Review Article

“Exploring the Potential of Pearl Millet for Eco-Friendly Sugar Syrup Production”

Abstract

Pearl millet is a widely cultivated crop that finds its way into a variety of cuisines around the globe. PM is esteemed for its nutritional advantages, highlighting the importance of large-scale processing. It stands out as a sustainable and eco-friendly crop, demonstrating remarkable adaptability in both arid and rainfed areas. Its high productivity coupled with minimal water needs positions it as a significant contributor to addressing food insecurity and poverty challenges. This review highlights the significance of pearl millet as a promising source for the production of glucose, malt, and sugar syrup. The advancements in the sugar extraction process, focusing on techniques such as enzymatic hydrolysis and the application of hydraulic press mechanization has been examined. The implementation of strategies aimed at enhancing sugar-syrup production from PM presents a promising opportunity to decrease dependence on traditional sugar production methods, which typically require significant inputs from high-input crops.

Keywords: Pearl millet, starch modification, sugar syrup, sustainable food production and value-added products

1. Introduction

In light of the expanding global population and the necessity to boost food production efficiency, there is a perceived necessity to allocate resources towards the cultivation of crops with the capacity for broader consumption. In this particular context, Millet has the potential to address the nutritional requirements of a wide range of consumers residing in both rural and urban regions, irrespective of their socioeconomic standing, within both emerging and developed economies [1]. Additionally, millets are a non-gluten food source, making them very suitable for producing non-allergenic food products. The world production of millets accounts for about 32.09 million Metric tons with India ranking first with 42% of the total production (12.84 million Metric tons). Other major millet producers are Nigeria, Niger, China, Mali, Sudan, Burkina Faso, Senegal, and Ethiopia [2]

Pennisetum glaucum (L.), commonly referred to as Pearl millet (PM) belongs to the Poaceae family. It is also known by many common names such as Bajra, Bulrush, Cattail, Gero, Dukhon, and Babala in different regions across the globe [3]. PM, commonly regarded as having originated from Africa, holds the distinction of being the most extensively consumed millet globally [4]. The historical practice of cultivating PM in India may be traced back to the Neolithic period in South India, specifically from 2000 to 1200 BC. PM is the predominant variety of millet cultivated in India, with the highest production levels observed in the states of Rajasthan, Uttar Pradesh, Gujarat, Madhya Pradesh, and Haryana. These five states collectively contribute approximately 56% (9 Mt) of the total millet production in the country [5]. PM demonstrates a high degree of adaptability to unfavourable climate conditions, namely in regions where rainfall is below 250 mm and temperatures above 30°C. Its cultivation is primarily undertaken by subsistence farmers across the continents of Africa, Asia, and Australia [6]. It is a 'C4 type' photosynthetic crop and is well known for its higher productivity. Studies have reported that PM has a significantly lower carbon footprint 3218 kg CO2 eq/ha compared to commercial sources of cereals and grains such as wheat (3,968 kg CO2 eq/ha) rice (3,401kg CO2 eq/ha and maize 4052 kg CO2 eq/ha [7-12]. Also, the production of PM requires less fertilizers and pesticides in comparison to cash crops like sugarcane, making them an eco-friendly crop [7]. Integration of PM production with agroforestry can also be done as its deep rooting system helps in sequestering atmospheric carbon in the soil and it can help restore soil organic carbon in degraded lands, reducing net emissions [8]

From an economic perspective PM cultivation involves lower upfront costs, reduced dependency on expensive inputs, and minimal irrigation infrastructure, while delivering stable yields even under adverse conditions. This makes PM not only a scientifically and ecologically superior alternative but also an economically viable crop. It can be considered superior to crops like sugarcane and corn as they are less prone to yield losses and water stress along with lower utilization of groundwater sources. In terms of returns also the short growing season of PM allows for quicker income generation and can help farmers practise multiple cropping systems enhancing profitability.

PM have nutri-rich properties which are important for human health because of its alkaline properties in the gut, which can be beneficial for stomach ulcers Moreover, the rich mineral content can help in controlling blood pressure and managing respiratory problems [9]. Research has demonstrated its positive impact on bone health, while its high dietary fiber content promotes digestion and assists in controlling blood sugar levels [10]. Although phytic acid and tannins are present, they can help regulate blood cholesterol levels in specific cases [11]. Various processing steps like dehulling, soaking, germination, milling, fermentation, and parboiling can greatly impact millet starch digestibility [12]. Due to its relatively lower cost in comparison to crops like rice, corn and sugarcane, PM exhibits significant potential in several food applications. The bioavailability of nutrients in PM has been observed to be enhanced by processes such as fermentation [13–15]. Several studies have demonstrated the possible application of PM in the synthesis of enzymes such as α-amylase [16] and laccase [17]. Current research efforts are primarily directed toward augmenting the overall characteristics of this particular crop, encompassing its quality, quantity, and processing techniques. An overview of the processing and production of value-added products from PM is shown in Fig. 1.

