RESEARCH PAPER

Synergistic Effects of Alkali Pretreatment and Microwave Irradiation: A Green Strategy for Efficient Lignocellulosic Bioethanol Production

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ABSTRACT

The second generation bioethanol should not be converted using lignocellulosic biomass because it does not dissolve easily due to its rigid structure and lignin-carbohydrate bonding. Pre-treatment is thus an important procedure to increase the fermentation efficiency and enzymatic access. The use of pretreatment with alkali followed by microwave irradiation has become one of the potential green and energy-saving strategies of biomass valorization in recent years. This review is a critical analysis of the synergistic effect of using the microwave-assisted alkali pretreatment of lignocellulosic feedstocks, particularly corncob, a sustainable raw material. The concurrent process takes advantage of the fast dielectric heating of the microwave and the delignification nature of the alkali reagents to promote the level of accessibility, crystallinity, akarunanind reaction time of cellulose. Comparative analysis indicates that, Microwave-assisted alkali pretreatment has a substantial level of delignification, saccharification and ethanol yielding with minimal chemical usage and process severity relative to the conventional processes. The mechanistic understandings, the optimization parameters of processes and the downstream effects on the enzymatic hydrolysis and fermentation are well-explained. Moreover, the review supports the sustainability, techno-economic viability, and scale-up issue of this hybrid technology. Altogether, microwave-assisted alkali pretreatment is a potentially promising and ecologically friendly process intensification strategy in lignocellulosic biorefinery, which will allow effective ethanol and other value bioproducts to be produced within a circular bioeconomy platform..

Keywords: Microwave-Assisted Pretreatment, Alkali Pretreatment, Corncob Valorization, Lignocellulosic Biomass, Second-Generation Bioethanol, Delignification, Process Intensification, Sustainable Biorefinery.

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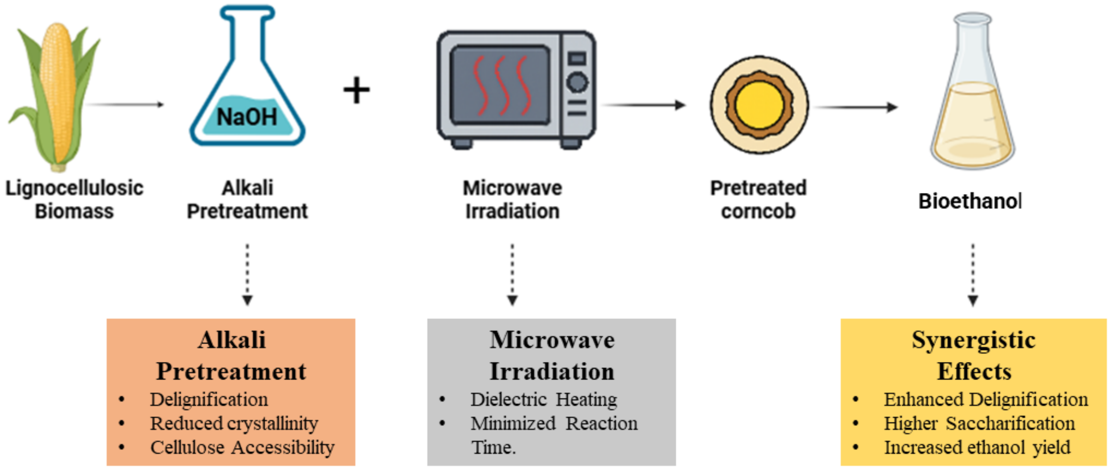

INTRODUCTION

With the growing worldwide search in finding sustainable and low-carbon sources of energy, the lignocellulosic bioethanol has been emerging as a potential renewable energy source. Lignocellulosic biomass, which includes agricultural wastes, and energy crops as well as forestry wastes, is inexpensive and abundant but has a complex structural structure of

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**Author for Correspondence: usha.biotech@sathyabama.ac.in* cellulose microfibrils entrenched within hemicellulose and lignin. This complex structure forms a significant obstacle to enzyme hydrolysis, viz. biomass recalcitrance, a significant hurdle in the second generation production of bioethanol [1];[2]. Pretreatment is thus essential to efficient fermentation to break lignin-carbohydrate, increase access to enzymes, as well as increase fermentable sugars contents.

