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Research article

Bioethanol production from pineapple fruit waste juice using bakery yeast

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ABSTRACT

The declining oil production stemming from decreasing raw material reserves has clashes with rising demands and has created a supply-demand gap in the overall energy sector. Excessive consumption of fossil fuel oil exacerbates environmental issues, potentially leading to global climate change and increased natural disasters. Consequently, there are efforts in looking for alternate renewable fuel sources. The study included physical pre-treatment, natural hydrolysis, natural fermentation, fermentation of pineapple waste juice using bakery yeast, and subsequent distillation. The pineapple wastes produced juice with 12.67 °Brix and pH range of 3.16–3.18. The present study reports bioethanol production from pineapple waste mixed with bakery yeast (*Saccharomyces cerevisiae)* and pineapple wastes juice without bakery yeast, revealing that the yeast-amended mixture yielded bioethanol with alcohol content of 45 % compared to 36 % from pineapple juice alone. Re-distillation enhanced bioethanol content from 25 % - 45 %–85 % which aligns well with E85 fuel specifications, indicating bioethanol's suitability as fuel. Thus, bioethanol derived from pineapple fruit wastes presents a promising renewable energy solution. This study investigates the production of bioethanol from pineapple waste juice by comparing two methods: one using bakery yeast and the other without yeast. Both methods are conducted at room temperature to evaluate their efficiency and effectiveness in converting pineapple waste juice into bioethanol.

1. Introduction

The world is undergoing substantial global warming primarily because of the widespread use of fossil fuels [1]. These fuels, which include coal, oil, and natural gas, are heavily utilized for electricity generation, transportation, and various industrial activities [2]. This led to increased research, investment, and innovation in renewable energy technologies such as solar, wind, and biofuels [3]. Biofuel, a promising renewable energy source, is produced from lignocellulosic materials like wood, agricultural residues, and forest by-products [4]. One type of agricultural waste that is valuable for biofuel production is pineapple waste [5]. The pineapple fruit (PI) holds significant global importance and ranks among the most edible fruits worldwide [6]. The PI fruits ranks the third highest tropical fruit in terms of global production [7]. It is consumed both fresh and in juice form, appreciated for its refreshing taste and versatility in culinary applications [8]. Commercially, PI fruit is primarily processed into canned fruit as well as juices, concentrates, and jams [7].

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The processing of PI into various products generates substantial wastes, estimated to account for approximately 40–50 % of the fruit's weight in the form of peels [9,10]. This is primarily because certain components are unsuitable for human eating thus, are selected and eliminated as waste. Studies have reported PI waste to poses significant environmental challenges as it accumulates without any commercial value [10]. Since such wastes are costly to dispose of due to transportation expenses and limited landfill availability, they are often discarded irresponsibly and hence, raising several environmental concerns [11]. Still, projections show that rejected PI wastes can be exploited for further industrial uses such as bioethanol generation and the extraction of bioactive components [12]. This is an opportunity to not only reduce wastes but also extract valuable resources for various applications [12]. The PI wastes are rich in sugar, making them excellent raw materials for bioethanol production [13]. The high sugar content in these wastes enhances the efficiency of bioethanol production processes [13]. Studies indicate that PI peels contain a considerable quantity of an insoluble fibre-rich fraction, comprising mainly cellulose, pectin substances, hemicellulose, and significant levels of lignin [14]. These components serve as valuable raw materials for production of bioethanol, contributing to sustainability of biofuel production processes [14]. These wastes are susceptible to microbial spoilage due to their organic composition and high moisture content [15]. Consequently, they create suitable environment for fermentation using naturally occurring microbes, which efficiently convert the sugars present in the waste material into bioethanol [13]. Several naturally occurring microorganisms such as fungi, yeast, and bacteria, have been assessed for their ability to from PI wastes during bioethanol production [16]. Microorganisms such as *Saccharomyces cerevisiae* and *Zymomonas mobilis* have been employed for bioethanol production through fermentation of PIFWs juice as they increase the rate of bioethanol generation [16].