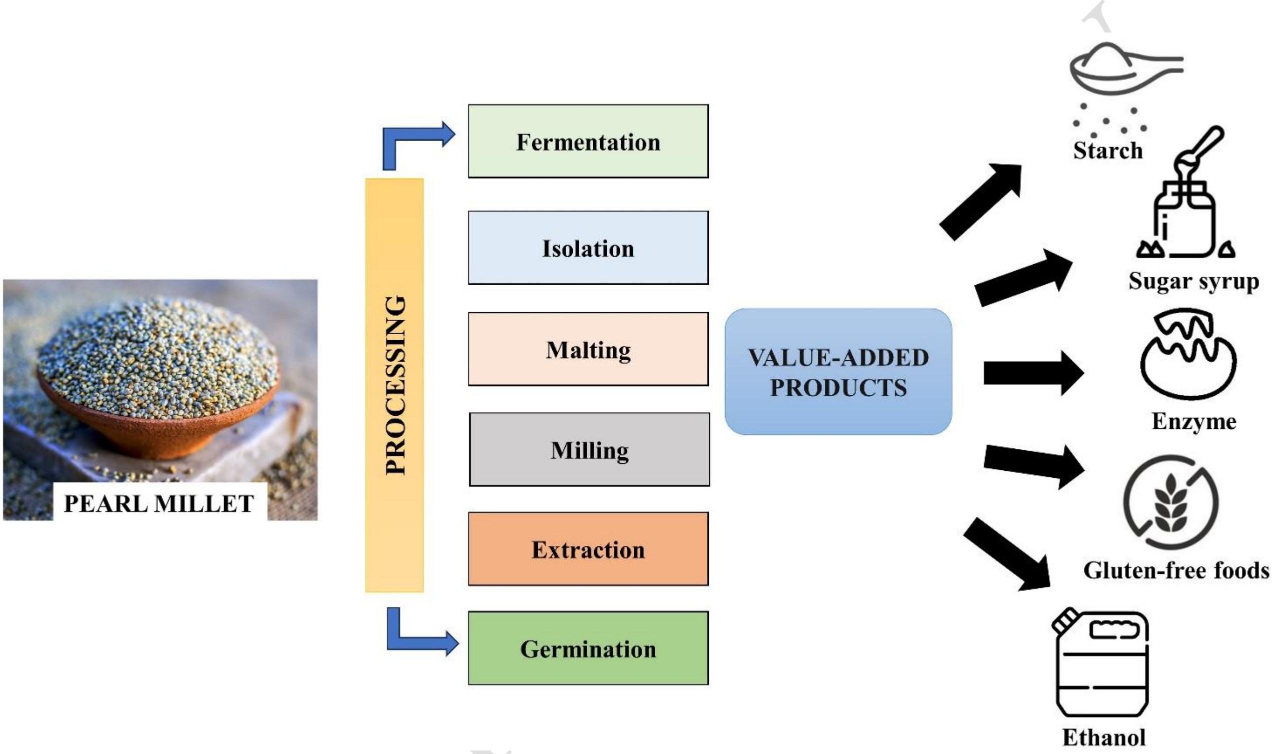

Fig.1: An overview of the processing and production of value-added products from PM

The decrease in the utilization of millet and its by-products can be ascribed to various factors, encompassing the swift progression of urbanization, alterations in consumer inclinations, insufficiencies in domestic infrastructure, the significant energy and time needed in the preparation of millet-based food, constraints in processing methodologies, inadequate marketing amenities, the relative scarcity of millet and its derivatives, unreliable supply networks, and comparisons drawn between millet and alternative food choices. Research on millet in general and PM, in particular, emphasizes how little is known about their potential as a source of sugar. PM are highly sustainable crop requiring less water and fertilizers compared to sugarcane or beets. It can be grown in marginal soils reducing pressure on fertile lands. It creates lower environmental footprint making it an attractive option for sustainable production. This article aims to explore the utilization of pearl millet for the production of starch-derived syrups, with emphasis on processing technologies and limitations.

2.0 Composition of PM

The various constituents of PM, namely the endosperm, germ, and bran, are utilized in a range of industries encompassing animal feed, fodder, silage, biogas production, and composting. PMs are recognized for their high energy content, with approximately 361 kcal [18]. The starch content in PM grains is approximately 70%, whereas the fat content in the germ constitutes approximately 80% of the grain [19].

The carbohydrate content of PM exhibits considerable variability, ranging from 61.5% to 89.1% [1]. The fat content of PM is reported to be around 7.8%, while the protein content is estimated to be approximately 13.6%. Insoluble ash constitutes around 2.1% of the composition, while crude fiber makes up approximately 2.8%. PM possesses a glycemic index (GI) of 55, rendering it the grain with the most minimal GI value. Its rich dietary fiber content and resistant starch, along with polyphenols helps in slowing down the release of glucose into the bloodstream. This makes it a good choice for managing blood sugar levels and supporting overall metabolic health [20].

