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Sugarcane Waste (Bagasse), a Goldmine: Quantifying Furfural Production Potential and Feasibility in Rahim Yar Khan District

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Abstract

This study investigates the untapped potential of sugarcane bagasse in Rahim Yar Khan for furfural synthesis, a valuable chemical produced from agricultural waste. This study analyzes the production potential and assesses the economic viability of extracting furfural from bagasse using acid-catalyzed hydrolysis. The study involved collecting bagasse samples from various sugarcane mills, performing experiments, and analyzing the detected furfural using colorimetric and analytical techniques. Furfural extraction is profitable, as the economic study shows, with a significant return on investment anticipated. The results emphasize the sugarcane sector of Rahim Yar Khan as a possible source for sustainable furfural production, supporting a circular economy and opening doors for the chemical industry in Pakistan. . This study provides essential data for future research and implementation of furfural production in Pakistan, laying the groundwork for additional exploration of this subject.

(Keywords: Sugarcane Bagasse, Furfural, Rahim Yar Khan District, Quantitative Estimation, Feasibility, Economic Analysis, Renewable Energy, Agricultural By-products.)

1 Introduction

The agricultural industry is a pillar of Pakistan's economy, not only supplying food but also boosting exports and alleviating poverty through the provision of raw resources. Sugarcane stands out among the key crops not just as a critical food source but also as a formidable energy crop with far-reaching applications [1-3] . Because of its complex genome and resilience, sugarcane is an excellent option for genetic manipulation. It is a member of the Poaceae family of grasses [4]. Sugarcane displays its worth as a global cash crop, flourishing in tropical and subtropical regions. Brazil, India, China, Thailand, and our own Pakistan dominate sugarcane production, playing critical roles in the global landscape shown in *figure 1.1*[5, 6].

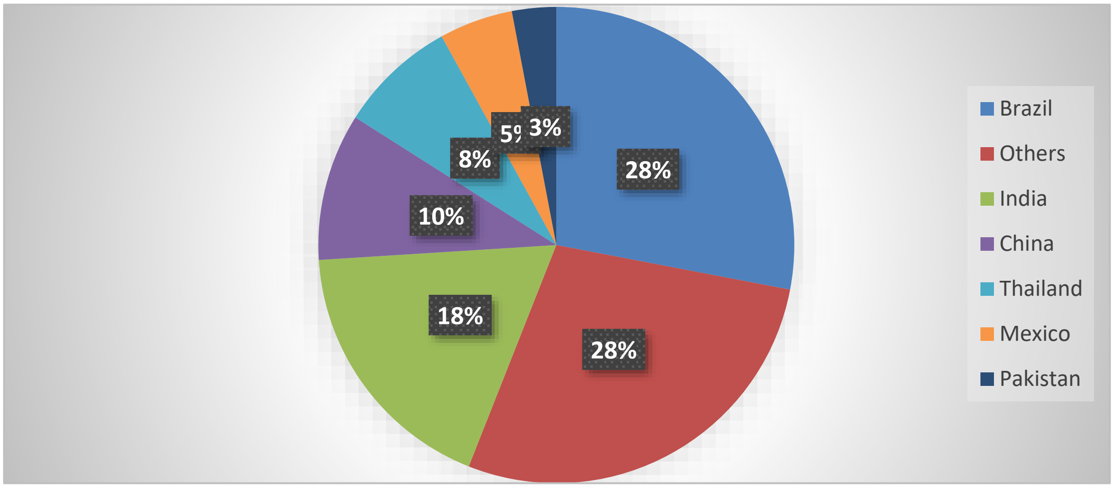

Figure 1.1: World Major Sugarcane Producing Countries

1.1 Sugarcane: A Cash Crop in Pakistan

Sugarcane is the second most important crop in Pakistan's agricultural tapestry, providing the second most revenue. It supports a significant portion of the economy by making contribution to the sugar industry. This verdant crop is grown across provinces, with Punjab leading the way in output [4]. The distribution of sugarcane output across the provinces is explained in *Table 1.1*, which provides a clear illustration of the essential role that each area plays in maintaining this important industry.

Table 1.1: Production of Sugarcane in Provinces of Pakistan

Name of PROVINCES	**LAND AREA *(hectors)***			**TOTAL PRODUCTION *(tons)***		
	2020-21	2021-22	2022-23	2020-21	2021-22	2022-23

Sindh	276	280	280	20,365	22,365	22,565
Punjab	780	900	905	54,778	59,777	60,077
KPK	108	109	109	5,810	6,810	6,810
Baluchistan	1	1	1	47	48	48
Total	1,165	1,290	1,295	81,000	89,000	89,500

Source: MNFSR, PSMA, and FAS/Islamabad (Marketing Year 2022-23)

1.2 Is Sugarcane Just a Sweetener?

Sugarcane has many uses beyond sweetness [7]. It serves as a crucial component of various sectors, catalyzing the manufacture of textiles, ethanol, medicines, and animal feed. Going further, we investigate the wealth of by-products that sugarcane industry has produced. These by-products power several businesses, ranging from the widely used molasses to the frequently disregarded press mud and bagasse. *Table 1.2* provides an overview of the products obtained from this adaptable plant[8].

