technique to obtain ethanol at higher levels (Yeni *et al.*, 2016). By bridging this gap, this study offers a comprehensive framework that advances theoretical understanding and provides practical insights for industrial-scale applications. Emphasis is placed on the interplay between enzyme activity, microbial dynamics, and substrate properties within SSF processes, especially under the nonideal conditions commonly encountered in real-world operations. The integration of traditional mechanistic modeling with modern computational tools, such as machine learning algorithms, sensitivity analysis, and dynamic optimization techniques, allows for the identification of critical control points and performance bottlenecks. Furthermore, incorporating experimental validation into the modeling workflow ensures that the

simulation outputs remain grounded in empirical reality, thereby enhancing their predictive accuracy and utility in decision-making. This multifaceted modeling strategy contributes significantly to the ongoing development of more robust, scalable, and economically viable SSF processes, ultimately supporting the transition toward cleaner and more sustainable biofuel technologies in the future.

This paper is structured as follows: Section 2 outlines the data collection and methodology used to identify research trends, gaps, and processes within SSF studies. Section 3 presents the key findings from the topical analysis, focusing on academic contributions to the SSF knowledge base and exploring the interconnections among these contributions. Finally, Section 4 concludes with a comprehensive scientific framework that integrates insights from the reviewed literature, offering a cohesive overview of the current state of SSF research and its future directions.

RESEARCH AND METHODS

This study uses the Systematic Literature Review (SLR) method to identify research trends, gaps (gap analysis), and potential for further development in the SSF simulation model for bioethanol production from bamboo shoots. This approach refers to several previous studies that have applied mathematical analysis models in scientific studies, such as the exploration of the growth kinetics of *Bacillus sp* in glucose medium as a carbon source and nitrogen source by (Wijaya *et al.*, 2019). In the Journal of *Response Surface Methodology Heliyon* as well as systematic literature analysis methods used in various bioethanol and biotechnology studies.

Litelatur Search Strategy

In conducting this SLR, a comprehensive and methodical literature search strategy was employed to ensure the inclusion of relevant and high-quality studies related to the SSF process for bioethanol production.

Timeframe of Literature Search

The search focused on studies published over the past 10 years (2014–2024) to capture the most up-to-date advancements in the field of SSF-based bioethanol production. This 10 year period was chosen to ensure the inclusion of contemporary research that reflects the current state of knowledge and technological progress in bioethanol production, modeling approaches, and microbial applications.

Inclusion and Exclusion Criteria

Inclusion criteria in literature selection

- Articles discussing SSF-based bioethanol fermentation models (Zhang *et al.*, 2024). Only studies that specifically addressed the SSF process for bioethanol production were included.
- Studies using the Monod Model in the fermentation kinetics approach.

Exclusion criteria

Studies using the Menten Model or other complex enzymatic models that are not in accordance with this research approach, all studies that used the Menten Model or other complex enzymatic models that did not align with the based kinetic approach for describing microbial fermentation and enzyme action were excluded. This search method is consistent with the techniques used in bibliometric studies in the field of renewable biotechnology. Only articles published in English or Indonesian were included in this SLR.

Data Analysis and Visualization

The selected literature was analyzed using network analysis software and equation model mathematical analysis in various fields of science. The analysis included the identification of research trends related to SSF and bioethanol based on the Monod Model. It describes the growth rate of microorganisms as a function of substrate concentration and has been adopted in numerous studies on bioethanol production.

Synthesis of the Results and Preparation of Gap Analysis

Following the systematic review of selected studies obtained from reputable academic databases (Scopus, Web of Science, and Google Scholar), the results were synthesized to collate, compare, and critically analyze the available research findings. This synthesis aimed to identify consistent patterns, emerging trends, and potential contradictions within the literature. Particular attention was given to the methodologies employed, range of substrates used, and performance metrics applied across studies, such as ethanol yield, glucose consumption rate, and fermentation efficiency (Olofsson *et al.*, 2010). By evaluating these parameters, this review not only highlights the current state of knowledge in the field of bioethanol production, especially via SSF, but also reveals existing research gaps and opportunities for future investigation. The comparative analysis further facilitated the identification of best practices and innovative

approaches that have demonstrated potential for enhancing the efficiency and scalability of the SSF process.