In PM, the composition of free soluble sugars, including glucose, fructose, sucrose, and raffinose, constitutes approximately 1.2% to 2.6% of the total weight, free reducing sugars ranging from 0.9% to 2.5%, and non-reducing sugars ranging from 1.3% to 1.4%. The concentrations of glucose and fructose are approximately 0.6%,1.8%, and 0.3%, and 0.7%, respectively [21] .The main types of sugars found in whole grains consist of maltose and D-ribose, with fructose and glucose also present, although in relatively small amounts [22]. The degree of polymerization (DP) indicates the quantity of glucose monomer units found in the chain. The DP of PM starch was reported to be 1060-1250 for amylose and 9000-9100 for amylopectin, with an average chain length of 260-270 and 20-21, respectively [23]. The average chain length of amylose in PM was 18.0 [24]. The composition of pentosans in PM mostly consists of arabinose, xylose, and galactose, with rhamnose and fucose being present in smaller quantities [25] .The composition of PM starch is given in Table 1.

Table 1: Composition of PM starch [23,26]

Parameters	Values
Amylose	
Molecular weight	1 x 106 g/mol
Degree of polymerization	250 to 1000 D-glucose units
DP*	1060–1250
Chain lengths	260–270
Amylopectin	

Molecular weight	1 x 107 to 1 x 109 g/mol
Degree of polymerization	5000 to 50,000 D-glucose units
DP	9000–9100
Chain lengths	20–21

PM exhibits promising characteristics as an unconventional starchy substrate that can be efficiently employed for sugar-syrup production. In addition, its high carbohydrate content makes it a cost-effective choice as a starch source [27]. PM starch that has been altered chemically has been utilized in cooking dishes such as custards and ice cream [28,29], as well as in pharmacological uses [30,31]. Using starch from less common sources such as PM can help decrease dependence on traditional staple crops such as rice, wheat, potato, and corn. Due to its slow digestive properties and affordability, it is a valuable ingredient for creating functional food items tailored for infants, as well as individuals dealing with obesity and diabetes [32]. Unfortunately, despite its considerable potential, it has not been completely utilized in technologically advanced industrial sectors for sugar production and product preparations.

3.0 Transforming techniques for the development of pearl millet sugar syrups

The inherent characteristics of native PM do not possess the desired attributes for utilization in industrial settings. Consequently, it becomes vital to undertake a transformative approach involving chemical (alkali pre-treatment for biomass conversion to reducing sugars), physical (mechanical press treatment for extraction of sugars from stovers), and enzymatic methodologies (bacteria derived enzymes for hydrolysis of starch to simple sugars) to enhance its value and render it suitable for various applications [19]. The process of pure culture fermentation of PM has been identified as a novel approach to improving its nutritional composition [33]. This method has been found to induce notable alterations in the levels of protein, fat, vitamins, and accessible minerals in PM [34]. The conversion of starch to sugar in its natural state in PM is not readily achievable, necessitating the utilization of diverse enzymes during processing. The conversion of starch into glucose, maltose, and dextrin in industrial settings is achieved through a series of processes, namely gelatinization, liquefaction, and saccharification. In contrast to well-documented sources like barley and sorghum, the scientific understanding of millet malting, particularly about the process and optimal germination conditions for PM malting, remains relatively limited.

3.1 Germination of PM

The temperature at which steeping occurs has a crucial role in determining the gelatinization temperature of the starch material. This impact of steeping temperature and germination was evaluated by [35]. Their study found that at 30◦C, β- and α-amylase activity were at their highest regardless of germination time. This study is relevant to understanding how different temperatures of germinations can be useful to carry out superior germination processes thus leading to efficient breakdown of starch from the PM to produce glucose syrups. An observation wherein the starch production in PM exhibited an increase as the duration of steeping time progressed from 0 to 24 hours, and further up to 48 hours was observed by [36]. However, after this period, a subsequent drop in starch yield was noted.

In the process of germination, starch undergoes enzymatic degradation facilitated by amylase enzymes, resulting in the formation of smaller, more easily digestible carbohydrates with lower molecular weights, specifically oligo- and disaccharides. The activation of hydrolytic enzymes that occurs during germination induces various biochemical alterations, structural adaptations, and the production of novel compounds, several of which exhibit notable bioactivity. These bioactive compounds have the potential to enhance the nutritional composition of the grains [37]. Germination, when combined with pure culture fermentation, has resulted in a notable alteration in the composition of carbohydrates present in PM. When compared to raw PM grain, fermented sprouts had significantly less starch and a higher percentage of soluble carbohydrates [38]. A preliminary rise in the levels of reducing sugar as a result of the hydrolysis of starch and oligosaccharides was found in the unfermented samples of PM [39,40]. However, a subsequent decline was also seen in the amount of reducing sugar at later stages of fermentation, which can be attributed to the consumption of sugars by the microorganisms involved in the fermentation process. Therefore, the process of fermentation resulted in a notable alteration in the overall levels of soluble sugars, reducing sugars, non-reducing sugars, and starch content within PM flour. The fermented grains exhibited a reduced carbohydrate content and an increased presence of soluble and reducing sugars compared to the uncooked grains.