Table 1.2: Products of Sugarcane

Food	Fructose, sucrose, syrups, and jaggery.
Fodder	Top-portion, Green Leaves.
Fiber	Cellulitic materials
Chemicals	Bagasse, alcohol, and press mud.
Fuel	Residue/waste materials

1.3 Bagasse: A Valuable Source of Various Products

Bagasse is a dry pulp waste received during sugarcane juice extraction. Bagasse has many potential uses, but it is frequently considered waste. Bagasse, a lignocellulosic material [9] , is used in different applications such as the paper industry, raw materials, and bio-fuels [10, 11]. Potential applications of bagasse are given in *figure 1.2*.

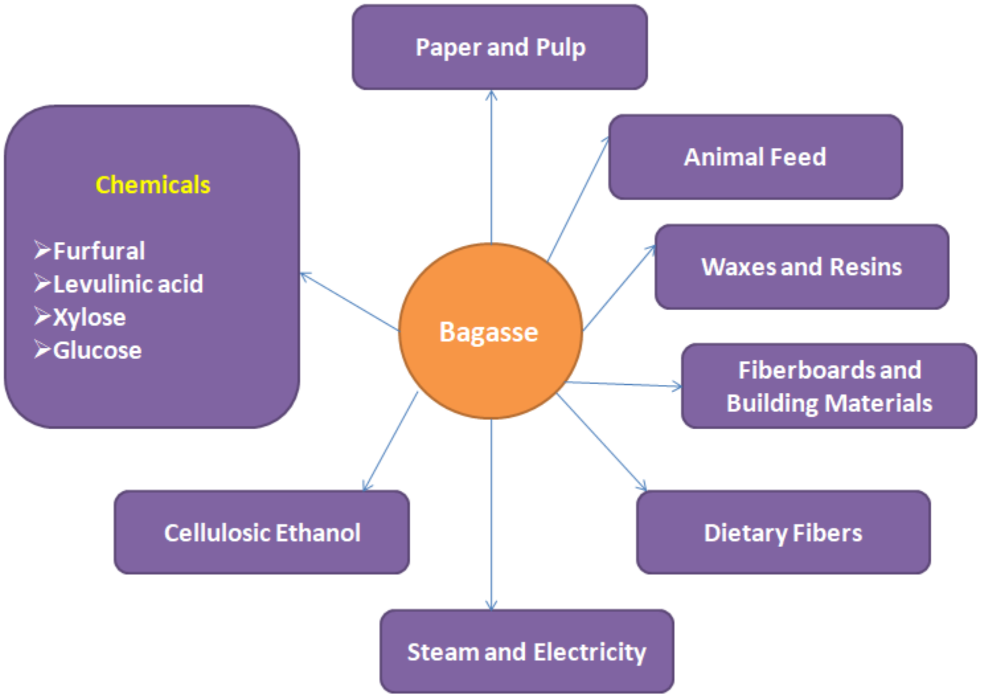

Figure 1.2: Potential Applications of Bagasse

1.3.1 Chemical composition of Bagasse

Table 1.3 provides a breakdown of its chemical makeup and suggests a variety of uses, including the production of paper and biofuel [12].

Table 1.3: Chemical Composition of Bagasse

Name of the Content	Percentage
Hemicellulose	25–28
Cellulose	47-52
Lignin	20–21
Ash	1-5
Other	0.8-3

1.4 Furfural: The Gold Garbage

Furfural, sometimes known as "**Garbage Gold** "is a valuable and reasonably priced chemical extracted from agricultural waste, mainly corncobs and sugarcane bagasse. It is a colourless to yellow liquid that smells like almonds. The German Chemist Dobereiner isolated furfural in 1821 and it has been a vital player in the industry since the Quaker Oats Corporation began producing it on a large scale in 1922. It is the chemical equivalent of 5-hydroxymethylfurfural (HMF), as shown in *Figure 1.3* [13-17].

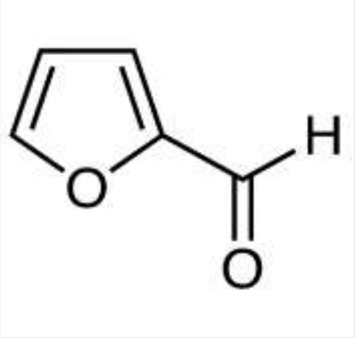

Figure 1.3: Furfural Structure

1.4.1 Furfural Applications

Furfural is a bio-based alternative in a variety of applications, including paints, plastics, antacids, Biofuels, and fertilizers, making it a significant resource for sustainable production. *Figure 1.4* shows furfural potential applications.