Several steps are used in the production of bioethanol from pineapple wastes, with pre-treatment being a crucial initial phase. Pre-treatment breaks down the complex structure of lignocellulosic biomass comprising cellulose, hemicellulose, and lignin to release fermentable sugars, which are essential for efficient bioethanol production. This step enhances the yield by maximizing sugar availability and minimizing the formation of inhibitory compounds that could impede fermentation. Various pre-treatment methods, including physical (e.g, Microwaves and water pretreatment) [17], chemical (e.g., acid, alkaline, organosolv, oxidative treatments), and biological approaches, are utilized [18]. Physical pretreatment methods like mechanical comminution and steam explosion increase biomass surface area and disrupt its structure, enhancing enzyme accessibility [19]. Chemical methods, including acid, alkaline, organosolv, and oxidative treatments, use chemicals to break down lignin and hemicellulose, releasing cellulose for hydrolysis but may produce fermentation inhibitors [20]. Biological pretreatment employs fungi, bacteria, or enzymes to selectively degrade lignin and hemicellulose; it's environmentally friendly but slower [21]. Hydrolysis is essential in bioethanol production, converting polysaccharides in biomass into simple sugars like glucose and xylose [22]. This can be done through enzymatic hydrolysis, using specific enzymes to break down cellulose and hemicellulose, or acid hydrolysis, which uses strong acids but may produce unwanted by-products [22]. Albeit, hydrolysis of fruit wastes by acids can lead to the degradation of sugars, forming unwanted by-products such as furfural and 5-HMF, which can negatively impact sugar availability for fermentation [23]. Fermentation is the process where fermentable sugars are converted into ethanol [24]. This is achieved by using yeast or other microorganisms that consume the sugars and produce ethanol and carbon dioxide as by-products [25]. The efficiency of ethanol production can be significantly influenced by the choice of microorganism and the fermentation conditions, such as temperature and pH [26]. Distillation is used to separate ethanol from the fermentation mixture by concentrating it and removing water and other impurities, which is essential for achieving high bioethanol purity [24].

Bioethanol serves as a green, sustainable and renewable alternative energy source, offering a promising substitute for traditional fossil fuels (FFs) [27]. Bioethanol production contributes to energy security by diversifying the energy mix and promoting sustainable energy practices [16]. The adaptability of bioethanol extends beyond its use as a sustainable fuel. Research show that bioethanol is blended with gasoline in various proportions to create biofuel blends suitable for conventional combustion engines [28]. For instance, an 85 % bioethanol and 15 % gasoline blend, known as E85, is commonly used as a renewable fuel for vehicles [29]. New engine designs have been developed to run entirely on pure ethanol, and there are also flexible fuel vehicles that can operate on various mixtures of ethanol and gasoline, with ethanol concentrations ranging from 0 % to 85 % (E85) [4]. This blend, often referred to as flex-fuel offers benefits such as reduced emissions and decreased dependence on FFs. Still, bioethanol applications extend beyond fuel [29] and serve as a precursors for various valuable products such as preservative, where its antimicrobial properties make it effective for extending the shelf life of certain products [30]. Besides, it is used as a solvent in pharmaceuticals, cosmetics, and cleaning products, where it is valued for its ability to dissolve substances and facilitate processes like extraction and purification [31]. By diversifying its applications, bioethanol contributes to reducing reliance on FFs while supporting sustainable practices in multiple industries [32]. Various bioethanol yields from PI wastes have been reported; Fermenting enzymatically hydrolyzed PI waste with *Saccharomyces cerevisiae* produced 10.07 g/L of bioethanol [22]. The diluted pineapple waste juice, supplemented with sorghum flour as an additional source of fermentable sugar, yielded a 25 % bioethanol concentration [24]. Additionally, a bioethanol concentration of 25 % was achieved from pineapple waste hydrolyzed with *Trichoderma harzianum* [5]. Apart from bioethanol production, lignocellulose can produce other value-added products, including bio-chemicals and platform chemicals, biopolymers and enzymes through microbial fermentation, enzymatic processes, or thermo-chemical conversion of lignocellulose biomass [33]. Moreover, xylitol, butanol, biogas, nanocellulose and polyhydroxyalkanoate are produced from lignocellulose biomass [34]. Despite numerous studies investigating bioethanol production from PI wastes juice, there remains limited information regarding the production of bioethanol utilizing PI wastes juice with bakery yeast (*Saccharomyces cerevisiae)* as source of fermenting microbes at room temperature. Therefore, the current study is focused on generation of bioethanol from PI wastes juice using bakery yeast (*Saccharomyces cerevisiae*) at room temperature. This dual approach capitalizes on the essential microbial population in PI wastes which includes a variety of fungi, yeast, and bacteria capable of fermenting sugar into ethanol. By introducing *Saccharomyces cerevisiae*, a well-known and efficient ethanol-producing yeast strain commonly used in industrial fermentation processes, bioethanol production from PI wastes juice is