The comparison on the germinative energy and germinative capacity of sorghum and PM was done by [41]. The findings revealed that sorghum exhibited superior germinative energy and germination capacity, with approximately 90% for sorghum and 85% for PM. With germination properties reaching an approximate threshold of 90%, both millets exhibit promising potential as viable sources for the production of malt syrup. Although PM exhibits adequate malt production, it lacks the malting yield and germination capacity commonly found in commercial sources like barley. Furthermore, it presents significant challenges in terms of malting losses. Therefore, this particular factor may serve as a significant limitation in its application as an industrial source for the production of malt syrups.

Studies have reported that germinated PM contained more total soluble sugars (6.13 g/100 g), reducing sugar (3.43 g/100 g), and non-reducing sugar (2.70 g/100 g) than the control sample (1.76, 0.36, 1.40 g/100 g [38]. The homogenization and autoclaving of germinated slurry resulted in a further improvement of these constituents and a decrease in starch content, which may have been caused by starch hydrolysis and the release of more soluble carbohydrates.

3.2 Malting of PM

Malting is a biotechnological process that entails the deliberate initiation of germination in cereal grains. The objective of this process is to activate enzyme systems that facilitate the hydrolysis of complex reserved food materials, such as proteins, starches, and cell wall substances [42].This controlled environment becomes the nurturing ground for the germination of cereal grain and consequently enables the extraction of fermentable materials [14]. The potential of millet malting has been hindered by the existence of the active lipase enzyme and the occurrence of mold development [47] during the germination process. Nevertheless, when compared to other tropical cereals, millet malting exhibits a significantly advantageous ratio of α-amylase. If appropriate malting conditions are implemented, millet malt has the potential to serve as a high-quality raw material for the production of nutrient-dense specialty foods [43]. Tropical cereals, such as PM, exhibit a low presence of α-amylase but lack β-amylase in their ungerminated state. However, the process of germination triggers the synthesis of both amylases, with α-amylase being the dominant enzyme [44].

The diastatic power refers to the measure of the combined enzymatic activity of α and β-amylase in malt and is expressed as Degree Lintner (◦L). There exists a correlation between the diastatic power of malts and the levels of α amylase and β amylase activity. According to [45]the diastatic power of PM malt was shown to be significantly higher when compared to sorghum malts. The diastatic power of millet malt was shown to rise with the duration of steeping, and this increase was found to be closely correlated with the moisture content during the steep-out process [46]. In a study conducted by [47] the positive impact of a steeping regime, particularly the implementation of air rests, on the quality of sorghum malt, specifically about β-amylase activity was demonstrated. The utilization of air-rests likely facilitates enhanced oxygen availability, hence promoting a more expedited elevation in seedling metabolic activity. This method could thus be utilized to increase the diastatic power of PM. Due to the relatively small size of PM grains, the recommended duration for steeping is rather brief, in contrast to the 48–72-hour range suggested for barley. Previous studies have indicated that the steeping period for PM grains can vary between 6 and 16 hours [48].

3.3 PM malt syrup

Malt-based syrup can be described as a highly concentrated solution consisting of a combination of nutritive saccharides derived from edible starches found in malted cereal grains, all suspended in water [41]. There is a paucity of research conducted on the efficient conversion and extraction of sugar from starch derived from PM.

The method of creating malt-based syrups can be divided into three essential stages: malt production, wort preparation through infusion or decoction mashing, and subsequent saccharification of the wort into malt syrup with the aid of external starch hydrolyzing enzymes. The syrup obtained from the combination of saccharides is subsequently condensed to achieve a solid content of around eighty percent (80%) [35]. These processes rely on the utilization of amylolytic enzymes derived from microbial and plant sources [49]. α-amylase and glucoamylase are some of the commonly employed enzymes in conjunction with de-branching enzymes within industrial settings to facilitate the conversion of starch that has been liquefied by α-amylase into glucose.

Malt syrup made from sorghum, PM, and barley were analyzed and compared by [41]. His work exhibits significant potential for application in advancing comprehension and establishing a standardized protocol for the manufacturing of malt syrup derived from PM. Malt syrup was made using the steps depicted in Fig.1. The procedure involved preparing the wort and then saccharifying it with an exogenous glucoamylase enzyme. A steep duration of 50 hours was employed, during which the cereal exhibited the highest diastatic values. The time frame facilitated obtaining an optimal moisture content of 33% in the combination, which is advantageous because a higher moisture level during germination results in the maximum activity of malt β-amylase [50]. The findings indicate that ungerminated grain did not exhibit any quantifiable diastatic power. However, diastatic power significantly increased from 1 to 3 days of germination and reached its maximum level after 5 days of germination in millet grains, measuring at 27°L. The findings of this study align with those of [46] and [51] who also reported an inability to measure diastatic power during the early stages of seed germination.

A notable rise in malting loss was seen during 2-4 days of germination, as the process of germination leads to malting loss in grains. Millet malts exhibited malting losses ranging from 16% to 20% within a germination period of 4 to 7 days. According to the findings of the research, the observed phenomenon of uncontrolled grain growth during germination could perhaps be attributed to an excessive level of serration that occurred during the steeping process. The malting loss may also be attributed to an extended steeping phase, as this can lead to the leaching of components into the steep water [41].

