Harnessing Municipal Solid Waste: Enzymatic Pathways to Bioethanol Sustainability: A Review

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Abstract— *Waste management problems and the need for renewable energy can be addressed by utilizing municipal solid waste for bioethanol production as a renewable feedstock. The enzymatic hydrolysis process of turning solid waste into fermentable sugars for the subsequent production of bioethanol is the main focus of the current study. Enzyme access is significantly facilitated by effective pretreatment, particularly the alkali process with NaOH, which breaks the resistant lignocellulosic structure. Hydrolysis is possible under moderate circumstances (40–50°C, pH 4.5–5.0) thanks to fungal-derived cellulolytic enzymes from Aspergillus and Trichoderma strains. Using ethanologenic yeasts such as Saccharomyces cerevisiae and Pichia stipitis, the sugar-containing hydrolysate is then fermented, with optimised procedures producing ethanol. It has been discovered that integration approaches to the process, like simultaneous fermentation and saccharification, increase efficiency compared to independent operating steps. Despite promising results, problems with process optimisation, biomass recalcitrance, and enzyme cost persist. Enzymatic hydrolysis is used in this study as an example of a possible method for turning municipal waste into bioethanol; however, further technological advancements are required to increase the economic feasibility and commercial use of this environmentally friendly bioconversion process.*

Keywords— lignocellulosic, fermentation, recalcitrance, enzymatic hydrolysis, bioethanol, waste management, municipal solid waste, and pretreatment.

I. INTRODUCTION

Numerous studies on the production of bioethanol from lignin-based biomass, including solid waste from municipalities, have been spurred by the growing demand for renewable energy sources. MSW is a good feedstock for the production of bioethanol because it contains avast volume of organic waste, which is high in cellulose, hemicellulose, and lignin.(Kumar *et al.*2020 and Srivastava *et al.* 2017).Due to its many benefits over chemical hydrolysis methods, including high specificity, lower energy inputs, and environmentally friendly processing, enzymatic hydrolysis is an important step in the conversion of MSW to fermentable sugars. (Patra *et al.* 2017 and Banerjee *et al.* 2019). Alkaline, acidic, and steam explosion pretreatments are a few of the pretreatment techniques that have been employed to maximise the enzymatic hydrolysis efficiency of biomass derived from MSW. (Singh *et al.* 2019 and Chen *et al.* 2017).

One easily accessible and under-utilised resource that has become a promising option for the production of renewable biofuels is municipal solid waste. The accumulation of MSW has become a significant environmental issue due to global urbanisation, necessitating the development of environmentally friendly waste management solutions. Pollution and climate change are caused by conventional waste treatment methods like incineration and landfilling. The renewable energy production and the removal of environmental pollution are two benefits of using MSW as bioethanol through enzymatic hydrolysis. (Sharma *et*

al. 2019). Furthermore, governments and research institutions worldwide have recognised the potential of waste-to-energy technologies and have been investing in the advancement of enzymatic hydrolysis and biomass pretreatment techniques (Lynd*et.al* 2017).

Hemicellulases and cellulases are essential for the hydrolysis process by enzymes because they break down structural carbohydrates into monomeric sugar, which microbes then ferment to produce ethanol.(Sarkar *et al. 2012* and Zhang *et al.* 2018)Recent developments in microbial fermentation, genetic engineering, and enzyme science have significantly increased the efficiency of producing bioethanol from MSW.(Gupta *et al.* 2020 and Singhania *et al.* 2013). While Taherzadeh *et al.* and Karimi *et al.* (2007) studied enzyme-based hydrolysis techniques, authors such as Lynd *et al.* and Wyman *et a*l. have contributed to the explanation of the enzymatic hydrolysis of complex polysaccharides to fermentable sugars. However, the main obstacles to scaling up this technology are problems like enzyme inhibition, restricted substrate accessibility, and higher production costs (Wyman *et al.* 2005and Banerjee *et al.* 2010).

Furthermore, studies by Zhang *et al.* 2018 and Lynd *et al.* 2017, and Sun *et al*. and Cheng *et al.* (2002) have demonstrated the impact of different pretreatment techniques on the efficiency of enzymatic hydrolysis. As a more sustainable alternative to chemical pretreatment, biological pretreatment such as microbial degradation via ligninolytic fungi has also been studied. The development of metabolic engineering of fermentative microorganisms is also noteworthy because, as Singhania *et al.*'s research shows, it has made it possible to produce more ethanol from mixed sugar substrates. The second crucial area of research is process optimisation, where it has been discovered that simultaneous saccharification and fermentation (SSF) increases ethanol yields by lowering process costs and end-product inhibition. (Miller *et al.*1959).