enhanced and accelerated. This combined strategy harnesses the natural fermentation potential of PI wastes juice while incorporating a known fermenting agent to optimize bioethanol yields.

2. Material and methods

2.1. Pineapple wastes collection sites and preparation

The PIFWs in this study were sourced from various locations, including the Mashine Tatu market, hotels, restaurants, and juice-processing vendors situated within Iringa Municipality. These establishments regularly generate large amount of PI wastes, which typically include discarded peels and rotten PI. By collecting PI wastes from these diverse sources, the study ensured representative sampling of the available residues, facilitating a comprehensive analysis of their suitability for bioethanol production. The PI wastes were grinded using a grinding mill and blended with a blender (KENWOOD-BLPA-10) to achieve a non-viscous juice consistently, the obtained juice was sieved with a clean sterile sieve. This physical pre-treatment processing approach was employed to break down the solid components of the PI wastes into smaller particles, facilitating simple juice extraction.

2.2. Hydrolysis

The study employed natural hydrolysis methods to break down complex carbohydrates in fruit wastes. This approach involved utilizing the essential enzymatic activities of naturally occurring enzymes within the fruit. Specifically, natural hydrolysis enzymes such as pectinase, cellulase, and hemicellulase, which are naturally present in the fruit or introduced through microbial action. By avoiding the use of synthetic chemicals or costly external enzymes, the study aimed to enhance the sustainability of the hydrolysis process, making it more environmentally friendly and cost-effective. This method not only reduced the environmental impact but also minimized operational costs, aligning with the study's goals of efficiency and eco-friendliness in bioethanol production.

2.3. Fermentation of pineapple wastes juice

In the present study, fermentation was carried out in two separate fermenting broths, each with a capacity of 10 L. In the first broth, PI wastes juice alone was allowed to ferment without use of bakery yeast while in the second broth, 200 gm of bakery yeast were added to 10 L of PI wastes juice to facilitate fermentation. This allowed for a comparative analysis between the two fermenting broths. Fermentation was conducted at room temperature ranging from 21 °C to 25 °C to simulate typical environmental conditions and facilitate microbial activity. Variations in the pH was also noted during the fermentation process and ranged from 3.17 ± 0.01 to 2.14 ± 0.01. Measurements of specific gravity, pH, and total soluble solids (TSS) were taken at 24-h intervals over 11 day's retention period and the progress of fermentation was monitored. Stirring around 50–75 revolutions per minute (RPM) was performed daily after measuring TSS, pH, alcohol content, and specific gravity to ensure even distribution of TSS in the pineapple juice.

2.4. Distillation of fermented PI wastes juice

Each batch of fermented PI wastes juice was filtered using a clean sterile sieve after completion of the process of fermentation. The filtrate was distilled using a distillation apparatus connected to an electrical source with the temperature controlled distiller (Delta Temperature Controller-DTA4848R0), to extract the alcohol from fermented PI wastes juice. A distillation apparatus connected to an electrical source and set at 80 °C was utilized to control the distillation process, aiming at maximizing bioethanol yield in the final product. The distillate was collected at a consistent temperature, in which three aliquots, were collected to provide the best possible yield of bioethanol. During distillation, the initial drop was collected after 20 min, followed by the collection of 100 mL of bioethanol after an additional of 3 min. The distillate was collected in an individual container (BOECO GERMANY) and its concentration was determined using an alcoholmeter (Alcoholmeter Gay Lussac), with each container labelled with the corresponding bioethanol concentration.