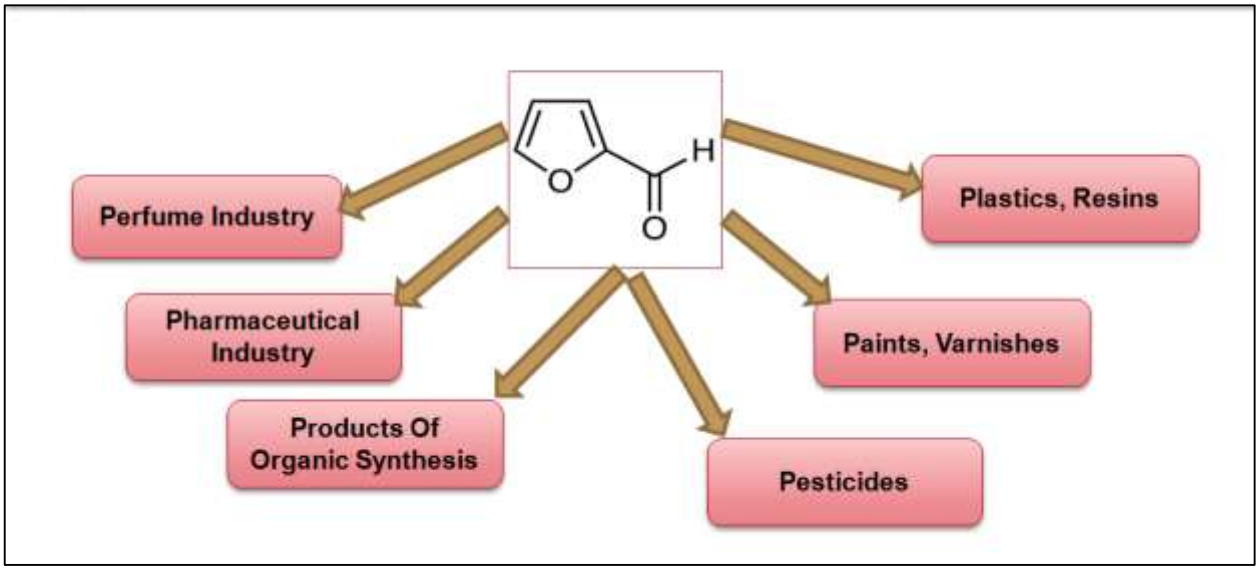

Figure 1.3: Applications of Furfural

1.4.2 The Furfural Market

The furfural market is projected to develop at a compound annual growth rate (CAGR) of 4.9% to reach $700 million by 2024 from 340 tons produced in 2019 valued at $551 million [18, 19]. South Africa, the Dominican Republic, and China are major manufacturing hubs driven by the demand for furfural derivatives in the oil refining and pharmaceutical industries [13, 20, 21] . Furfural is a precursor for more than 80 chemicals, with furfuryl alcohol being the most important (>50% of the market). Methylfuran, tetrahydrofuran, tetrahydrofurfuryl alcohol, methyltetrahydrofuran, and furoic acid are other derivatives produced by a variety of catalytic processes, including hydrogenation, hydrocracking, oxidation, reduction, and decarboxylation[18, 22]. Furfural market is explained in *figure 1.5*.

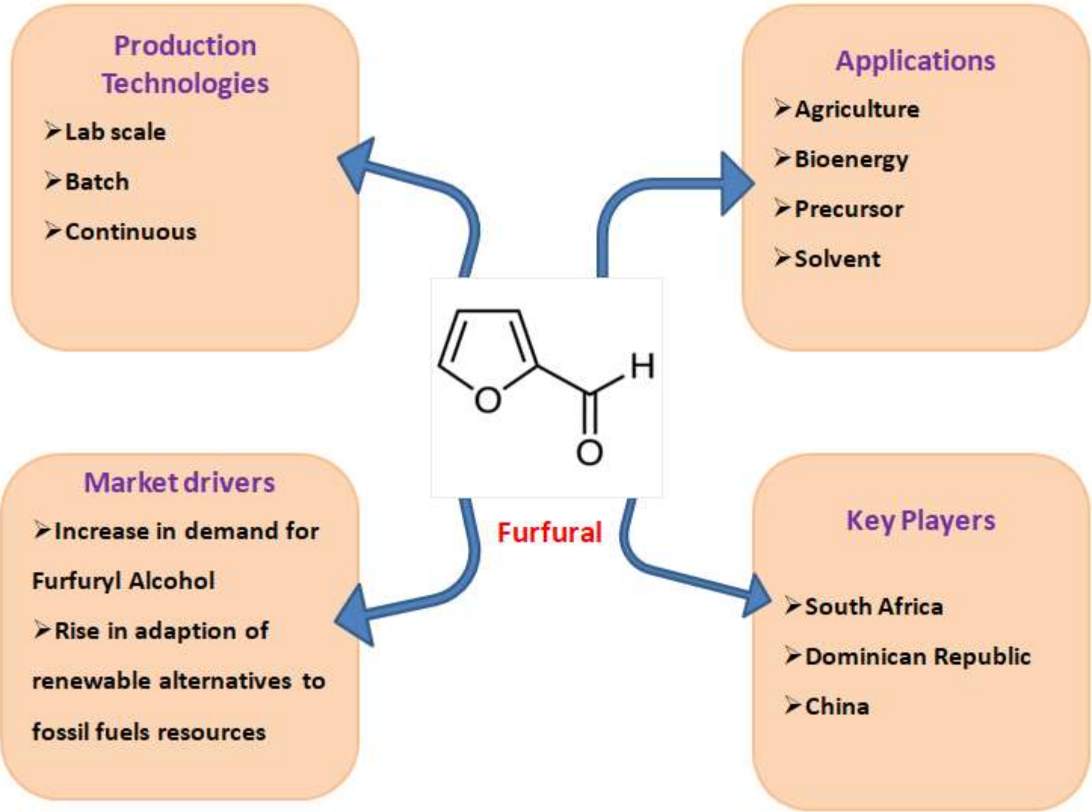

Figure 1.4: Furfural Market

1.5 Research Goals

❖ To determine the amount of untapped furfural in sugarcane bagasse for its viability