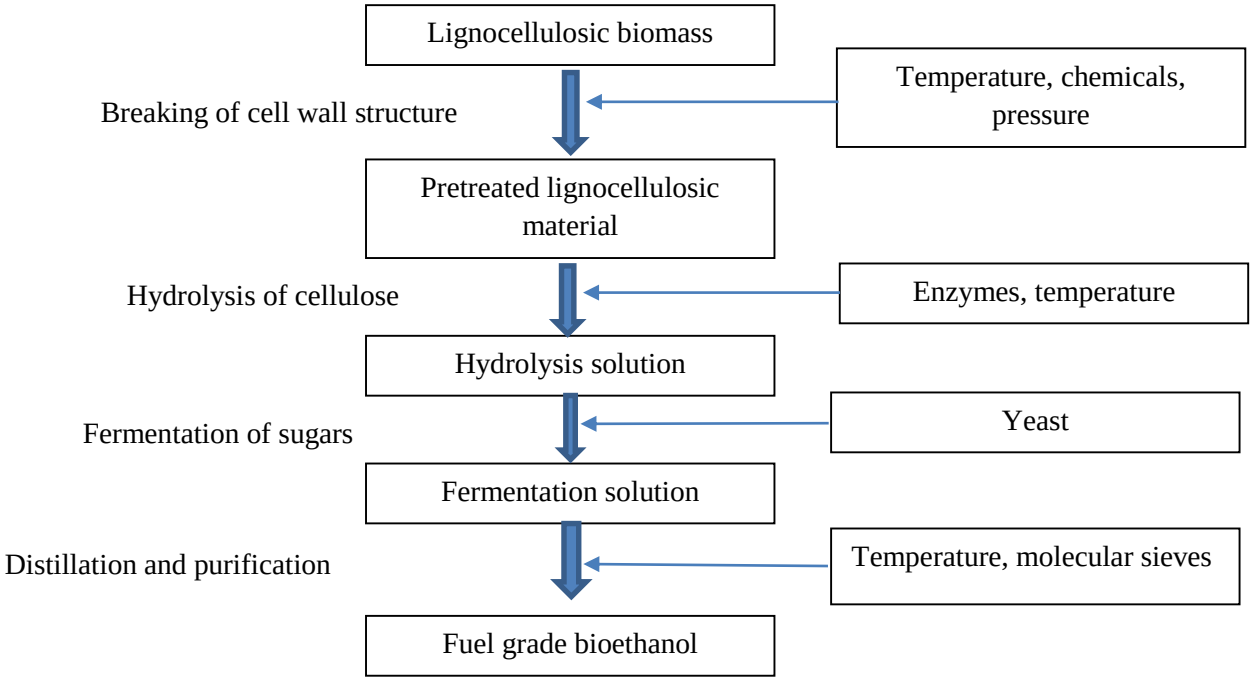

FIGURE 1: Schematic representation of the biomass conversion into bioethanol.

All things considered, the transition to using MSW for the production of bioethanol is a significant step towards a circular economy, in which waste is recycled to create beneficial biofuels. The recent developments in the enzymatic hydrolysis of MSW are examined in this review, with a focus on process integration, fermentation tactics, enzyme optimisation, and pretreatment methods for effective bioethanol production. This research aims to contribute to the ongoing efforts to make bioethanol a viable and scalable alternative to fossil fuels by addressing current issues and identifying potential technological advancements.