Moreover, the review underscored the significance of operational parameters, such as temperature, pH, enzyme loading, inoculum concentration, and agitation rate, all of which play critical roles in determining the overall success of SSF processes. Studies that integrated process intensification strategies, such as fed-batch operation, co-culture systems, and in situ product recovery, achieved higher ethanol concentrations and productivity, particularly when utilizing lignocellulosic feedstocks such as bamboo, rice straw, and corn stover. Despite these advancements, a lack of standardization in experimental protocols and reporting metrics has been observed, complicating direct comparisons across studies. This highlights the need for more harmonized methodologies and comprehensive techno-economic assessments to better evaluate the feasibility of SSF on a commercial scale. In this context, future research should focus on developing standardized performance benchmarks and incorporating lifecycle and sustainability assessments to ensure that technological improvements align with environmental and economic goals.

RESULTS AND DISCUSSION

This section presents the results of SLR conducted to identify research trends related to SSF for bioethanol research, as illustrated in Figure 1. About production from bamboo shoots, as well as a gap analysis of previous studies.

Bioethanol is produced using leaf waste that undergoes pretreatment (delignification). Delignification is the process of breaking down lignocellulose into lignin, cellulose, and hemicellulose (Deivy Andhika Permata *et al.*, 2021). Delignification aims to remove lignin, increase the availability of cellulose and hemicellulose for hydrolysis and fermentation, increase the porosity and surface area and the biomass structure, and make the cellulose and hemicellulose more susceptible to enzymatic hydrolysis (Tsegaye *et al.*, 2019) (Mikulski and Kłosowski, 2022). Based on the analysis of literature obtained from Scopus, Web of Science, and Google Scholar, there has been a significant increase in research on bioethanol produced via SSF in the last 10 years (2014–2024). A systematic literature review was conducted to identify and analyze trends in SSF research for bioethanol production over the last decade

(2014–2024).

Data was collected from major academic databases using a structured search strategy and specific inclusion and exclusion criteria. Governments and industries are pushing for innovative biotechnological solutions. Most studies have focused on lignocellulosic raw materials such as rice straw, sugarcane stalks, and hardwoods, but very few have explored young bamboo (bamboo shoots) as a fermentation substrate (Zhang *et al.*, 2024). In SSF research, *Saccharomyces cerevisiae* remains the dominant microorganism employed for ethanol fermentation because of its high ethanol yield and tolerance (Walker and Stewart, 2016).

Kinetic Models in SSF Bioethanol

Based on a comprehensive analysis of the scientific literature sourced from major databases, kinetic modeling plays a crucial role in understanding and optimizing the SSF process for bioethanol production. Modeling kinetics is fundamental for predicting substrate utilization, microbial growth, and product (ethanol) formation over time, which is vital for both laboratory-scale experimentation and industrial-scale process design.

The literature analysis revealed that most studies on SSF bioethanol research predominantly employ enzymatic kinetic models as shown in Figure 2, especially the Michaelis Menten equation, to describe the hydrolysis of cellulose into fermentable sugars during the saccharification phase (Olofsson *et al.*, 2010). Although effective in capturing enzyme substrate interactions, these models often assume ideal conditions and fail to fully account for complex real-world interactions, such as enzyme deactivation or mass transfer limitations.

Models that are widely recognized for their ability to simulate microbial growth and substrate consumption have been comparatively underutilized in SSF studies. Several variables can be optimized in the SSF process, such as enzymes, temperature, yeast, nutrients, composition, incubation time, and others (Wahono *et al.*, 2015). This imbalance underscores a critical research gap: the lack of integrated modeling approaches that concurrently account for both enzymatic hydrolysis and microbial fermentation kinetics within a unified and dynamic framework. Because the SSF process inherently couples these two biological phenomena, separate modeling fails to accurately predict system behavior under changing environmental and operational conditions