❖ To investigate the possibility of producing economical and sustainable furfural from sugarcane bagasse

❖ To discover hidden potential in sugarcane bagasse in Rahim Yar Khan District, beyond conventional agricultural boundaries, for a sustainable future

2 Literature Review

2.1 Brief Description of Furfural

Furfural, a heterocyclic aldehyde discovered in 1821, as a byproduct in formic acid synthesis. Large-scale production was first implemented by the Quaker Oats Company in 1922, utilizing agricultural wastes such as sugarcane bagasse and corncobs[16]. Although it is a potentially useful chemical, traditional processes that use mineral acids have drawbacks that force plant closure. Research is being conducted on alternative industrial processes using lignocellulosic biomass and plentiful waste from forestry and agriculture. Autocatalytic processes are promising; however, their commercialization is hampered by solvent recovery issues. Despite being better suited to the environment, solid catalytic systems have issues with their yield and selectivity. Despite current obstacles, the availability of lignocellulosic waste offers a chance for innovation and further study to maximize furfural production, highlighting the necessity for better solid catalytic systems and solvent recovery designs [23].

2.2 Furfural Synthesis from Lignocellulosic Materials

The primary source of furfural is a lignocellulosic biomass with high hemicellulose content. However, based on the species and ecological growth conditions, lignocellulosic biomass has different compositions and structures. Corncobs and sugarcane bagasse are the most frequently used sources for furfural manufacturing [24, 25] provide a thorough analysis and important data on biomass compositions given in *table 2.1*.

Table 2.1: Different Lignocellulosic Biomass Composition

Lignocellulosic biomass	**Hemicelluloses %**	**Cellulose %**	**Lignin %**
Sugarcane bagasse	24	40	25
Corncob	**35**	**39**	**15**
Corn fiber	**35**	**35**	**8**
Rice straw	**25**	**35**	**12**
Wheat straw	**21.2**	**38.2**	**23.4**

Corn straw	**25**	**40**	**17**

2.3 Furfural Formation Chemistry

Hemicellulose is converted to furfural in 2 steps[26]. In the 1st step, hydrolysis of polysaccharides to simple sugars takes place. Xylan is reduced to monomeric xylose. Xylose is then converted to furfural by dehydration, which removes three water molecules in the second step (*figure 2.1*) [27].