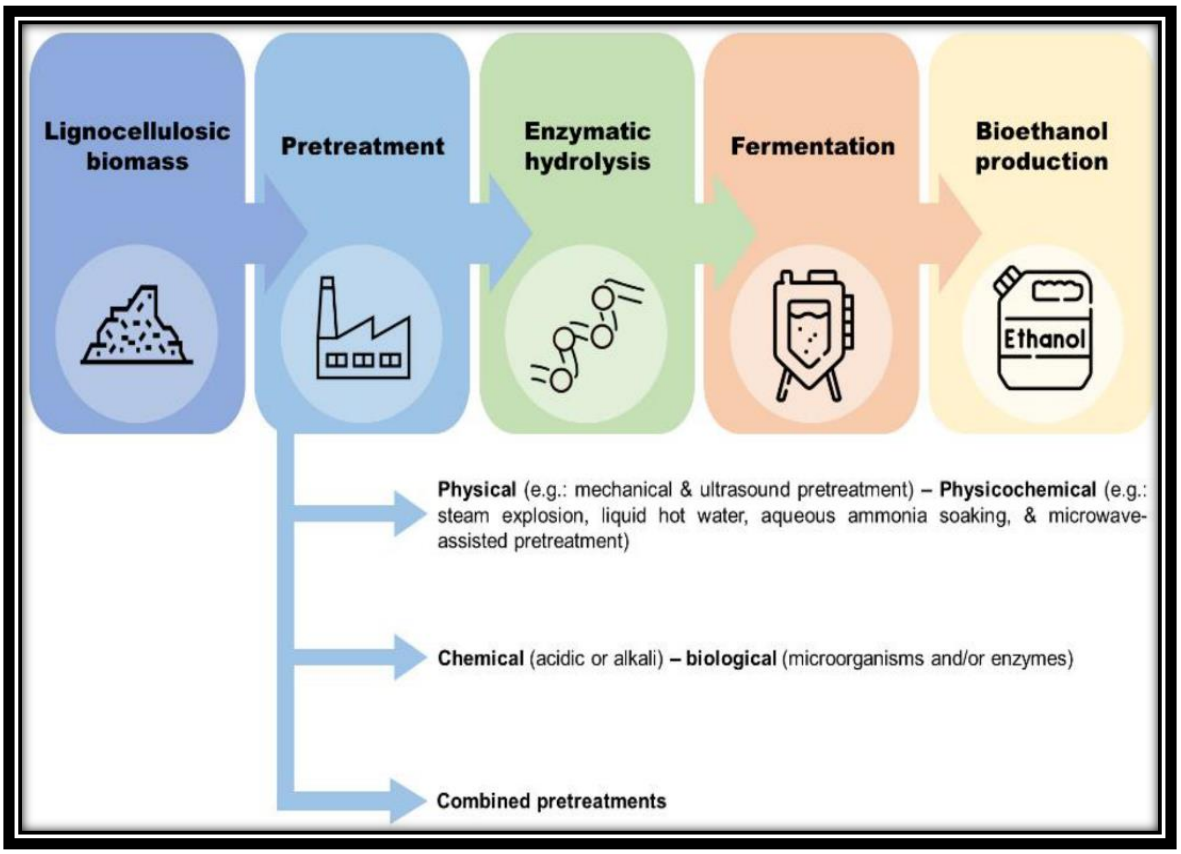

FIGURE 2: General overview of bioethanol production from lignocellulosic biomass.

II. MATERIALS AND METHODS

The significant amount of cellulose-containing waste materials, such as paper, cardboard, and food waste, MSW, was selected as the feedstock. (Sun *et al.* 2002 and Mood *et al.* 2013). The source and collection method affect the structure and content of MSW, which in turn affects how it is used for enzymatic hydrolysis (Taherzadeh *et al.* and Karimi *et al*. 2007, and Wyman *et al*. 2005). To determine MSW's suitability as a feedstock for the production of bioethanol, some studies have looked at its physicochemical characteristics**.** (Banerjee *et al.* 2010 and Jönsson *et al* 2016).

To break the resistant structure of the lignocellulosic compounds in MSW, pretreatment is required. To break down lignin and enhance enzyme access, alkaline hydrolysis using NaOH or ammonia was used (Kumar *et al.* 2020 and Mansfield *et al.*1999).

To hydrolyse hemicellulose and get rid of inhibitors, acid hydrolysis using diluted sulphuric or hydrochloric acid was done.(Hendriks *et al.* 2009 and Bansal *et al.* 2012). By upsetting the structure of the biomass, steam explosion, a high-pressure steam process was used to improve enzymatic digestibility. (Miller *et al.* 1959 and Chang *et al.* 2016) Furthermore, lignin and hemicellulose were preferentially broken down by biological pretreatment using microbial cultures or enzymes, increasing the accessibility of cellulose (Sun *et al.* 2002 and Mood *et al.* 2013).

Cellulose and hemicellulose were hydrolyzed to fermentable sugars by enzymatic hydrolysis using a combination of cellulases and hemicellulases.(Taherzadeh *et al*. 2007 and Wyman *et al.* 2005).Altering the enzyme concentration (5–20 FPU/g substrate), temperature (45–55°C), pH (4.8–5.5), reaction time (24–72 hours), and substrate loading (5–20% w/v) allowed for optimisation.(Banerjee *et al.* 2010 and Jönsson *et al* 2016). To improve hydrolysis efficiency, several enzyme cocktails were screened, such as ***Aspergillus niger*** hemicellulases and industrial cellulases from ***Trichoderma reesei***. (Kumar *et al.* 2020 and Mansfield *et al.*1999).

To evaluate enzyme stability and sugar recovery, hydrolysis was performed in batch and fed-batch operations. The process was made cost-effective by utilising enzyme recycling techniques, such as immobilisation and adsorption-desorption procedures (Hendriks *et al.* 2009 and Bansal *et al.* 2012).