The optimal temperature and duration for the kilning process, which aims to halt the germination of PM, was determined to be 45°C for 48 hours. The time-temperature relationship is mostly influenced by the moisture level of the green malt and the desired moisture content of the malt. These earlier studies also indicated that a kilning temperature of 70°C led to a substantial decrease in diastatic activity. Furthermore, they found that exposing finger millet, sorghum, and barley to temperatures ranging from 40 to 60°C resulted in only minimal destruction. Thus, the recorded temperature of 45°C can be used as an optimum temperature for the kilning process. The millet and sorghum grains had a considerably lower total carbohydrate content (53.35% and 71.63% respectively) compared to the resultant malts (47.93% and 54.40% respectively). The observed reduction in carbohydrate content may be attributed to heightened metabolic processes caused by elevated levels of amylase activity [41].

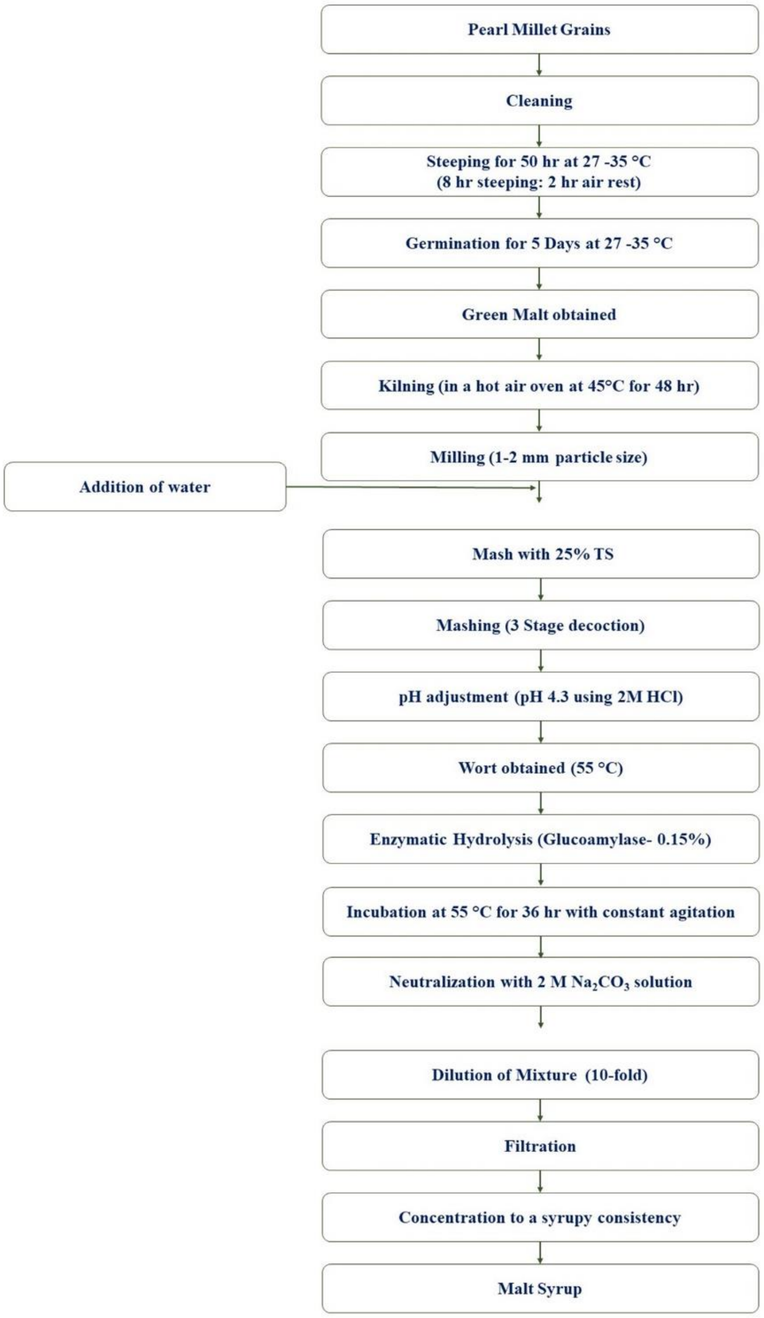

Fig. 2: Production of maltose syrup from PM [41]

To achieve full gelatinization of malt starch during wort extraction, a three-stage decoction procedure was employed. The utilization of this approach resulted in obtaining elevated quantities of extracts and fermentable sugars [52]. A mash consisting of 25% TS was subjected to incubation at a temperature of 40°C for 30 minutes. A portion constituting one-third of the mash was extracted, subjected to a boiling process lasting for 5 minutes, and afterwards reintroduced into the primary mash. The temperature of the mash increased to 50°C and was thereafter sustained at this level for 15 minutes while maintaining a pH of 6.5. Subsequently, a fraction equivalent to one-third of the mash was once again extracted, subjected to a boiling process lasting for 5 minutes, and subsequently reintroduced into the primary mash. The temperature of the mash was elevated to 60°C and thereafter sustained within the range of 60-65°C for 30 minutes. A further one-third fraction of the mash was extracted, subjected to a boiling process lasting 5 minutes, and afterwards reintroduced into the original mash. The temperature increased and afterwards remained within the range of 70 – 75°C for 30 minutes. The technique of mixing the parts back into the main mash was shown to expedite the saccharification of starch by the malt α-amylase [53].