Alkali pretreatment is a popular method of chemical pretreatment to address the lignocellulosic recalcitrance. Alkaline compounds like sodium hydroxide (NaOH), potassium hydroxide (KOH), and calcium hydroxide [$Ca(OH)_2$] selectively eliminate lignin and partially solubilize hemicellulose, and soften the structure of the cellulose so as to expose the sites of enzyme binding. This process of delignification also cleaves the linkages in all the ester and ether parts of the lignin and lignin-carbohydrate complex which enhance the efficiency of the hydrolysis process[3][4]. The alkali procedures are relatively mild and have less fermentation inhibitors than the acid or oxidative pretreatments, but they may be restricted by lengthy reaction times, high chemical usage, and generation of wastewater [5].

New developments also show that the combination of alkali pretreatment and mega radiations can prove highly effective and efficient in converting biomasses to generate efficiently and sustainably acceptable products. Microwave heating provides the benefit of a volumetric energy transfer that is faster and produces higher speeds in chemical reactions as well as improves the speed of solvent penetration. Microwave energy interferes with cellulose crystalline regions when applied to the lignocellulosic materials, destabilizes the lignin-carbohydrate interactions, and enhances reagent diffusion within the biomass structure [6]. In many cases, the synergistic effects of microwave irradiation and alkaline chemistry have caused excellent delignification, short pretreatment, and increased fermentable sugar than with alkali pretreatment alone [7][8].

These synergistic effects have been proved on various types of biomass by several studies. It was stated that the alkaline pretreatment of algal waste with the assistance of the microwave technique gave a significant rise in the concentration of fermentable sugars and produce of ethanol ([6]). [9] showed an increase in the efficiency of hydrolysis on both the softwood and the hardwood biomass and non-wood biomass using high pressure of microwave-assisted NaOH pretreatment. On the same note, [10] had up to 83.7% delignification and high ethanol yield with white grape pomace during optimized conditions: microwave-alkaline pretreatment (3% NaOH, 90 ^{o} C, 45 min). In addition to this, blending of the alkaline glycerol with microwver heating has been observed to perform better in delignification and saccharification of corn straw and rice husk than aqueous systems alone [11].

Considering the variety of feedstocks, the type of alkali and the application of various microwave operating conditions (power, duration, solvent medium), an important synthesis of the underlying processes, relative efficiency, and environmental impact needs to be undertaken. The purpose of this review is to synthesize existing information on the microwave-assisted alkali pretreatment, shed some light on the mechanism behind the observed synergy, and where to focus on in future to scale-up the present green, energy-saving strategy to lignocellulosic bioethanol production.

2. Fundamentals of Lignocellulosic Biomass

Lignocellulosic biomass is considered the greatest renewable organic resource on the planet and the basis of sustainable bioethanol generation. It mainly includes three interconnected structural polymers namely cellulose, hemicellulose and lignin that make up a complex structure giving rigidity, strength and chemical resistance of the plant cell walls [12] [13]. The complex physicochemical complex between these groups makes the biomass extremely difficult to degrade by enzymes, which is a significant problem of biofuel production.

One of the linked polymeric structures of lignocellulosic biomass is the linear homopolysaccharide of 1-4 linked D-glucose of the micro-fibrils, formed through the extensive intra and inter-molecular hydrogen bonding. It has high crystallinity level and polymerization which limits access of enzymes, hence lowering the level of hydrolysis[14].

Hemicellulose, on the other hand, is a heterogeneous and amorphous polysaccharide, made out of pentoses (xylose, arabinose), hexoses (mannose, glucose, galactose), thereby bonded with uronic acid and acetyl groups. Even though it is most vulnerable to hydrolysis as compared to cellulose, its high association with lignin and cellulose is an additional source of biomass rigidity[15].

Lignin refers to an amorphous combination of the polyphenolic polymer that is three dimensional produced as an assemblage of monolignols: coniferyl, sinapyl and p-coumaryl alcohols. It offers hydrophobicity, mechanical strength and pathogen resistance, and, at the same time, serves as a physical, as well as, chemical barrier to an enzyme attack, and non-productively adsorbs enzymes [16].