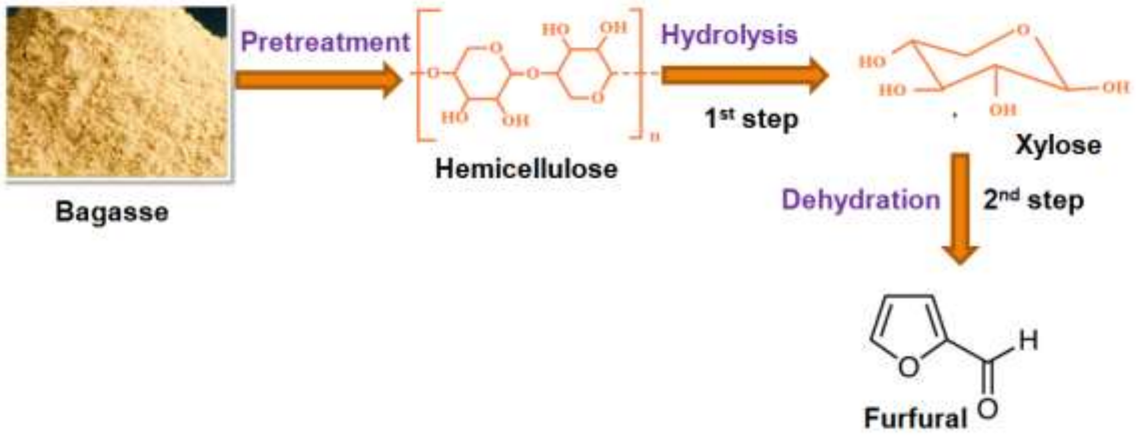

Figure 2.1: Furfural Formation Chemistry

2.4 Furfural Production from Sugarcane Bagasse

The investigation of furfural production from lignocellulosic biomass, specifically sugarcane bagasse, has received considerable attention. In 2002, Lavarack *et al.* focused on the negative environmental effects of bagasse storage and suggested more energy-efficient ways to reduce the amount of bagasse used in sugar mill boilers[28]. Uppal *et al.*'s (2008) study on furfural production in sugarcane cultivars focused on the effects of acid treatment on yield[29]. Mesa *et* *al*. (2014) investigated enzymatic hydrolysis for the manufacture of ethanol by delving into the restructuring processes for furfural and xylose from bagasse[30]. Ameh *et al*. (2016) examined the effects of various acids on yields while concentrating on the synthesis of furfural through acid hydrolysis[31]. Yazdizadeh *et al*. (2016) presented a novel method for furfural synthesis that uses neural network analysis for prediction and $NaHSO_4$ as a promoter and H_2SO_4 as a catalyst[32]. Li *et al.* (2016) discussed the difficulties with solid catalytic systems, stressing the need for solvent recovery and looking at specific circumstances for the synthesis of furfural[33]. Zhang *et al*. (2016) tested several catalysts and highlighted the effectiveness of modified beta zeolites in the transformation of cellulose and glucose[25]. Brønsted acidic ionic liquids were introduced by Matsagar *et al*. (2017) for the production of furfural and C_5 sugars in high yields[34]. Wang *et al*. (2018, 2019) demonstrated effective furfural and levulinic acid syntheses in two steps using solid acids and $FePO_4$ catalysts[35, 36]. In their 2020 study, Catrinck *et al.* focused on the selective hemicellulose de-polymerization of niobium-phosphate and niobic acid catalysts [37].The possibility of using a magnetic sulfonated graphene oxide catalyst for furfural synthesis was highlighted by Trung *et al.* (2020) [38]. Lee *et al.* (2020) examined solvent systems for furfural synthesis, emphasizing the need for enhanced economic performance[27]. Contreras *et al.* (2020) optimized furfural manufacturing plants by considering several pretreatment methods and purification procedures[39]. Li *et al*. (2021) created a sulfonated Al-coconut shell activated carbon catalyst to synthesize furfural from sugarcane bagasse[40]. Ntimbani *et al.* (2021) investigated joint synthesis of furfural and ethanol, assessing various scenarios for feasibility[41]. Dulie *et al.* (2021) studied bagasse hydrolysis optimized conditions for xylose yield and incorporating a solid acid catalyst[14]. Almeida *et al.* (2022) performed techno-economic analyses of furfural synthesis from sugarcane bagasse[42]. Huong *et al.* (2022) investigated process conditions by studying sulfonated graphene-oxide catalysts for furfural synthesis[43].Amesho *et al.* (2022) proposed a microwave-mediated furfural synthesis system from sugarcane bagasse waste, generating high yields of furfural, 5-hydroxymethylfurfural, and levulinic acid[44]. Gomes *et al.* (2023) proposed an environmentally friendly approach that maximizes furfural yields by producing furfural from bagasse acid hydrolysate utilizing a bi-phasic system [45].Zhou *et al.* (2023) identified a novel and recyclable heterogeneous catalyst, Pd-PdO/$ZnSO_4$, for furfural synthesis via flash pyrolysis of lignocellulosic biomass[46].

3 Material and Method

3.1 Sample Collection

Bagasse samples were collected from the following different sugarcane mills located in Rahim Yar Khan District of Pakistan.

Sample A: Eithad Sugar Mills, Karmabad

Sample B: Jamal Din Wali Sugar Mills Jamal Din Wali

Sample C: Hamza Sugar Mills Ltd. Jetha Bhutta Khanpur

Sample D: RYK Sugar Mills Ltd. Mouza Puraran Sharif, Janpur, Liaquatpur

3.2 Sample Identification

The samples (A-D) were dried in an oven at 60°C to eliminate moisture, and then they were ground to a fine powder and bagasse samples were successfully identified botany laboratory. Bagasse sample is shown in *figure 3.1*.

Figure 3.1: Sugarcane Bagasse sample

3.3 Chemicals and Reagents

Sulfuric acid (H_2SO_4, 98%) was purchased from Sigma-Aldrich (USA). NaCl (99%) was obtained from Merck (Germany). Furfural (98%) was purchased from Fluka (Switzerland). All other chemicals and reagents were of analytical grade and obtained from local suppliers.

3.4 Chemical Apparatus

I used the apparatus reported by Gebre *et al*. (2015) for the manufacturing of furfural from bagasse in the laboratory.

- Grinder
- Sieve
- Tube and Condenser
- Round bottom flask
- Beaker
- Shaker (stirrer)
- Burette
- Thermometer
- Measuring cylinder
- Oil bath

Reference: Synthesis of furfural from bagasse [47]

3.5 Experimental Procedure

In this experiment, in a 500 ml round-bottomed flask 15 g of dried powdered bagasse having a thickness of about 1 mm, 150 ml of 2 % sulfuric acid (H_2SO_4), and 15 g of salt was taken. After creating a uniform mixture by shaking the flask, it was attached to a tube and water condenser, as shown in *Figure 3.2*. Heating was performed in oil bath, and the flame's intensity was controlled to ensure that the liquid was distilled with appropriate rate. The distillation procedure was carried out until virtually no more furfural was received in the receiving flask.

Figure 3.2: Experimental Setup for Furfural Formation

Ethyl acetate was added in the distillate with 1:1 (v/v) ratio. The mixture was decanted to allow the layers of furfural, and Ethylacetate to separate, with the furfural-Ethylacetate layer floating on the top. The furfural-Ethylacetate mixture was subsequently treated with anhydrous Na_2SO_4 to remove any remaining water. Through filtration Na_2SO_4 was removed, and the mixture of furfural and Ethylacetate was distilled at 77.1°C to produce brownish-yellow liquid furfural, in pure form.