During the mashing period, the enzymatic activity of β-amylase is enhanced by a temperature of 60°C, leading to the production of sugars. The temperature profile for mashing is a delicate equilibrium between the temperature necessary for starch gelatinization, which is crucial for enabling effective hydrolysis, and the pace at which these enzymes are deactivated due to heat factors [54].

The high levels of reducing sugars observed for PM in the study by [41] for millet (65.45%) may be related to the enzymatic breakdown of amylose and amylopectin components of starch by α-amylase, resulting in the formation of a mixture of linear and branching dextrins during the mashing procedures. The glucoamylase enzyme utilized in the procedure efficiently and comprehensively converts the linear dextrins into D-glucose at a rapid rate. Branched dextrins exhibit a much-reduced susceptibility to hydrolysis. The Dextrose Equivalent (DE) of the syrups exhibits a range of values between 81.60% (PM) and 85.52%(sorghum) in commercial contexts [41]. According to [55] it is advised to have a minimum DE of greater than 20 for glucose syrup. The elevated DE values seen in PM can be attributed to the implementation of a three-stage decoction mashing technique, subsequent hydrolysis of wort facilitated by amyloglucosidase, and the duration of the saccharification process.

[56] chose the PM hybrid HHB-67, which has the highest starch content (56.88%) to activate amylolytic enzymes during malting. The experimental procedure involved subjecting the malt to a steeping period of 10 hours, followed by a germination period of 72 hours at a temperature of

20°C. This particular treatment yielded the highest levels of α and β-amylase activity per gram of green malt. The researchers analyzed various wort samples that were made using different combinations of pearl malt with varying levels of grit. Within the set of samples that were analyzed, it was seen that the PM wort exhibited a reduced extract content, accompanied by decreasing sugar concentrations that were lower in comparison to the control barley wort. The findings of this study demonstrate that PM exhibits significant potential in terms of amylolytic enzyme production. However, its low yields during saccharification hinder its utilization as a viable source for syrup manufacture.

3.4 Glucose production from PM

Using a steeping technique for 72 hours and the sedimentation method for purification, [36] attempted to produce glucose from PM, sorghum, and maize. A total of 5 grams of PM grains that had been washed were immersed in a solution containing 30 millilitres of sodium metabisulfite with a concentration of 1%. This process took place at room temperature for 72 hours. Subsequently, the pericarp and germ were manually extracted. Each endosperm was placed in a 50 mL centrifuge tube containing 10 mL of distilled water. The endosperm was then homogenized using a vortex-type tissue homogenizer (Ultra Turrax, 170W, 20000 rpm) with a centrifugal force of 5000 x g for 2 minutes. The homogenized slurry underwent filtration using a muslin cloth, with many rinses performed until the wash water achieved clarity, resulting in a final volume of 500mL. The starch slurry was let to undergo sedimentation, and afterwards, the liquid portion above the sediment, known as the supernatant, was removed. Millet starch was successfully extracted by rinsing it with 250 mL of distilled water, draining it twice, and letting the sediment dry in the air, for a final yield of 65.94%. The starches that were obtained were subjected to enzymatic conversion into glucose through the utilization of highly purified amyloglucosidase derived from *Rhizopus* Mold. The measured yield of glucose derived from millet was determined to be 15.79±0.20 mg/mL. The viscosity of the millet syrup was measured to be 6400Cp, while the ideal concentration of glucose was achieved after a reaction time of 10 minutes [36].

Based on a more comprehensive examination, it was determined that the process of starch hydrolysis in PM using commercially available amyloglucosidase ceases after a maximum duration of 30 minutes. The results of the investigation indicate that the gelatinization temperatures of PM starch were significantly higher compared to those of yellow maize and sorghum. Specifically, the onset temperature was measured to be 67.25 ± 0.96◦C, while the peak temperature was found to be 71.25 ± 0.96◦C. Typically, starches with higher onset and peak temperatures exhibit a greater demand for energy and heat to achieve complete gelatinization. The variation in the gelatinization process may be attributed to several factors, including the relative proportions of amylose and amylopectin, the molecular arrangement of the starch, and the potential influence of other chemicals. Typically, sugar syrup derived from commercially available sources such as corn has a DE within the range of 50-70%. The findings of this study indicate that PM glucose syrup had the lowest average total solid content (45.0 ± 0.30) when compared to sorghum and maize. When comparing the DE of PM (68.75 ± 0.63) to that of sorghum (78.28 ± 0.57) and maize (73.50 ± 0.66), it is evident that PM exhibited the lowest DE. This shows that starch-based syrup obtained from pearl millet has been less broken down to smaller sugar molecules resulting in lower sweetness, which necessitates to deepen the use of enzymes. From a nutritional perspective a low DE syrup is likely to have lower GI resulting in slower rise in blood sugar levels. The potential reasons for the decrease in total solid content and DE values may be attributed to the utilization of a singular enzyme for hydrolysis, which could potentially diminish the overall effectiveness of the procedure [36]. For scaling up for industrial purposes, variants of PM variant could be developed that can render higher sugar content when broken down by hydrolysis.