2.5. Re-distillation

After the initial distillation, bioethanol with a lower concentration was combined together, and a second distillation was performed at a temperature of 78 °C to enhance its purity. This temperature was chosen based on its effectiveness in evaporating ethanol while leaving behind impurities, thus improving the purity and concentration of bioethanol. This step aimed at removing any remaining impurities and increases the overall bioethanol purity, ensuring a higher quality end product suitable for various industrial and commercial applications.

The overall process of bioethanol production from PI wastes is summarized in Fig. 3.

2.6. Analytical methods

2.6.1. Total soluble solids analysis

The assessment of sugar content in PI wastes juice involved determining the concentration of sugars within the extracted juice. The TSS in degrees Brix (°Brix) was determined using a refractometer (ERMA TOKYO). One-degree Brix represents the strength of the

solution as a percentage by weight (% w/w), with each degree Brix equivalent to 1 g of sucrose in 100 g of solution [35]. The °Brix measurement provides an approximate assessment of the TSS content within the PI wastes juice. It offers an insight into the sugar content as well as other soluble solids present in the solution.

2.6.2. pH measurement

A Hanna pH meter (Model HI98129) manufactured by HANNA Instruments in Woonsocket, RI, USA, and Romania, was utilized to measure the pH of the PI waste juice. To ensure accuracy, the pH measurement instrument was first calibrated at pH values of 4 and 7. The pH readings were taken prior to and during fermentation in order to track any changes in acidity or alkalinity during the fermentation process.

2.6.3. Determination of the quantity of bioethanol

The quantity of bioethanol produced was established by measuring the volume of bioethanol obtained through distillation. The measuring cylinder (AXIOM GERMANY) was employed to measure the distillate collected from multiple bottles containing bioethanol content produced as a result of distillation.

2.6.4. Determination of the quality of bioethanol

The concentration of bioethanol obtained from fermentation was used to measure the quality of bioethanol generated in addition to the distillation process. This was accomplished using an alcoholmeter (Alcoholmeter Gay Lussac), which precisely measures the bioethanol concentration in the end product. Monitoring the bioethanol concentration not only helps to establish the purity and quality of bioethanol but also ensures its compliance with regulatory standards and specifications set for different industrial and commercial applications.

2.7. Data analysis

Data analysis from experiments conducted in triplicate was performed using Microsoft Excel (2016). Statistical analysis was performed using Analysis of Variance (ONE WAY ANOVA) and the probability value (P-value) ≤ 0.05 was achieved as a significant difference.

3. Results and discussion

3.1. Pre-treatment of pineapple wastes

The PI waste was physically pre-treated to obtain the juice. The TSS and pH of PI wastes juice are presented in Table 1. The quantity of FWs used yields a sufficient amount of juice suitable for bioethanol production. This not only ensures a consistent supply of fermentable material but also aids in waste management by repurposing discarded waste materials into a valuable renewable energy source.

Results show that the PI wastes juice exhibited an average TSS of 12.67 ± 0.03 °Brix. TSS levels reflect more fermentable sugars available for microbes' metabolism during fermentation, which in turn increase the rate at which bioethanol is produced. Therefore, the physical pre-treatment method utilized in this study is effective in recovering the juice with a significant amount of sugar content from PI wastes juice, which is crucial for subsequent bioethanol production. Further, the PI wastes juice exhibited an average pH of 3.17 ± 0.01 after physical pre-treatment. The observed pH in the current study aligns closely with the previous documented pH range of 3.08–4.25 [13]. Therefore, the pre-treatment method used in this study proves effective in maintaining the pH of the PI wastes juice, ensuring its suitability for subsequent fermentation processes.

3.2. Hydrolysis

In the present study, natural hydrolysis was involved through utilizing enzymes and natural microbial activities present in PI wastes. Natural hydrolysis in PI juice occurs through the processes facilitated by the juice's essential properties and natural microbial activity [36]. The PI juice contains natural pectinase enzymes including Polygalacturonase (PG), pectin methylesterase (PME) and Pectate lyase, which break down pectin, a major polysaccharide in fruit cell walls, leading to the partial hydrolysis of pectin into simpler sugars and other compounds [14]. The PG breaks down pectin by hydrolyzing glycosidic bonds, while PME demethylates pectin, making it more susceptible to degradation and Pectate lyase further cleaves demethylated pectin into smaller fragments, together facilitating efficient pectin breakdown during fermentation [37]. Additionally, although present in lower concentrations,

Table 1
Total soluble solids and pH of PI waste juice.