Figure 3.3: Furfural Obtained

3.6 Analysis of furfural

Following techniques are used for furfural analysis.

3.6.1 Colorimetric Furfural-Aniline Test

In a ratio of 25:2 (v/v), furfural distillate was mixed with aniline, to conduct the furfural-aniline test. After shaking the mixture, 2 ml of concentrated hydrochloric acid (HCl) was added. The presence of furfural is indicated by a reddish-orange color.

3.6.2 Analytical Techniques

Furfural was identified using UV and FTIR spectroscopy. By using UV spectroscopy absorbance at maximum wavelength of different samples, with the help of unique peaks is determined and compared with standard value. Through FTIR spectroscopy, aldehyde functional group in different samples is determined through specific vibrational bands giving unique peaks.

3.7 Data Analysis and Data Precision

The following equation was used to calculate the percentage yield of furfural:

Percentage yield of furfural = mass of furfural obtained/mass of raw material ×100

The results were analyzed using statistical methods.

The experiments were performed three times, to ensure the accuracy of the analysis. All the tools and materials used were appropriately calibrated and standardized.

3.8 Feasibility of Furfural Extraction from Bagasse

The cost of production for the extraction of furfural from bagasse samples was evaluated based on the cost of the raw materials and the market price of furfural.

4 Result and Discussion

4.1 A Brief Overview

The goal of this study was to estimate quantitatively and evaluate the feasibility of furfural extraction from bagasse produced in the Rahim Yar Khan district using sulfuric acid (H_2SO_4) and NaCl. In the extraction process, four different bagasse samples were used and the amount of furfural produced was quantified. The Furfural-Aniline test and Analytical techniques (UV, FTIR) identified furfural, later, the feasibility of furfural extraction was also determined.

4.2 Identification of Furfural

Following technique was used to identify the furfural in distillates.

4.2.1 A Colorimetric Furfural-Aniline Test

Furfural is detected by Furfural-aniline test. When test was performed, an orange red colour was appeared which is the confirmation of the presence of furfural.

Table 4.1: Furfural-Aniline Test for Identification of Furfural Distillates

Samples	Colour	Result
A	Orange Red	Positive
B	Orange Red	Positive
C	Orange Red	Positive
D	Orange Red	Positive

4.2.2 Analytical Techniques

4.2.2.1 UV Spectroscopy

The findings of the UV scans for the prepared samples are shown in Figures 4.1–4.4. Saturated aldehyde and ketones containing carbonyl groups show strong absorption bands in the UV range of 270–300 nm. This absorption band shifts to longer wavelengths, notably 300–350 nm, when the carbonyl group is conjugated with a double bond[48] .

As shown in *Figure 4.1*, **Sample A** contained a carbonyl group because of the noticeable absorption peak at 283.6 nm. Likewise, **sample B** in *Figure 4.2* appears to have an aldehyde functional group owing to a significant absorbance at approximately 279 nm

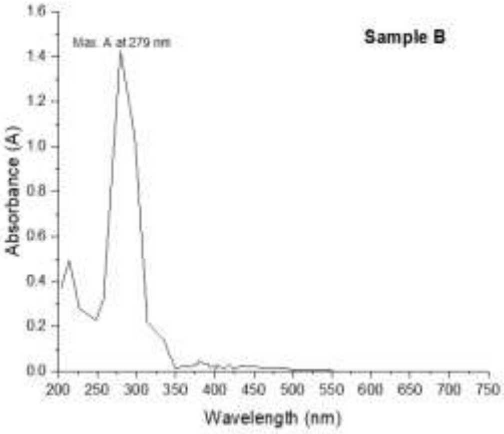

Figure 4.2:UV Graph Sample B

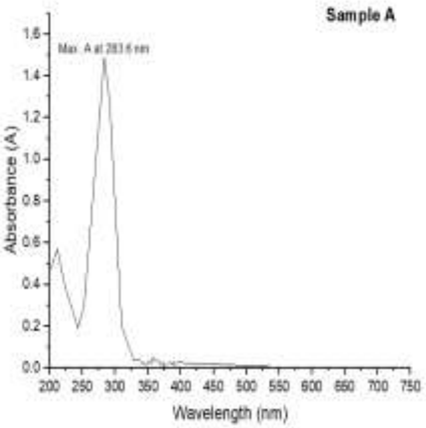

Figure 4.1: UV Graph Sample A

The distillate of **sample C** showed a clear peak at approximately 277 nm (*Figure 4.3*). As shown in *Figure 4.4*, distillate **sample D** has an aldehyde functional group, with a strong absorbance at 276.9 nm.