The recalcitrance of lignocellulosic biomass is affected by a number of structural factors. The crystallinity of cellulose, long chain length of polymer (degree of polymerization), and low porosity inhibit diffusion of the enzyme and catalytic action [17]. On the contrary, lignin-carbohydrate complexes disruption, crystallinity degradation, and surface area increase contributes to a great deal towards the efficiency of the enzymatic hydrolysis process [18]. Relative amounts of cellulose (3050 percent), hemicellulose (1535 percent), and lignin (1025 percent) depend on the type of feedstock (e.g., hardwood, softwood, grasses, agricultural residues) and the environment[15].

The chemical composition, microstructure, and physicochemical interactions of lignocellulosic biomass are major factors in the understanding that enable economic development of pretreatment technologies. The use of alkali treatment, in particular, in conjunction with microwave irradiation or mechanical disruption, is meant to modify these inherent characteristics, make the matrix less crystalline, delignify it, and expose more surface, so that efficient enzymatic saccharification can be followed by the generation of bioethanol.

3. Alkali Pretreatment: Principles and Effects

Alkali pretreatment is a very highly important chemical approach in transforming lignocellulosic biomass into fermentable sugars. This procedure is carried out with the help of alkaline reagents in the form of sodium hydroxide (NaOH), potassium hydroxide (KOH), calcium hydroxide [Ca(OH) 2], or aqueous ammonia to modify the structural framework of vegetable biomass and provide greater enzymatic accessibility [19][20]. These reagents attack the recalcitrate lignin-carbohydrate network in lignocellulose and is one of the principal factors in biomass recalcitrance [12][21].

3.1 Delignification and Lignin Modification

One of the effects of the alkali pretreatment is the selective removal in addition to alteration of lignin. The alkaline agents disperse the ester and ether bonds of the lignin and between lignin and hemicellulose solubilising the lignin fragments and decreasing the undesired lignin-enzyme interactions [22][23]. Having reduced lignin content and reduced its structure, cellulases can access cellulose surfaces better- enhancing hydrolysis performance [24].

3.2 Hemicellulose Solubilisation and Deacetylation

Besides removing the lignin, alkali treatments nearly completely solubilize hemicellulose and depict acetyl or uronic substituents off of it. This disrupts the hemicellulose, cellulose, and lignin network [25] [17]. Consequently, alkaline pretreatment does not only eliminate the type of inhibitory barriers but also increases the effective surface area of the polysaccharides which are acted upon by the enzyme.

3.3 Changes in Crystallinity, Fiber Morphology and Porosity

The physical architecture of biomass is changed by the alkali treatments that swell fibers, enlarge the pore sizes and decrease cellulose crystallinity (make the crystalline areas accessible). The example of this is indicated in a study on Xyris capensis that showed that 4% NaOH pretreatment over 20 min decreased crystallinity, surface area, and yielded a higher amount of methane by about 143 compared to untreated biomass [26]. This strength deformation reduces the resistance to mass-transfer of enzymes to resistance [27][28].

3.4 Preservation of Cellulose and Minimisation of Sugar Losses

A major benefit of the optimized alkaline pre treating is that the cellulose portion is not lost, and lignin and hemicellulose are removed. Researchers were able to obtain a lignin removation of about 44.4 percent, cellulose retention of about 86.6 percent and glucose output after hydrolysis of 91.9 percent by using a wet carbonate alkaline mechanical pretreatment procedure on corn stover(3% NaOH + milling) [17]. These results indicate that optimum concentration, temperature and time of the alkali can be maximised to maximise sugar yield [29][30].

3.5 Limitations and Process Optimization

Alkali pretreatment is effective but suffers shortcomings concerning chemical reuse, wastewater level, and heating and additional energy required during treatment. Cellulose degradation and formation of inhibitory [31], [32] can happen as a result of overexposure to alkali. Consequently, alkali pretreatment can be used together with other energy-efficient processes like microwave irradiation or ultrasound to increase lignin removal and reduce the volume of reagents used [33], [34] . The sustainable and green probably biomass valorization strategies are built on these hybrid processes.

4. Microwave Irradiation: Principles and Mechanistic Insights

Promising in pretreatment of transformation of biomass into valuable products is the microwave irradiation because of its volumetric heating at high rates and its increased mass-transfer performance. The microphysicological processes of biomass-microwave interaction consist in dipolar polarization and ionic conduction: polar molecules (water, hydroxyl groups in cellulose / lignin) are rotated by the changing behaving field, and mobile ions (no. 3. ka-Na-OH) ions flow by the electric component of the field. These processes produce internal heating (hot spots) which increases the degradation and loosening of the plant cell-wall matrix [35], [36], [37].