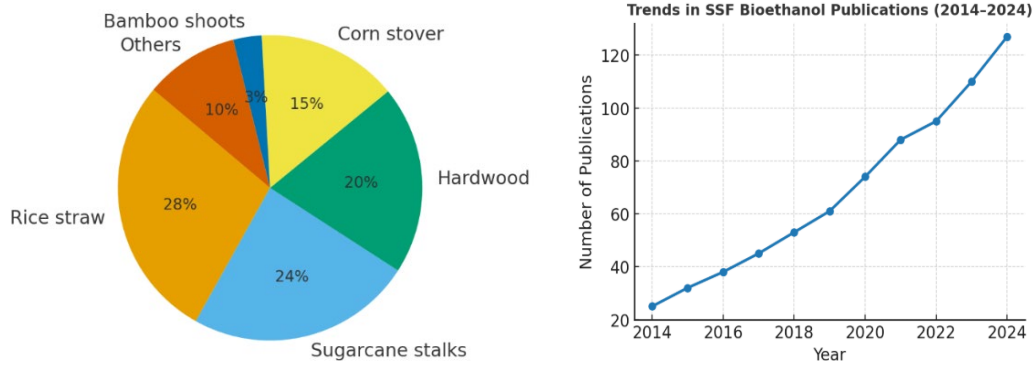


Figure 1. Trends in SSF bioethanol publication and feedstock distribution in bioethanol studies

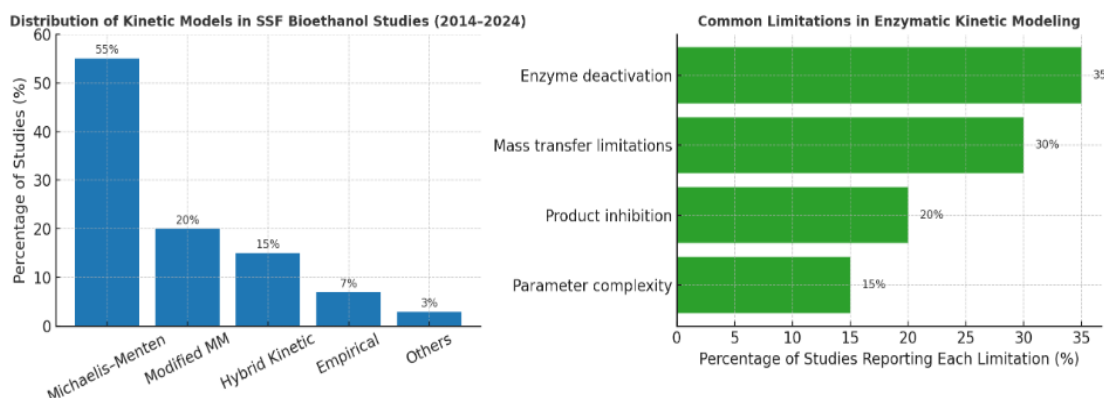


Figure 2. Evidence of enzymatic kinetic models used in SSF bioethanol research

Recent advancements have highlighted the potential of hybrid and multiphase kinetic models that combine enzyme reaction kinetics, microbial growth, mass transfer, and inhibition mechanisms into a single simulation environment. These models offer improved predictive capabilities and better reflect the nonlinear dynamics and feedback loops present in SSF systems. However, their broader adoption is constrained by challenges such as complex parameter estimation, the need for extensive experimental data for model calibration, and limited scalability to pilot or industrial levels (Zhang *et al.*, 2024).

Moreover, the review indicates a notable deficiency in the incorporation of inhibitory effects, such as ethanol accumulation, substrate inhibition, and end-product feedback, within most current kinetic models (Olofsson *et al.*, 2010). Neglecting these factors can lead to overestimations of system performance and reduced accuracy in the process control. Despite their critical role in real-world fermentation scenarios, inhibitory kinetics are often oversimplified or excluded, particularly in static or deterministic models.