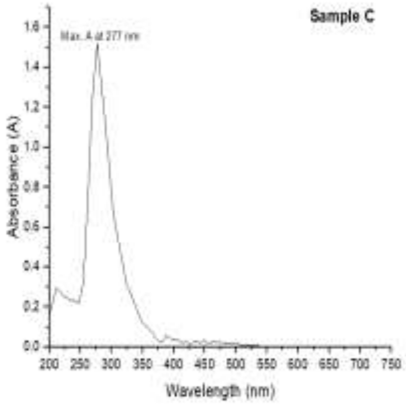

Figure 4.3: UV Graph Sample C

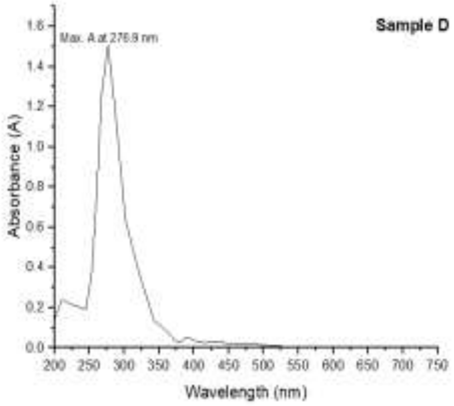

Figure 4.4: UV Graph Sample D

4.2.2.2 FTIR spectroscopy

The Furfural presence is verified by FTIR spectroscopy using functional group comparison with the reference spectra. The vibrational bands of C-H stretching (2900-2700 cm^{-1}), C=O stretching (1740-1620 cm^{-1}), aromatic C=C stretching (1620-1560 cm^{-1}), aromatic C-H stretching (3060-3010 cm^{-1}), and C-O-C stretching (1140-1070 cm^{-1}) are peculiar to the aldehyde functional group in furfural[49].

FTIR analysis of **Sample A** (*Figure 4.5*) showed characteristic vibrational patterns at 2840 cm^{-1} (C-H stretching) and 1696 cm^{-1} (C=O bond), C-O-C group at 1110 cm^{-1}, and the aromatic C=C group displayed vibrations at 1587 cm^{-1}. FTIR examination of **Sample B (** *Figure 4.6)* revealed distinguishing peaks of the aldehyde functional group in furfural, such as C-H stretching vibrations (2847 cm^{-1}) ,C=O bonds (1699 cm^{-1}), aromatic C=C group (1591 cm^{-1}) and C-O-C group (1137 cm^{-1}).

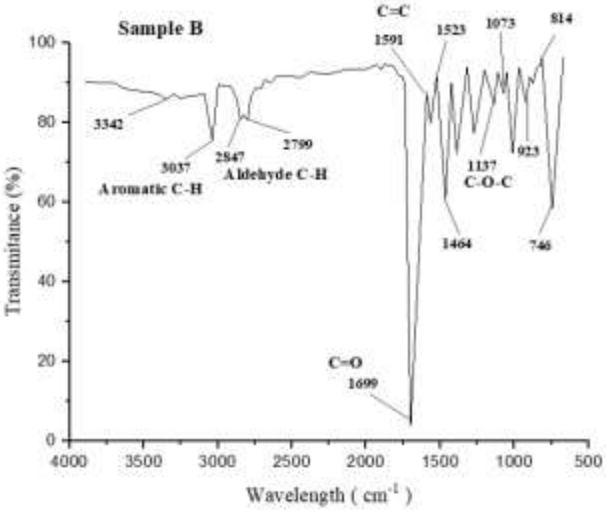

Figure 4.6: FTIR Plot of Sample B

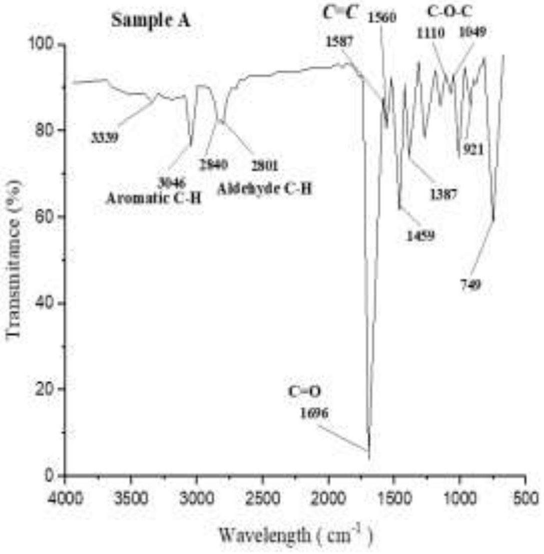

Figure 4.5:FTIR Plot of Sample A

Sample C (*Figure 4.7*) showed distinct vibrational patterns at 2854 cm^{-1} (C-H stretching), 1706 cm^{-1} (C=O bond), 1594 cm^{-1} (aromatic C=C stretching), and 3023 cm^{-1} (aromatic C-H group), and the vibration peak at 1121 cm^{-1}(C-O-C group). FTIR analysis of **Sample D** (*Figure 4.8)* showed a C=O bond at 1691 cm^{-1}, C-H stretching vibrations at 2843 cm^{-1}, aromatic C=C group stretching vibrations at 1601 cm^{-1}, aromatic C-H group absorption at 3017 cm^{-1}, and a C-O-C group vibration peak at 1096 cm^{-1}.