PI fruit wastes	Mass (Kg)	Volume of juice (L)	TSS (°Brix)	pH
PI wastes	17	13	12.7	3.16
	17	13	12.6	3.17
	17	13	12.7	3.18

cellulase and hemicellulase enzymes in PI juice further contribute to the breakdown of cellulose and hemicellulose, enhancing the hydrolysis process [38]. Thus, the present study is both environmentally and economically friendly as it minimizes the use of harmful chemicals and costly enzymes in the hydrolysis process. By leveraging natural enzymatic activities and microbial processes, the study reduces the reliance on synthetic substances and expensive reagents, making it a more sustainable and cost-effective approach. This not only benefits the environment by reducing chemical waste but also lowers operational costs, contributing to a more efficient and eco-friendly bioethanol production process (see Fig. 1).

3.3. Effect of fermentation on total soluble solids

The effect of fermentation on TSS of PI wastes juice with and without bakery yeast is illustrated in Fig. 2. The findings show that the fermentation process decreases the TSS of PI wastes juice, indicating the conversion of fermentable sugars into bioethanol. The findings indicate a rapid decrease in TSS of PI wastes juice mixed with bakery yeast as compared to PI wastes juice without bakery yeast. The TSS of PI wastes juice without yeast decreased during the first four days of fermentation, as shown in Fig. 2. Simple sugars accumulate in the juice before converting into bioethanol, while secondary metabolite production by specific microbes and enzymatic activity during fermentation could also raise TSS levels in the PI wastes juice [13]. The observed rise in TSS levels of PIFWs juice during fermentation in the present study aligns with previous findings, where TSS of PI wastes juice increased from 7.97 ± 0.05 to 9.80 ± 0.00 °Brix during the fermentation process [13]. From day 9–11 the fermentation process was maintained, indicating that the fermenting agents had reached a balanced phase, where the consumption of substrates and production of fermentation byproducts were at equilibrium. Following the initial decrease in TSS in the PI wastes juice, the TSS level stabilized due to a balance between sugar consumption and bioethanol production, along with the metabolic activities taking place during fermentation [39]. Thus the TSS remains constant during the stationary phase when microbial growth and death rates are balanced [39]. Furthermore, statistical analysis demonstrated a significant difference in TSS levels during the fermentation process, with a P-value of 3.97×10^{-35}, which is less than 0.05 ($P < 0.05$). Generally, the decline in TSS levels is associated with microbes which consume fermentable sugars during fermentation, converting them into bioethanol and weak acids through metabolism. Therefore, the rate of fermentation of PI wastes juice with added bakery yeast was significantly faster and more efficient compared to PI fruit wastes juice without additional of bakery yeast. The added bakery yeast rapidly consumed sugars, leading to a quicker decrease in TSS, while fermentation without additional of bakery yeast is slower in reducing TSS levels. Therefore, employing bakery yeast in the fermentation of PI wastes juice accelerates bioethanol production compared to relying on natural fermentation by wild microorganisms. Yeast ensures a faster, more efficient conversion of sugars to bioethanol, resulting in higher yield and consistent production.

3.4. Effect of fermentation on pH of pineapple wastes juice

The impact of pH on the fermentation of PI wastes juice with and without bakery yeast is illustrated in Fig. 2. As fermentation progressed, the pH of the fermenting PI wastes juice decreased consistently up to day 10 when it remained constant. The observed decrease in pH is primarily due to the consumption of sugar by the microbes during fermentation which yield alcohol and organic acids as reported previously [40]. These organic acids and carbon dioxide during fermentation contribute to the overall acidity of the fermentation broth, leading to a decrease in pH of PI wastes juice [41]. Moreover, previous research which support this phenomenon shows that during PI wastes juice fermentation, the pH decreased from 4.1 to 3.3 [42]. This indicates that as fermentation progresses, the pH decreases, leading to a more acidic environment in the PI wastes juice. Therefore, the pH of PI wastes juice with added bakery yeast typically decreases more rapidly and consistently during the fermentation process compared to PI wastes juice without additional of bakery yeast. This is due to the controlled and efficient metabolic activity of the yeast. In contrast, natural fermentation without