3.5 Starch hydrolysis of PM for sugar production

The essential quality parameters of malting encompass the attainment of a high grain germination capacity and germinative energy, as well as the presence of α and β-amylase activity and free α-amino nitrogen. The process of starch hydrolysis is facilitated by malt enzymes such as α-amylase, β-amylase, limit dextrinase, and α-glucosidase [39]. These parameters have been extensively studied and documented by [54]. The starch liquefying and dextrinising power is referred to as α-amylase activity while the starch saccharifying or saccharolytic power is referred to as β-amylase activity [53]. Dextrins are generated as a result of the activity of α and β-amylase on starch components [57]. Understanding the enzymatic action on starch is important for elucidating the impact of varying germination temperatures on the efficacy of germination processes, specifically concerning the enzymatic hydrolysis of starch in PM, resulting in the production of glucose syrups with enhanced efficiency [58].

The removal of bran in PM has led to an increase in starch content [32]. Conversely, the processes of soaking, dry heat treatment, and germination were seen to decrease the starch content in PM. The reduction of starch occurs as a result of the processes of soaking and germination, which lead to the activation of amylase. These treatments ultimately lead to the hydrolysis of starch.

It has been well documented that fermenting bacteria possess both α and β amylases. Both single and mixed cultures of yeasts, specifically *Saccharomyces cerevisiae* or *Saccharomyces diastaticus*, along with Lactobacilli, namely *Lactobacillus brevis* or *Lactobacillus fermentum*, was used by [38]carry out the fermentation process of PM. They observed that wet-heating PM flour could potentially lead to the degradation of starch and a subsequent decrease in starch content in the flour after autoclaving. This degradation process may therefore increase the overall concentration of soluble sugars. During the early phases of fermentation, it is possible to observe elevated amounts of soluble sugars [41]. The enzymatic breakdown of starch, due to the processes of germination and/or fermentation, led to a rise in the overall concentration of soluble sugars, including both reducing and non-reducing sugars. However, as fermentation progresses, these sugars can be metabolized, resulting in a fermented product with lower sugar content compared to the original concentration of sugars in the fermenting mixes.

From the results observed by [38] the sprouts that underwent fermentation with the combination of *S. diastaticus* and *L. brevis* exhibited the highest levels of total soluble, reducing, and nonreducing sugars. Additionally, various combinations exhibited elevated levels of total soluble, reducing, and non-reducing sugars in comparison to the unprocessed PM, but these levels were lower than those observed in germinated grains. The decrease in starch content seen in the fermented product can be attributed to the enzymatic breakdown of starch by microorganisms present in the fermenting mixture.

In the study conducted by [59] PM starch was hydrolyzed using a commercially available α-amylase derived from *Bacillus licheniformis*, as well as a crude glucoamylase derived from *Aspergillus sp*. NA21. Based on the analysis, it was concluded that a slurry concentration comprising 25% starch is both practical and idealistic in the context of syrup production. Liquefying PM starch through the application of steam at a pressure range of 2.06-2.75 N/cm^2, along with a temperature range of 104-105°C, proved to be both economically viable and highly effective. In the initial experimental setup, the slurry with a concentration of 25% (w/v) underwent a liquefaction process, which was successfully achieved within a time frame of 60 minutes. The determination of the ideal pH for liquefaction was found to be 5.0, while the introduction of 150 ppm $CaCl_2$ to the slurry led to a 33% decrease in the required enzyme dosage. Under optimal experimental conditions, specifically 24 hours at a pH level of 5.0, it was observed that a significant proportion of the liquid PM underwent a conversion process, resulting in the production of sugar. It is important to point out that glucose emerged as the primary breakdown product during this transformation. Finally, the process of saccharification in PM exhibited optimal efficiency when conducted at a temperature of 45 °C. There have been multiple studies related to the potential of sorghum, another major millet, and its potential as a source for syrup preparations. These studies have indicated that sorghum is an excellent and cheaper source for the production of syrups with greater conversion rates into sugar [60–62]. One potential rationale for not utilizing PM in malt production is its comparatively higher energy and time requirements for germination and malting procedures, in comparison to barley and sorghum.

3.6 Utilization of PM stovers for sugar production

A significant portion of crop stovers, comprising leaves and stalks, are employed in the commercial manufacture of sugar and ethanol. PM has been identified as a valuable source of fermentable sugars, primarily found in its stalks [63]. The valuation of sweet stalks of forage derived from PM is contingent upon the residual sugars present in the stover or the sugars collected within the green forage. Various pressing methods can be employed to extract sugars in the form of green, sugary juice. In the case of sweet PM, the stems exhibit a significantly higher concentration of water-soluble carbohydrates (WSC) compared to the leaves. According to [63], stems comprise about 90% of the overall output of water-soluble carbohydrates (WSC).