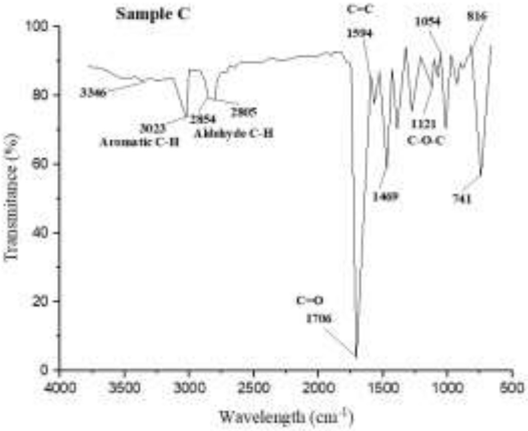

Figure 4.8: FTIR Plot of Sample C

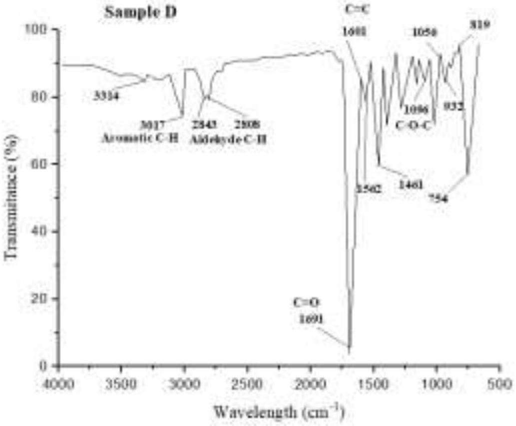

Figure 4.7: FTIR Plot of Sample D

Furfural was successfully identified using analytical techniques (FTIR, UV) and colorimetric testing. Furfural identification in the samples was strongly supported by vibrational peaks in the FTIR research and distinct absorption patterns in the UV spectrum, as well as by positive colorimetric test results.

4.3 Feasibility of furfural extraction

The growing sugarcane sector in Rahim Yar Khan, Punjab, provides an abundance of bagasse, a by-product of sugar extraction. It is possible to extract valuable furfural from bagasse by hydrolyzing and dehydrating it using acid-catalyzed procedures. Furfural has the potential to be a versatile molecule, with applications including solvents, furan resins, furfuryl alcohol, and food ingredients. The growing demand for furfural in pharmaceutical applications is expected to propel the compound annual growth rate (CAGR) to 5.6% between 2022 and 2031. With 193.03 thousand hectares of farmland, the area guarantees a reliable and reasonably priced raw material.[50, 51]

4.3.1 Economic Analysis of Small Scale Project

This economic analysis focuses on a small-scale plant that can process 100 kg of bagasse per day and generate 10 kg of furfural with a 10% yield. According to local suppliers, the price of primary raw material, bagasse, is 2800 PKR per ton, whereas the market price of furfural in Pakistan ranges from 17,000 to 20,000 PKR per kg.

Table 4.2: Cost of Raw Material

Components	**Price (million PKR)**
Cost of 100 kg bagasse per day	0.00028
Other raw material (H_2SO_4, NaCl etc.) per day	0.08122
Operational cost (Labor cost, utility, maintenance) per day	0.0075
Total cost per day	0.089 m
Total cost per year (325 working days)	28.925

4.3.1.1 Expected Revenue of Furfural Production

Daily produced furfural = 10 kg

Market price (Whole sale) of furfural = 12000 (0.012 m) PKR per Kg

Revenue per day = 12000 × 10 = 120,000 (0.12m) PKR

Revenue per year (325 working days) = 39 million PKR

Net profit (NP) per year = Revenue – total cost

NP /per year = 39 – 28.925 = 10.075 millions PKR

Estimated revenue per year is 10.075m (ten million 75 thousand) before taxes.

4.3.1.2 Return on Investment

Estimated cost of infrastructure and land (Local Area) = 2 million PKR

Estimated cost of equipment = 3 million PKR

Total cost of raw material (per year) = 28.925 million PKR

Total investment = 33.925 million PKR

Return on investment (ROI) = net profit/total investment × 100

ROI = 10.075/33.925 ×100 = **29.7%**

With expected annual revenue of 10.075 million PKR and a healthy net profit, furfural production from sugarcane bagasse in Rahim Yar Khan appears to be a viable operation. Financial viability is illustrated by a 29.7% return on investment (ROI). The proven availability of bagasse as a raw material highlights the importance of carefully evaluating its market dynamics, competitiveness, and hazards. Further research is required to evaluate these findings and investigate new growth potential.[52, 53]

4.4 Conclusion

This study unlocks the potential of furfural extraction from sugarcane bagasse in Rahim Yar Khan, showcasing a yield of 10% and confirming feasibility through tailored reaction conditions. The process not only produces furfural but also valuable by-products like levulinic acid, xylose and glucose enhancing economic viability. While further optimization and scale-up studies are warranted, this approach holds promise for sustainable bio-based chemicals, fostering a circular economy. Despite the need for comprehensive economic and environmental analysis, this exploration positions Rahim Yar Khan's sugarcane bagasse as a profitable source for furfural production, offering a pathway to a thriving industry in Pakistan.

4.5 Acknowledgment

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