4.1 Mechanism of Heating and Biomass Disruption

Direct Heating of Biomass Volumetric heating of biomass is offered by the microwave power as compared with gradient heating by thermal conduction where the surface of the material is heated first before heating the inner portions of the item. This gives quicker and evenly distributed temperature which causes further disruption of lignocellulosic fabric, lignocellulosic cell wall swelling, pore expansion, and partial delignification. A study on Miscanthus × giganteus found that treatment using a microwave at 130200 o C of 20 min, with either NaOH or H 2 SO 4 at high concentrations of each acid, could reach approximately 86% lignin removal and ten times higher hydrolysability than that of untreated biomass [38]. The high heating rate ensures the released sugars are not degraded and enhances consistency of the overall pretreatment process [11].

4.2 Structural and Physicochemical Effects

The morphological and physicochemical characteristics of lignocellulosic materials are changed through the pretreatment using the microwave. Reported effects include:

- Decrease in the crystallinity of the cellulose and an increase in available amorphous space that improves the efficiency of enzymatic hydrolysis [39], [40].
- Hydrolysis of lignin-carbohydrate complexes (LCCs) and partial solubilization of hemicellulose, which leads to high porosity and accessibility of enzymes [41], [42].
- Production of micro- and nano-fissures, cellulose microfibrils and swelling of cell walls [43], [44].

These structural changes are the reason behind shorter reaction times, increased rate of digestibility, and decreased severity of the processes that implies that the conventional thermal pretreatments were more severe.

4.3 Process Parameters Influencing Efficiency

Microwave pretreatment relies on the following parameters, which affect the efficiency of the treatment; microwave power, irradiation time, biomass moisture content, dielectric properties, solvent or media (e.g., water, alkali, glycerol), and solids loading [45]. The heat generation and depth of penetration is dependent on the dielectric constant of a solvent to a large extent. As an illustration, alkaline glycerol pretreated biomass under microwave radiations gave better yields of saccharification with corn straw and rice husk than did aqueous systems [11]. Nevertheless, the optimum conditions are feedstock-dependent and should be in between adequate structural disruption and low sugar degradation or subsequent development of inhibitors (However, the optimum conditions are feedstock-dependent and should exist between enough structural disruption and low degradation of sugars or development of inhibitors [35].

4.4 Advantages and Constraints

Microwave-assisted pretreatment has a number of benefits:

- Rapid volumetric heating,
- Efficiency of high delignification and hydrolysis,
- Decreased residence time and chemical consumption, and
- Reduced total energy use maximized [46], [47].

Nevertheless, there are still limitations, such as difficulties with the scaling due to non-uniform distribution of electromagnetic fields, increasing equipment prices, possible local overheating or charring, and fluctuation of feedstock dielectric [48], [49].

4.5 Implications for Hybrid Alkali–Microwave Pretreatment

Combined treatment of microwave irradiation and alkali pretreatment improves delignification and structural damage that individual processes cannot accomplish[50]. Alkali reagents dissolvate hemicellulose and solubilize lignin-carbohydrate complexes (LCCs), as well as hastens reaction kinetics and enhances penetration of reagents with the use of microwave irradiation [51], [52]. Such synergistic mixture can significantly enhance enzymatic digestibility and yield of bioethanol and reduce inputs of chemicals and energy [11], [35]. Consequently, microwave-based alkali pretreatment is one of the potential directions of process intensification and green biorefinery.

5. Synergistic Integration of Alkali Pretreatment and Microwave Irradiation

5.1 Synergistic Mechanisms and Process Enhancement

The microwave irradiation and pretreatment of the alkali are highly synergistic that enhances better the process of disintegration of the lignocellulosic biomass and results in increased efficiency of enzymatic hydrolysis [9], [53]. The process ensures quick homogeneous energy transfer such that diffusion of the reagents occurs over super-fast heating of the lignocellulosic matrix during microwave heating, in addition to enhancing penetration of alkali into the lignocellulosic matrix [51]. At the same time, alkali separates lignin- carbohydrate complexes (LCCs) and dissolves lignin creating active locales in subsequent structural breaking [54].