Therefore, future research should prioritize the

development of comprehensive dynamic models that integrate both enzymatic and microbial kinetics, include inhibitory effects, and are validated through multi-scale experimentation. Additionally, the incorporation of uncertainty analysis, sensitivity testing, and optimization algorithms is essential to enhance the model robustness and utility in industrial-scale SSF bioethanol production. Cross-disciplinary approaches that merge systems biology, biochemical engineering, and computational modeling are needed to overcome existing barriers and support the design of more efficient, adaptive, and economically viable SSF processes.

Gap Analysis and Research Gaps

From the literature review that has been conducted, several major gaps were found in SSF bioethanol research, including a lack of research using bamboo shoots as the main substrate, even though it has high cellulose and low lignin content, which has the potential to increase fermentation efficiency. Most previous studies have focused on conventional

lignocellulosic feedstocks, such as rice straw, sugarcane bagasse, corn stover, and hardwood residues (Zhang *et al.*, 2024). This reveals an underexplored opportunity to utilize bamboo shoots as a rapidly renewable and widely available biomass as a promising alternative feedstock for SSF-based bioethanol production. Despite their advantageous chemical composition, including high hemicellulose and cellulose content and relatively low lignin content, bamboo shoots remain underrepresented in empirical and modeling studies for different types of biomass. Optimum temperature for bioethanol production (Ona *et al.*, 2019)

Furthermore, specific technical challenges in SSF application using bamboo shoots remain insufficiently explored. These include the need to determine optimal pretreatment methods that effectively remove residual lignin and hemicellulose without generating inhibitory compounds, as well as addressing contamination risks caused by the rich nutrient profile of bamboo shoots that can promote unwanted microbial growth. The variability in bamboo shoot composition depending on harvest time and species also poses challenges in process consistency and enzyme efficiency. Addressing these aspects through systematic pretreatment optimization and microbial control strategies will be essential for improving SSF stability and scalability (Pawitra *et al.*, 2019). Another identified gap lies in the limited integration of comprehensive kinetic modeling approaches specific to bamboo-based substrates, which is crucial for optimizing enzymatic hydrolysis and fermentation conditions tailored to their unique physicochemical characteristics. Moreover, most existing studies lack long-term or pilot-scale validation, particularly in tropical and subtropical regions, where bamboo is most abundant. The absence of techno-economic analyses and life cycle assessments (LCA) in studies utilizing bamboo further limits their applicability in policy and industrial decision-making contexts.

Implications for Further Research

The results of this SLR indicate that there is still much room for research and development in the field of Monod Model-based SSF bioethanol. This graph illustrates the simulated changes in substrate concentration (glucose), microbial biomass (*Saccharomyces cerevisiae*), and product (bioethanol) during batch fermentation. The simulation data were generated using the Monod kinetic model implemented in Python based on parameters synthesized from several literature sources (Walker and Stewart, 2016).

The model describes direct glucose fermentation, which serves as a simplified representation of the microbial kinetics relevant to SSF systems. The simulation results of glucose fermentation dynamics using the Monod model are presented in Figure 3. Although the Figure 3 represents pure glucose fermentation, this dynamic behavior provides a useful framework for understanding substrate–microbe–product interactions in the SSF bioethanol process. In an actual SSF system, glucose is continuously released from cellulose hydrolysis and is simultaneously consumed by *S. cerevisiae* for ethanol production. Therefore, the balance between glucose release and uptake is a critical control parameter. Excess glucose accumulation can cause substrate inhibition or catabolite repression, thereby reducing enzymatic activity and fermentation efficiency. Conversely, insufficient glucose availability slows microbial metabolism and limits ethanol productivity. Most existing kinetic models in the literature focus on monosaccharide fermentation rather than integrated SSF systems, highlighting a research gap in the modeling of the coupling between enzymatic saccharification and microbial fermentation. Therefore, future improvements should integrate hydrolysis kinetics, enzyme inhibition, and substrate feedback mechanisms into hybrid models. Such integration would better represent the temporal complexity of glucose dynamics observed in lignocellulosic SSF processes and improve the predictive accuracy of bioethanol yield simulation. Although numerous studies have successfully applied the Monod model to describe microbial kinetics in glucose-based fermentation, its direct application to SSF remains limited. Most kinetic studies have focused on single-substrate systems under ideal conditions, where substrate availability and mass transfer are assumed to be uniform. However, in SSF, the release of fermentable sugars depends on the enzymatic hydrolysis of complex lignocellulosic materials, introducing dynamic and nonlinear interactions between enzyme activity, substrate accessibility, and microbial uptake.