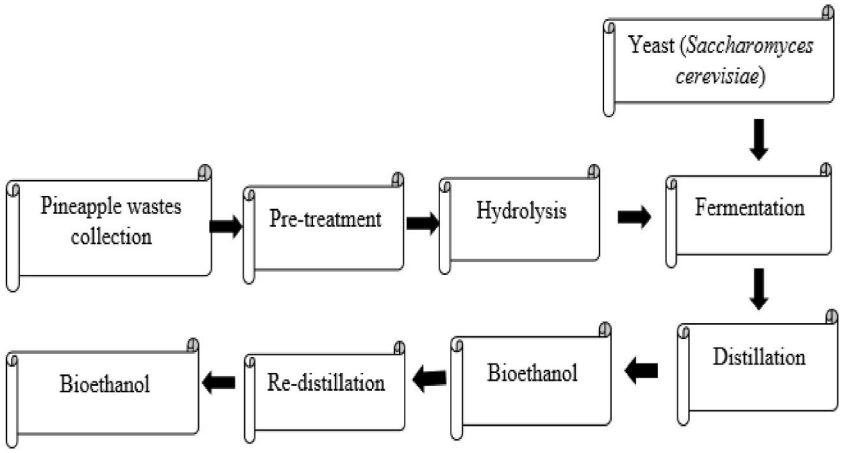

Fig. 1. Steps for bioethanol generation from pineapple fruit wastes.

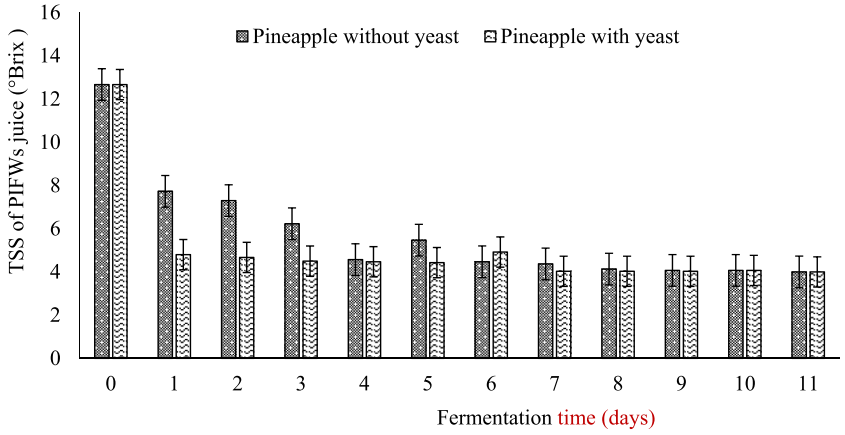

Fig. 2. Effect of fermentation on total soluble solids of pineapple wastes juice.

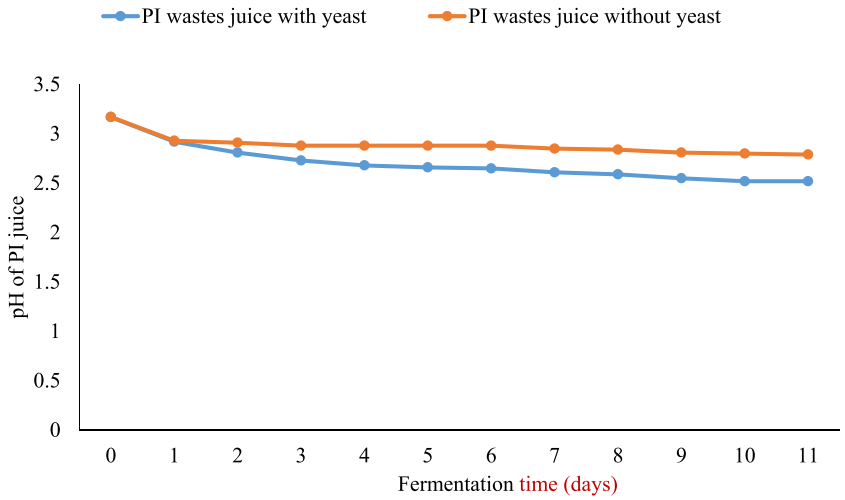

Fig. 3. Effect of fermentation on pH of pineapple waste's juice.

added yeast results in a slower and more variable pH decrease due to the diverse and less predictable microbial activity [43].