A variety of enzymes derived from *Aspergillus nidulans* AKB-25 was utilized by [64] to conduct enzymatic hydrolysis of PM stover. Various concentrations of the enzyme were employed to investigate its impact on the hydrolysis process of PM stover, under conditions with and without surfactants. In comparison to the untreated sample, the application of alkali pre-treatment resulted in a significant enhancement of the Brunauer-Emmett-Teller (BET) surface area and water retention value (WRV) by 322.92% and 78.66%, respectively. The biomass conversion rate into reducing sugars exhibited an upward trend with the progressive increase in alkali dosage, reaching a maximum of 3%. Under the conditions of a 3% alkali dose and a hydrolysis time of 72 hours, the resulting yield of reducing sugars was determined to be 53.13%. The highest percentage of reducing sugars, amounting to 57.77%, was seen when the enzyme concentration was 15 FPU/g of the dry substrate following a hydrolysis period of 72 hours. The addition of surfactants Tween-80 and Tween-20 at a ratio of 0.15 g per gram of dry substrate led to an increase in saccharification yield. Specifically, the saccharification yield reached 62.14% and 64.77% for Tween-80 and Tween-20, respectively, compared to the control group which achieved a yield of 57.64%. Therefore, the enzyme accessibility of pre-treated PM stover is enhanced through the partial elimination of lignin and hemicelluloses with alkali pre-treatment. This characteristic renders it suitable for hydrolysis treatment aimed at converting it into reducing sugars.

In a further attempt to enhance the value of PM biomass, researchers employed diverse pressing methodologies to extract soluble sugars from PM. Effective extraction of approximately 22% to 38% of the total soluble sugars (TSS) present in sweet PM biomass was possible by the utilization of a hydraulic press [65] . This method yielded superior results in terms of sugar extraction when compared to a roller press. Similarly, the approach employed by [66] resulted in the retention of around 77 g kg-1 DM of total soluble solids (TSS) by the bagasse of sweet PM. This amount accounts for approximately 64% of the initial TSS content, which was measured at 121 g/kg DM. A second press impregnated with water was used by [67] to increase sugar extraction by reducing the retention of soluble sugars in the bagasse. In the experiment, a hydraulic press was used to squeeze juice from PM biomass for its soluble sugars. PM biomass was extracted for around 22.5% fructose and 30.5% glucose, respectively. Only sweet PM benefited from a more efficient sugar extraction after being pressed. From the sweet PM biomass, 47.5% of the soluble sugars were isolated.

In a subsequent investigation conducted by [65] the impact of compressive force on the volumetric properties and sugar composition of juice derived from finely minced sweet PM biomass was thoroughly examined. The experimental findings have demonstrated that applying a compressive force within the range of 310 to 379 kilopascals (kPa) has proven to be sufficient for the extraction of juice. The optimal yield of juice derived from sweet PM biomass was determined to be 509 mL juice per kg. The extraction of biomass from sweet PM was effectively accomplished by utilizing the screw press apparatus, resulting in a moisture content of 63.3%. Based on the findings, it can be deduced that the sugar concentration present in PM juice remained unaltered regardless of the magnitude of the compressive force exerted on the biomass.

4.0 Conclusion

The increasing global importance of PM can be attributed to its gluten-free composition [68] and hypoglycaemic properties [69]**.** The cost-effectiveness of PM renders it a viable option for utilization as a comparatively healthier source for preparation of functional food products. The primary factor contributing to the limited usage of PM for the production of starch and starch-derived sugar syrups may be attributed to the ample supply and accessibility of alternative sources like wheat, rice, potato, and corn. These alternative sources effectively meet the current demand for starch across many applications. Emphasizing the genetic enhancement of PM genotypes and their use for commercial utilization and as viable sources of feed and food crops should be of utmost importance. Despite having great potential and usage, the stigma associated with millet and millet products as being suitable only for individuals of lower socioeconomic status imposes limitations on their consumption among certain populations. Limited efforts have been made thus far to harness the potential of PM and other millet varieties for valorization, resulting in a decrease in their popularity and a lack of awareness among urban dwellers. Also, the absence of a viable commercial market for PM and its derived products has resulted in a discouraging environment for investment in the advancement and implementation of novel techniques and research in this crop and its by-products. PM sugar production is less established than traditional sugar production meaning higher costs due to limited scalability and processing infrastructure. This may require additional research and investment to make the extraction process commercially viable. Being the largest grown millet in the world, PM holds an immense number of opportunities to be completely utilized for potentially rendering value-added products like sugar syrups. The authors believe that the topic is highly relevant due to emerging search for alternate sugar source crops with lower carbon footprint.

Disclaimer (Artificial intelligence)

Option 1:

Author(s) hereby declares that NO generative AI technologies such as Large Language Models (ChatGPT, COPILOT, etc.) and text-to-image generators have been used during the writing or editing of this manuscript.

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