Existing models often neglect critical aspects, such as enzyme deactivation, mass transfer resistance, substrate inhibition, and microbial adaptation (lag phase), which can significantly alter fermentation kinetics. Furthermore, the accumulation of hydrolysis products, such as xylose and cellobiose can inhibit yeast growth and enzyme activity, leading to discrepancies between the simulated and actual performances in large-scale systems.

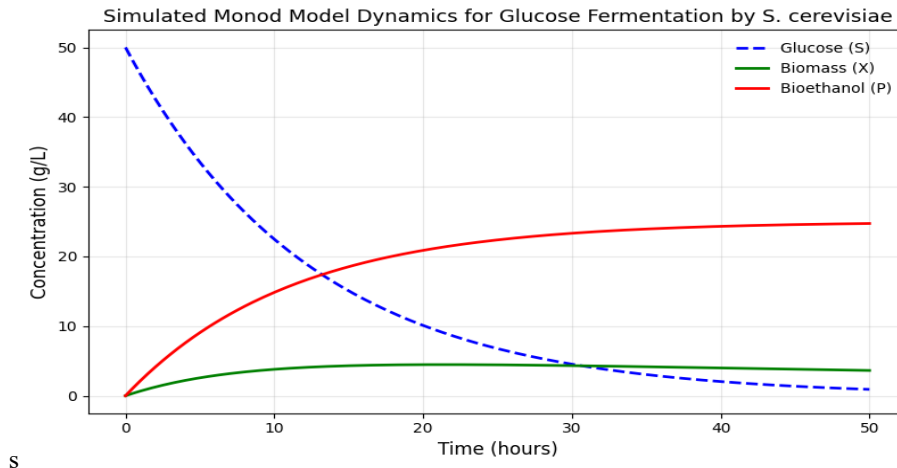


Figure 3. Glucose fermentation by *S. cerevisiae* using Monod model using Phyton

These limitations indicate a clear research gap in the development of integrated hybrid models that couple enzymatic saccharification with microbial growth and product formation dynamics. Therefore, future modeling efforts should incorporate multi-phase kinetics by combining enzyme hydrolysis, substrate inhibition, and adaptive microbial growth. The integration of empirical data from both enzyme kinetics and fermentation performance will enhance the predictive accuracy of SSF simulations. Such hybrid frameworks can be applied to optimize substrate loading, enzyme dosage, and operational conditions, ultimately improving the ethanol yield and process scalability for lignocellulosic bioethanol production. Based on Figure 3, the dynamics of each variable can be explained in detail as follows:

Glucose Concentration (S) (Blue Dashed Line)

In the context of the SSF process for bioethanol production, the dynamics of glucose concentration over time represent a critical aspect of the system's efficiency and effectiveness. At the beginning of fermentation, glucose concentration is quite high as the main carbon source for *S. cerevisiae*. As the process progresses, the enzymatic hydrolysis of cellulose continues to release glucose into the medium, while *S. cerevisiae* simultaneously consumes this glucose to produce ethanol. This creates a dynamic balance in which the rates of glucose release and consumption must be well coordinated. Excessive glucose accumulation may lead to substrate inhibition or cause catabolite repression, negatively affecting both enzyme activity and yeast metabolism. Conversely, if glucose levels drop too low, the fermentation rate may decrease because of limited substrate availability for the yeast. Therefore, maintaining an optimal glucose

concentration throughout the SSF process is essential for maximizing ethanol yield and productivity.