This two-fold activity causes both intermolecular hydrogen bonding to disrupt cellulose and ester and ether bonds to break in lignin and allow the delignification procedure and cellulose exposure to optimal capabilities [49], [55]. In particular, it has been shown that microwave-assisted pretreatment of NaOH can offer delignification of to 80-90 percent in comparison with other more traditional alkali or thermal pretreatment methods and enzymatic saccharification of over 70 percent [35], [56], [57].

5.2 Structural and Physicochemical Modifications

The help of a microwave gives the preliminary results of alkali treatment that results in drastic changes of the morphology and physicochemical properties of the biomass. It has been found that it leads to swelling, porosity, and fibrillation of the fiber structure that exposes cellulose microfibrils and augments surface area [49]. Also, the synergistic treatment improves the crystallinity and amorphous development of the cellulose, and the inside porosity of the cellulose and, they contribute to increasing the rate of conducting the enzymatic activities [26].

In addition, lignin is soluble and hemicellulose soluble to extract greater yield of fermentable carbohydrates with the help of alkaline solution by applying microwave irradiation without cellulose destruction [17]. The lignin content in the resulting biomass is also decreased, the glucan availability is also improved and the hydrolysis and fermentation of bioethanol are ideal [23].

5.3 Process Optimization and Energy Efficiency

Several factors influence the optimization of the microwave-alkali pretreatment that denotes that it is dependent on: alkali concentration, microwave power, irradiation period as well as moisture [8], [58]. Lozano Pérez et al., (2024) emphasized the moderate concentration of the alkali (2 4G of NaOH) and controlled heating of the microwaves (90-120 C 15-30 min) as the combination of which produces the most optimal delignification with the smallest effect on the degradation of sugar. Excessive power or time might result in excessive heating, loss of sugar or charring [35]. It should be mentioned that the energy use of microwave-aided systems may be decreased up to 4050 per cent of the conventional heating as it undergoes fewer residence times and direct volumetric heating [49]. This advantage enhances the sustainability or the hybrid pretreatment process and its scale.

5.4 Techno-Economic and Environmental Perspectives

Microwave-assisted alkali pretreatment is a favorable avenue in the pursuit of developing green biorefineries in an attempt to exploit agricultural residues as corncob, rice straw, and sugarcane bagasse in the technological microwave field. This reduction in utilization of chemicals, less time of processing and high rate of converting sugar to sugar reduces the downstream processing costs [59].

To be used in a circular bioeconomical manner, one can use re-cyclable/reusable alkali reagents (e.g., NaOH, $Ca(OH)2$) to make the effluent less toxic and then recycle the chemical products in closed loop [35]. The solution lies in scale-up of the processes using the continuous-flow reactors at the microwave frequencies, and renewable sources of alkali, namely the biodiesel waste products processed to alkaline glycerol.

6. Process Optimization and Scale-Up Challenges

6.1 Optimization of Process Parameters

The process of alkali pretreatment by the use of microwaves is highly dependent on the maximization of different variables which are interconnected including the microwave power, period of irradiation, the concentration of alkali, concentration of moisture and weight of biomass. The word parameters has influence both on the levels of delignification, cellulose crystal, and yield of the fermentable sugars. To illustrate using moderate power of microwaves (300 600 W), short residence time (1020 min) and 24percent NaOH concentration to generate the best structural disruption with minimal sugar destruction, Lozano Perez et al., (2024) have emphasized that sweetest results were obtained. The breakdown of the cellulose, charring or deposition of the inhibitors can be initiated by overpower in the microwave power or time.

Similarly, it was observed by Anoopkumar et al., (2023) that the most suitable temperature within which the process between the action of microwave-assisted alkali pretreatment yields a high level of performance is 90 0 C to 120 0 C, the highest point of which the process was the most efficient in delignifying the process yet maintaining the integrity of the polysaccharide. The predictability of the process and its reproducibility have been advanced further through optimization using Response Surface Methodology (RSM), and Artificial Neural Networks (ANNs), and increase its scalability even further [35].