3.5. *Effect of fermentation on specific gravity of pineapple wastes juice*

The influence of fermentation on specific gravity of PI wastes juice is shown in Table 2. Findings indicate that as fermentation progressed, specific gravity of PI wastes juice without bakery yeast decreased from 1.06 to 1.01 and PI wastes juice with bakery yeast decreased from 1.06 to 1.00 indicating the conversion of sugars into bioethanol and weak acids. However, the statistical analysis revealed no significance in specific gravity decrease during fermentation with as indicated by $F_{(0.05,\ 1)} = 0.008$, $P > 0.05$. Moreover, the results indicate that the decrease in specific gravity in PI waste juice with yeast was notably higher compared to PI waste juice without yeast. This is primarily due to the accelerated rate of sugar consumption by the yeast in the yeast-added PI waste juice. The presence of yeast actively ferments the sugars, leading to a more rapid conversion of sugar into alcohol and carbon dioxide, which directly contributes to the more significant reduction in specific gravity. In contrast, the absence of yeast results in slower sugar consumption, accounting for the smaller change in specific gravity. This decrease in the specific gravity directly correlates with the production of bioethanol, as it reflects the reduction in sugar content and the concurrent increase in bioethanol concentration in the fermentation

Table 2
Effect of fermentation on PI wastes juice specific gravity.

	Specific gravity before fermentation	Specific gravity after fermentation
PI wastes juice without yeast	1.06	1.01
PI wastes juice with yeast	1.06	1

broth. The observed decrease in specific gravity in the current study relates with the previous observed decrease in specific gravity from 1.066 to 1.01 [44]. The significant decline in specific gravity, representing the TSS, as fermentation advanced suggests the consumption of fermentable sugars by microorganisms to produce bioethanol and weak acids [45]. Therefore, the observed decrease in specific gravity during the fermentation process in current study is directly related to the conversion of sugars into bioethanol and carbon dioxide by the yeast. As fermentation progresses, yeast consumes the sugars present in the PI wastes juice, producing ethanol and carbon dioxide (CO_2). Since bioethanol is less dense than the sugars it replaces, the overall density of the liquid decreases, resulting in a lower specific gravity.

3.6. Distillation of fermented PI wastes juice

The fermented PI wastes juice was distilled at 80 °C and the % alcohol contents collected at different stages of the distillation process are summarized in Table 3. The results in Table 3 demonstrate that PI wastes juice mixed with bakery yeast produced the bioethanol with the highest % alcohol content of 45 % compared to PI wastes juice without bakery yeast, which yielded 36 % alcohol content for the first aliquot of 100 mL. However, statistical analysis indicated no significant difference between the % alcohol content levels produced with a P-value of 0.3 ($P > 0.05$). The bioethanol concentration obtained in the PI wastes juice mixed with bakery yeast in the current study surpasses the previously documented bioethanol concentration of 38.42 % obtained in fermented PI wastes juice mixed with bakery yeast [46,46]. Also the third aliquot with bioethanol content with 25 % suppress the previous documented bioethanol of 18 % reported by Ref. [47]. Furthermore, the bioethanol content of 45 % derived from PI wastes juice mixed with yeast in this study corresponds to a previous study that reported a similar bioethanol content of 45 % following acid and enzymatic pre-treatment of PI wastes [47]. Additionally, as the sugar content and the population of sugar-metabolizing microbes increase, the concentration of bioethanol also increases [46]. Therefore, PI wastes juice with added bakery yeast typically results in a higher % alcohol content because bakery yeast efficiently converts sugars into alcohol while PI wastes juice without additional of bakery yeast results to low % alcohol content since natural microbes are less efficient at this conversion.