Saccharomyces cerevisiae Biomass Growth (X) (Green Line):

Microbes experience an adaptation phase (lag phase) before starting to multiply exponentially, at the beginning of fermentation, microorganisms such as *S. cerevisiae* undergoes a lag phase during which cell growth is minimal. In this period, the cells adjust to the new environment, activate the necessary enzymes, and prepare their internal metabolism. Following this phase, microbes enter the exponential growth stage, where biomass increases rapidly and linearly on a logarithmic scale. Aeration allows cells to continue growing and Aeration helps cells carry out their metabolic activities (Syamsu *et al.*, 2020). The growth rate is influenced by the availability of nutrients and environmental conditions such as pH, temperature, and oxygen concentration. Another critical yet often underrepresented aspect in SSF kinetic modeling is the microbial adaptation or lag phase, which precedes the onset of exponential growth (Muller *et al.*, 2015). During this stage, *S. cerevisiae* undergoes physiological adjustments to acclimate to the new environment, including activating metabolic pathways, synthesizing essential enzymes, and repairing stress-induced cellular damage. This period is essential for a successful transition into the exponential phase, where microbial biomass begins to increase rapidly, typically following Monod-type or logistic growth patterns under optimal nutrient and environmental conditions. Moreover, the duration of the lag phase is highly sensitive to environmental factors such as pH, temperature, oxygen levels, and initial substrate concentration, as well as to the physiological state of the inoculum (Mueansichai *et*

al., 2022). An additional factor influencing this phase is the presence of inhibitory compounds derived from hemicellulose hydrolysis, particularly xylose, while being a fermentable sugar, cannot be efficiently metabolized by *S. cerevisiae* and thus tends to accumulate in the medium. This accumulation can inhibit cell growth by competing with glucose for transport systems, disrupting intracellular redox balance, and extending the lag phase. As a result, the specific growth rate (μ) and biomass yield ($Y_{x/s}$) are reduced, delaying the onset of exponential growth and lowering overall fermentation efficiency. Failing to account for such inhibitory effects, along with other environmental parameters, limits the accuracy of kinetic models—particularly in large-scale SSF systems where substrate heterogeneity and mass-transfer gradients are significant. Therefore, the inclusion of lag-phase modeling components, such as those derived from the modified Gompertz or Baranyi models, together with inhibitory kinetic parameters (e.g., for xylose inhibition), is recommended to enhance the predictive power of SSF kinetic models. Integrating these aspects allows for more accurate estimation of fermentation start-up times, optimization of inoculum strategies, and realistic simulation of process dynamics, particularly during early fermentation stages. Future research should aim to incorporate adaptive microbial kinetics alongside enzymatic hydrolysis and substrate inhibition effects, such as those caused by hemicellulosic sugars, into hybrid modeling

frameworks to fully capture the temporal and biochemical complexity of SSF systems for lignocellulosic bioethanol production.

Bioethanol Production (P) (Red Line):

In the context of SSF, bioethanol production (marked as P or red line in the diagram) is the stage in which glucose from enzymatic hydrolysis is directly fermented by fermentative microorganisms, such as *S. cerevisiae*, into bioethanol.

In the SSF process, two main steps, saccharification (the breakdown of cellulose into glucose by enzymes) and fermentation (the conversion of glucose into ethanol by microorganisms), are carried out simultaneously in one reactor.

Simulation research based on bibliometric analysis

Future research directions in SSF for bioethanol production were identified through bibliometric analysis using VOSviewer software. Co-occurrence analysis was conducted with a minimum threshold of five keyword appearances, resulting in a network of 136 keywords. Among these, “bioethanol” was the most frequently used keyword, appearing 120 times, demonstrating continued research interest in renewable energy (Figure 4). Bibliometric mapping identified four major clusters, each representing a distinct thematic focus within SSF research.