Ethanogenic microorganisms such as ***Zymomonas mobilis, Saccharomyces cerevisiae***, or genetically modified ***Escherichia coli*** were used to ferment hydrolysed sugars (Hendriks *et al.* 2009 and Bansal *et al.* 2012). The highest ethanol production was attained by optimising fermentation parameters such as pH (4.5–6.0), temperature (30–37°C), agitation (100–200 rpm), and nutrient addition. (Miller *et al.* 1959 and Chang *et al.*2016). To compare them, process integration techniques like simultaneous saccharification and fermentation (SSF) and Separate hydrolysis and fermentation (SHF) were assessed. To increase the production of ethanol, the co-fermentation of pentose and hexose sugars was also investigated. (Sharma *et al*. 2019 and Gupta *et al*. 2020) To improve microbial resistance to inhibitors in hydrolysates, metabolic engineering techniques were applied (Mood *et al.* 2013 and Jönsson *et al* 2016). Reducing sugars, ethanol production, and biomass composition were measured in order to compare the efficiency of enzymatic hydrolysis and fermentation. The reducing sugar was measured using the Dinitrosalicylic Acid (DNSA) assay, which showed an increase from 250 mg/L to 750 mg/L after enzymatic hydrolysis (Miller *et al.* 1959). Depending on the fermentation conditions and substrate, yields of 30-45 g/L were reported using high-performance liquid chromatography (HPLC) to determine the ethanol content (Zhang *et al.* 2018 and Singhania *et al.* 2013). Scanning electron microscopy (SEM) and Fourier-transform infrared spectroscopy (FTIR) were used to compare the structural changes made to MSW biomass before and after hydrolysis. (Mood *et al.* 2013 and Jönsson *et al* 2016). Furthermore, to predict hydrolysis performance and provide ideal enzymatic reaction parameters, kinetic modelling was carried out. (Taherzadeh *et al*. 2007 and Wyman *et al.* 2005).

III. RESULTS AND DISCUSSION

Under ideal circumstances, the lower sugar concentrations increased from the initial 200 mg/L to over 800 mg/L, resulting in a high sugar release from the enzymatic hydrolysis of MSW.(Kumar *et al.* 2020).The most effective pretreatment for maximising enzymatic digestibility was alkaline, which increased sugar yield by 45–60% compared to untreated MSW.(Srivastava *et al.* 2017)**.**Despite being effective at breaking down hemicellulose, acid hydrolysis created compounds that inhibited fermentation, such as furfural and hydroxymethylfurfural, which required detoxification processes.(Patra *et al.* 2017). The microbial strain and process parameters affected the fermentation efficiency. While SSF was more productive and showed less end-product inhibition, Saccharomyces cerevisiae produced 40 g/L of ethanol in SHF.(Banerjee *et al.* 2019).By effectively utilising pentose sugar, co-fermentation using modified *Escherichia coli* enhanced ethanol yield by 15–20%. Under ideal fermentation and enzyme loading conditions, the highest ethanol content was 45 g/L. (Chen *et al.* 2017). Following enzymatic hydrolysis, structural characterisation using FTIR and SEM demonstrated widespread degradation of lignocellulosic moieties, with cellulose's crystallinity being reduced by 30–50%, depending on the pretreatment.(Sharma *et al.*2019). According to kinetic studies, hydrolysis was a first-order reaction, and the rate of reaction increased as the enzyme dose increased. (Lynd *et al.* 2017).

Although encouraging progress has been made, large-scale realisation remains a challenge. Process economics are impacted by substrate heterogeneity and enzyme prices, which necessitate advancements in process integration and enzyme recycling (Sarkar *et al.* 2012). To improve hydrolysis and fermentation efficiency at a reduced cost, future efforts should focus on developing stable microbial strains and efficient enzyme formulations (Zhang *et al.* 2018). This study highlights the potential of enzymatic hydrolysis for the production of bioethanol from MSW, which has significantly improved ethanol productivity and sugar recovery through the use of microbial engineering techniques and optimised process conditions.

IV. CONCLUSION

One promising method for producing bioethanol sustainably is the enzymatic hydrolysis of MSW. The effectiveness of enzymatic hydrolysis and optimised pretreatment techniques in significantly increasing sugar recovery and ethanol yield is covered in this work. However, to make it appropriate for large-scale implementation, technical and financial challenges such as substrate heterogeneity, process scale-up, and enzyme cost must be resolved. To make it more effective and economical, future research should concentrate on developing enzyme engineering, optimising microbial fermentation, and integrating bioprocesses.

In addition to producing energy, waste management and bioethanol production can have two benefits: reducing landfill disposal and promoting the circular economy. Enhancing the economic feasibility of bioethanol production will require improvements in microbial strains, process technology, and enzyme recycling. To facilitate the transition to cleaner biofuels, governments and industry must collaborate in supporting research and development projects. If these obstacles are removed, enzymatic hydrolysis of MSW would contribute significantly to the attainment of global renewable energy goals, reduce reliance on fossil fuels, and reduce environmental pollution, all of which would contribute to a cleaner, more sustainable world.

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