During distillation, the first drop was observed after 20 min, followed by the collection of 100 mL of bioethanol within 3 min. These findings differ from those of the prior study, where bioethanol distillation lasted for 1 h, resulting in a bioethanol concentration of 38.42 %, as documented in previous study [46].Hence, the distillation apparatus employed in the present study is efficient and produced bioethanol in a notably short timeframe.

3.7. Re-distillation

In this study, various concentrations of bioethanol obtained in the first distillation were blended and subsequently subjected to a second distillation process. Results demonstrate that re-distillation significantly enhances the quality of bioethanol, increasing its % alcoholic content from 25 % to 45 %, and subsequently to 85. The bioethanol produced, reaching 85 % purity in the present study, is suitable for use as a biofuel to power vehicles, offering a renewable and environmentally friendly alternative to traditional FFs. The earlier findings that a combination of 85 % of bioethanol and 15 % of petrol operates automobiles, support the superiority bioethanol obtained in the current study [48]. The bioethanol content ranging from 25 % to 85 % obtained in this study can be used as a fuel for operating cars. This is supported by the previous document which reported the flexible fuel vehicles are capable of operating on blends of gasoline and ethanol, with ethanol content ranging from 0 % to 85 % (E85) [4].

4. Conclusion and recommendation

4.1. Conclusion

In the present study, PI wastes including; peels and rotten PI was physically pre-treated so that their TSS were more accessible to hydrolysis and fermentation by the microbes. A significant limitation of physical pretreatment methods for fruit wastes, such as grinding and milling, is the potential loss of valuable nutrients and bioactive compounds. These processes can cause mechanical damage to the fruit tissues, leading to the degradation or oxidation of sensitive compounds, such as vitamins and phenolics, which could otherwise be valuable for fermentation or as co-products. A small amount of PI wastes yielded a substantial amount of juice, which in turn produced a significant quantity of bioethanol. This demonstrates the efficiency and potential of using PI wastes as a feedstock for bioethanol production, making it a viable and sustainable alternative energy source. Bioethanol with the 45 % alcohol content was produced from fermentation of PI wastes juice using bakery yeast (*Saccharomyces cerevisiae)* as source of fermenting microbes after distillation. Additionally, PI wastes juice without bakery yeast was used to produce bioethanol with the 36 % alcohol content after distillation. This demonstrates the significant role of bakery yeast in enhancing the fermentation process and bioethanol production. Furthermore, re-distillation improved the quality of the bioethanol produced from 25 % to 45 % alcohol content to 85 %, underscoring the efficiency of this method in concentrating bioethanol content. This two-step distillation process not only improved the purity and concentration of bioethanol but also highlights the potential for scaling up production for commercial applications. The re-distillation step is particularly crucial in achieving higher bioethanol concentrations, which are essential for various industrial uses.

Table 3
Percentage alcohol contents of the bioethanol produced.

Fermentation broth	First aliquot (%)	Second aliquot (%)	Third aliquot (%)
PI wastes juice without yeast	36	32	25
PI wastes juice with yeast	45	37	30

4.2. Recommendation

i. Further studies should focus on optimizing fermentation conditions to increase bioethanol yield and minimize the formation of unwanted by-products.
ii. Research efforts should be directed towards assessing bioethanol production from different species of pineapple wastes individually.
iii. The study can be extended to commercialisation that would reduce importation of ethanol for use in various schools, hospitals and research institutions as solvent, preservatives and other related applications.
iv. Technology transfer and knowledge sharing initiatives should be established to disseminate research findings and best practices regarding bioethanol production from PI fruit wastes. Collaborative efforts among research institutions, industry stakeholders, and government agencies are essential to facilitate the adoption of bioethanol technology.

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Data availability statement

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Additional information

No additional information is available for this article.

CRediT authorship contribution statement

Shedrack Thomas Mgeni: Writing – review & editing, Writing – original draft, Conceptualization. **Lewis Atugonza Mtashobya:** Writing – review & editing, Supervision, Investigation. **Jovine Kamuhabwa Emmanuel:** Writing – review & editing, Supervision, Investigation, Conceptualization.

Declaration of competing interest

The author declares that there is no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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