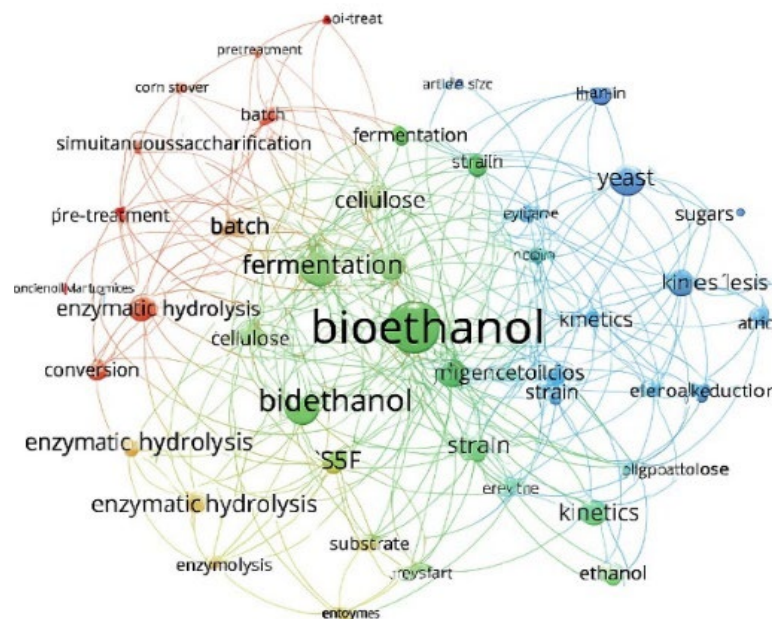


Figure 4. Research themes network

Cluster 1 (Red) is characterized by keywords such as "simultaneous saccharification", "bioethanol production", and "enzymatic hydrolysis", highlighting a strong emphasis on the integration of enzymatic hydrolysis with fermentation, the core of SSF processes. This cluster reflects research aimed at improving cellulose breakdown and sugar conversion efficiency within a single-step system.

Cluster 2 (Green), including terms such as "bioethanol", "ethanol", and "fermentation", focuses on the dynamics of fermentation under SSF conditions, including microbial tolerance to inhibitors, ethanol yield optimization, and adjustments to operational parameters such as pH, temperature, and enzyme loading. Cluster 3 (Blue) is defined by keywords such as "yeast", "hydrolysis", and "strain", centering on the selection and performance of microbial strains, particularly thermotolerant or genetically modified yeasts, to enhance the overall efficiency of SSF. Lastly, Cluster 4 (Yellow), which includes keywords such as "enzymatic hydrolysis", "SSF", and "substrate", represents research focused on the interaction between enzymes and substrates, covering aspects such as pretreatment strategies, substrate accessibility, and enzyme-substrate compatibility during the SSF process.

CONCLUSIONS AND RECOMMENDATIONS

Conclusions

This study reviews SSF for bioethanol production from bamboo shoots using the Monod model through the SLR approach. This study found that the use of bamboo shoots as a fermentation substrate has been minimally studied, although this material has great potential as a source of cellulose that is more easily degraded than other lignocelluloses, based on the analysis of literature obtained from Scopus, Web of Science, and Google Scholar (2014–2024). In addition, most previous studies have used the Michaelis–Menten model, which focuses on enzymatic kinetics, whereas the application of the Monod model in SSF bioethanol is still rarely performed. The Monod model is simpler and more practical for predicting microbial growth during bioethanol fermentation. Another factor that is still less studied is the role of microbial combinations in SSF, especially the use of *T. reesei* as a hydrolysis agent and *S. cerevisiae* as a fermentation microbe.

This combination of microbes has the potential to increase the efficiency of substrate conversion into bioethanol; however, further research is needed to optimize their interactions. The keyword network visualization formed four main clusters, each reflecting a different approach to improving SSF efficiency, such

as microorganism selection, enzyme efficiency, and substrate pretreatment. Density and overlay analyses have shown that issues such as co-fermentation, xylose utilization, and lignocellulosic substrates remain the focus of current research. However, there is a significant research gap, namely, the lack of exploration of alternative raw materials such as bamboo shoots in SSF systems. The absence of these keywords in the bibliometric map indicates that this topic has not been a major focus in the scientific literature, thus offering wide research opportunities for the future.

Recommendation

Further experimental validation in future studies should include direct measurements of ethanol production to validate model predictions more accurately and refine parameter estimations. Second, process optimization for additional research should explore a wider range of initial biomass concentrations and dilution rates to identify the optimal conditions for maximizing bioethanol yield. The results of this study should be tested in larger-scale bioreactors to assess the feasibility of industrial applications and identify potential challenges in upscaling the process.

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