6.2 Energy Efficiency and Economic Viability

The systems that are operated with the help of microwaves have been identified to possess a great betterment when it comes to energy efficiency in comparison with the traditional heating. Microwaves selective heating has also enabled volumetric heating which produces less energy being emitted to the environment allowing up to 4060 percent energy savings during pretreatment[49]. Together with slight alkali reagents like NaOH or Ca(OH) 2, the joint method has managed to achieve high delignification with limited usage of reagents having a positive impact on improving the economy as well as environmental performance of the technique.

On technical-economic appraisal, twenty-five percent or thirty per cent reduction in overall operations expenses is achievable through programmed-based alkali pretreatment due to reduced chemical and energy demands [59]. However, microwave reactor scalability, recuperation effectiveness, and lower stream integration in the biorefinery systems require numerous economic advantages.

6.3 Reactor Design and Scale-Up Limitations

Microwave-based systems cannot be scaled easily. Even heating is achieved in the case of laboratory scale, since distribution of the electromagnetic field is uniform in the case of laboratory scale where there exist no non-uniform distributions of power density of the reactors which creates hot spots and poor pretreatment in the case of industrial scale [35]. Continuous real-time microwave reactor, hybrid design and multimode cavity of continuous development is made to improve the scalability.

It is established that incorporation of rotating or stir reactors possesses an advantage of better heat distribution and no overheating arises in particular areas[49]. Moreover, the addition of a microwave system to mechanical stirring or ultrasound would also increase the homogeneity of energy and contact between the biomass and the reagents, which, in its turn, is concerned with the intensification of the process [35].

6.4 Environmental Sustainability and Circular Bioeconomy

The alkali pretreatment with the help of microwave is in line with the principles of the green chemistry and closed bioeconomy, first, regarding the reduction of the solvent use, second, regarding the reduction of the emissions, and third, regarding the enhanced recyclability of the alkali solutions. Ethaib et al. (2020) stressed that NaOH and Ca(OH) 2 could be reused successfully during the precipitation or ion-exchange in order to minimize the toxicity of effluents.

Better still, it could be possible to combine this process with the use of renewable energy (e.g. solar-powered microwave generators) which can help to reduce carbon footprints considerably [35]. It is these low-impact hybrid pretreatments that can be one of the potential paths that industry can take, and implement with the bioethanol industry transitioning to more sustainable production models using policies and policies.

7. Future Perspectives and Research Outlook

Though the integrated approach of microwave assisted alkali pretreatment methods have shown tremendous potentials in the alleviation of the biomass recalcitrance and the amplification of the sugar yields, there are still some of the research gaps and future research requirements besides, which would allow the application of the approach to be carried out at the industrial levels.

7.1 Reactor Technology and Continuous Operation

It is also a major issue that bench-scale batch systems are converted to continuous and large-scale reactors. The design of the engineering should consist of designs to spread out uniformly the microwave fields and with low thermal hotspots and a high-moisture and heterogeneous biomass. It has better microwave applicators, scaled cavity geometries and solid-state microwave sources which promise [59]. Both dielectric properties and temperature could be measured in real-time and hence detected to identify the dielectric properties and temperature gradient of biomass, and hence could result in proactive control of representative pretreatment [60].

7.2 Integration into Biorefinery Value Chains

The hybrid pretreatment must be seamlessly integrated into upstream (biomass handling, size-reduction) and downstream (hydrolysis, fermentation, product recovery) operations. Techno-economic and life-cycle assessment (TEA/LCA) studies suggest that energy savings from microwave volumetric heating and shorter reaction times can reduce process carbon footprint when powered by renewable electricity[35]. However, detailed LCA studies that encompass alkali recovery, wastewater treatment, and reactor scale-up are scarce.

7.3 Alkali Recycling and Circular Chemistry

To maintain sustainability, alkaline reagents (e.g., NaOH, $Ca(OH)_2$) used in the pretreatment must be recycled and reused. Research should emphasize closed-loop alkali systems, recovery of solubilized lignin for higher-value products, and minimization of effluent generation. Circular bioeconomy frameworks demand efficient processes with minimal chemical waste and maximal valorization of all biomass fractions [59].

7.4 Feedstock Diversification and Realistic Conditions

Most studies have used model agricultural residues under controlled lab conditions. Future work should expand the range of feedstocks (e.g., mixed agricultural-forest residues, urban lignocellulosics) and test pretreatment under realistic process conditions (higher solids loading, minimal pre-drying, continuous flow). Parameter sensitivity using machine learning or modeling approaches can accelerate optimization across feedstock types and scales [49].

7.5 Digitalization, AI & Smart Process Control

With the assistance of digital tools, artificial intelligence (AI), machine learning (ML), and data-driven feedback control, etc., it is possible to optimize pretreatment protocols in real-time [35]. Kinetics and properties of reactions, as well as microwave heating, would be forecasted at much less cost and time of experimental process.

7.6 Policy, Standardization and Sustainability Metrics

The performance and reporting structure measurements (e.g. the energy efficiency per ton biomass, sugar yield, the prohibiters levels) and benchmarking must be standardized to enable them to be used in industries. The government should strive to partake in policies on low-carbon pretreatment technology by offering more subsidies on pilot-scale demonstrations in relation to the developing economies. This consideration of sustainability should not be pegged on the utilization of energy and chemicals, water, quality of effluents, and product traceability should fall into the measurements.

8. Conclusion

One more procedure proven to be very powerful and eco friendly to the dilemma of the lignocellulosic biomass recalcitrance in the second-generation production of the ethanol is the alkali pretreatment that is enabled with the support of microwave. Alkali chemistry and microwave irradiation-based activity-based, enhancing fermentable sugar and ethanol product by delignification, disruption of lignin-carbohydrate complex, destabilization of cellulose crystallinity and accessibility of enzymes are all important products of synergy [61][62] .

The hybrid process requires a shorter period compared to traditional delignification processes, be they alkali or thermal, as well as less chemical compared to more traditional alkali or thermal delignification. This makes it cost effective in addition to being energy efficient especially to agricultural wastes like the corn cob, rice straw and the sugarcane bagasse. In addition, the principles of green chemistry, as well as the concept of a circular bioeconomy (e.e. solar-powered microwave devices) also will be encouraged to develop synergies between mild alkali solutions point (e.g. NaOH, Ca(OH) 2) and renewable energy sources [35], [59].

The scale of the microwave reactors, the perpetuation of the energy flow reclaimed the alkali reagents, which is a requirement in the interest of long-term economic feasibility is the challenge notwithstanding viable prospects such as its hypothetical potential [63]. To sustain continuous-flow or multimode and real mass production of dielectric properties requires systems that have high designs of reactors that can be translated in the industry properly. Additionally, the techno-economic analysis (TEA) and the life-cycle assessment (LCA) ought to be conducted in a methodical manner in order to draw a comparison between the output of this technology on the environment [64] [65].

The microwave-assisted alkali pretreatment is one of the possible routes to the development of sustainable lignocellulosic biorefineries within the framework of the bioenergy transformation at the world scale. This translates it as a breakthrough platform to generation of second generation bioethanol and bio-based chemicals mainly because it has greater benefits to intensification of processes consuming less chemical but has better product. Computer optimization, the diversification of feedstock, and the closed process of chemical recovery will also be applicable to study its industrial ability further in the future.

Table 1. Recommended process parameters for microwave-assisted alkali pretreatment of lignocellulosic biomass

Parameter	Typical Range	Description / Observed Effect	Reference
Alkali type	NaOH, KOH, $Ca(OH)_2$, alkaline glycerol	NaOH most effective for delignification; $Ca(OH)_2$ more eco-benign	[66], [67]
Alkali concentration	2 – 4 % (w/v)	Optimum for delignification without sugar degradation	[68]
Microwave power	300 – 600 W	Ensures rapid, uniform heating; excessive power causes charring	[68], [69]
Temperature range	90 – 120 °C	Ideal for lignin removal and cellulose preservation	[68], [69]
Residence time	10 – 30 min	Balances structural disruption with minimal sugar loss	[68]
Moisture content	15 – 30 %	Improves dielectric heating efficiency and reagent diffusion	[68]
Solid loading	5 – 15 % (w/w)	Higher solids possible with optimized mixing; reduces water use	[70], [71]
Delignification achieved	80 %	Significant reduction compared with conventional alkali	[72]
Glucan conversion efficiency	75 – 95 %	Indicates enhanced enzymatic saccharification	[68], [69]
Energy savings	40 – 60 % vs conventional heating	Due to rapid volumetric heating and reduced process time	[68]

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