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Triumpheta cordifolia gum extract in the clarification of *Safrari* sorghum wort

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Abstract:
This study aimed to investigate *Triumpheta cordifolia* A. Rich. gum extract as a clarifying agent in sorghum wort brewing.
The biological materials used in this study included the *Safrari* sorghum cultivar and the bark of *T. cordifolia*. We determined the key physicochemical characteristics, such as turbidity, pH, Brix (soluble solids), as well as color and polyphenol content of *Safrari* sorghum wort.
The response surface methodology employing a Box-Behnken experimental design with three factors was used to investigate the impact of adding *T. cordifolia* gum extract to *Safrari* sorghum wort during its clarification. The physicochemical properties of *Safrari* sorghum demonstrated satisfactory results for malting. The sorghum was malted and subsequently brewed, and the resulting wort was clarified according to the experimental design. The design factors included the volume of the gum extract (from 1.5 to 3.5 mL) for a fixed wort volume of 200 mL, the stirring speed (from 30 to 160 rpm), and the settling time (from 10 to 60 min). The responses were analyzed during 15 trials and included turbidity, pH, Brix, color, and polyphenol content. These responses were subjected to mathematical and statistical modeling. All obtained models were validated against several criteria, including the correlation coefficient ($R^2 > 0.90$), the absolute average deviation (absolute average deviation < 0.3), as well as the bias and accuracy factors (A_f and B_f between 0.75 and 1.25).
The optimal results suggested that the gum extracted from *T. cordifolia* could be effectively used as a clarifying agent in the brewing industry.

Keywords: *Safrari* sorghum, *Triumpheta cordifolia* gum extract, sorghum wort, clarification, malting, brewing, Box-Behnken design, RSM

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INTRODUCTION

Sorghum (*Sorghum bicolor* (L.) Moench) is a cereal of great importance for food security and socio-economic resilience across many African countries [1]. It grows particularly well in semi-arid tropical regions where other staple crops often fail due to insufficient rainfall, poor soils, or high temperatures. Its drought resistance, adaptability to marginal environments, and low input requirements make it a reliable source of calories and nutrients for millions of people. In addition to its value as a subsistence crop, sorghum plays a central role in traditional food systems and local economies.

Among the diverse uses of sorghum, one of the most culturally significant is its transformation into traditional fermented beverages. In numerous regions of sub-Saharan Africa, especially in northern Cameroon, sorghum-based beers are not only popular refreshments but also integral components of social rituals, festivals, and communal gatherings. These beverages are valued not only for their nutritional and caloric contributions but also for their deep-rooted role in heritage and identity [2–4]. Furthermore, sorghum is increasingly seen as a viable alternative to malted barley in brewing processes due to its cost-effectiveness and comparable enzymatic potential [5, 6].

Globally, sorghum ranks as the fifth most produced cereal after maize, rice, wheat, and barley, while in sub-Saharan Africa, it ranks second [7]. In Cameroon, especially the Far North Region, it serves as a cornerstone

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of human nutrition and animal feed. Beyond its use as a raw material in daily diets, sorghum is processed into a wide range of food products and fermented drinks, including various types of local beer that vary in composition and preparation methods from one community to another [4, 8].

Nevertheless, traditional sorghum beers often exhibit high turbidity and a cloudy appearance, which can significantly undermine their sensory appeal, stability, and commercial value. While some cloudiness is accepted in local markets, particularly in artisanal contexts where consumers are familiar with these beverages, efforts to improve clarity are becoming increasingly important. This is especially true as producers seek to scale up and formalize production or enter broader markets where visual clarity is associated with product quality. Thus, enhancing the physicochemical properties of sorghum beer has become a key focus for both researchers and producers [9–12]. In this respect, clarification represents a vital stage in the brewing process. It aims to remove suspended solids and colloidal substances responsible for turbidity, while preserving or even enhancing the beverage's sensory and nutritional qualities. Achieving a clear, shelf-stable sorghum-based beverage is a complex challenge, particularly in traditional production systems that lack access to industrial-grade clarifying agents and filtration equipment.

In recent years, the exploration of natural clarifying agents has gained momentum, driven by growing interest in clean-label products, sustainability, and the valorization of local plant resources [10, 13, 14]. Natural agents are increasingly favored due to their availability, safety profile, environmental compatibility, and potential to align with artisanal brewing traditions. Among these, plant-based gums have emerged as particularly promising candidates. These polysaccharide-rich substances have demonstrated a considerable capacity to interact with suspended particles, facilitating their flocculation and sedimentation through mechanisms that are both physicochemical and colloidal in nature [15, 16]. Several recent studies have demonstrated the effectiveness of plant-derived gums and hydrocolloids in beverage clarification. For instance, Venkatesh *et al*. [17] highlighted their utility in sugarcane juice processing, while Man-Ikri & Desobgo Zangué [10] successfully applied *Grewia mollis* Juss. powder to clarify sorghum *Mbayeri* wort. These findings underscore the use of natural, plant-based solutions in the beverage industry to ensure affordability and sustainability.

Triumpheta cordifolia A. Rich. gum has great potential in this context. Widely available in Cameroon, it has traditionally been underutilized despite its promising functional properties. The gum extracted from *T. cordifolia* bark could serve as a low-cost, locally sourced alternative to synthetic clarifiers. Its potential lies not only in its physicochemical properties, which may enhance clarification efficiency, but also in its role within a broader strategy for sustainable development. By using a readily available natural resource, producers could reduce production costs, stimulate local economies, and minimize dependency on imported or chemically synthesized inputs.

Evaluating the suitability of *T. cordifolia* gum as a clarifying agent requires a rigorous scientific approach that considers multiple variables. In this regard, the Response Surface Methodology stands out as a robust and versatile statistical tool. It can be used to model complex interactions among experimental variables, enabling researchers to identify optimal conditions for process performance [18–21]. This method can explore how key parameters, such as gum concentration, stirring speed, and settling time, affect clarification outcomes, particularly with respect to reducing turbidity and preserving the nutritional content.

In this study, we aimed to investigate the operational conditions associated with the use of *T. cordifolia* gum extract as a clarifying agent in sorghum wort brewing. Specifically, we sought to determine the influence of this natural gum on the key physicochemical characteristics of *Safrari* sorghum wort, including its turbidity, pH, Brix (soluble solids), color, and polyphenol content. Thus, our research contributes not only to the scientific understanding of natural clarifiers in traditional brewing systems, but also to the practical advancement of sustainable, locally rooted food processing technologies.

STUDY OBJECTS AND METHODS

The biological materials used in this study included the *Safrari* sorghum cultivar and the bark of *Triumpheta cordifolia* A. Rich., both sourced in Cameroon to ensure relevance to local agro-ecological and socio-economic conditions.

The *Safrari* sorghum was obtained from the Institute of Agricultural Research for Development located in the city of Maroua (the Far North Region of Cameroon). This specific cultivar was selected due to its favorable agronomic characteristics, such as high germination potential, a relatively large grain size, and good brewing suitability, all of which are essential for traditional beer production. In addition, the widespread cultivation and accessibility of this variety make it a logical choice for local-scale and experimental brewing systems.

The stems of *T. cordifolia* were procured from a regional market in Ngaoundéré, in the Adamawa Region. This particular plant material was selected due to its local abundance and traditional use in folk medicine and artisanal preparations. Its availability and affordability make it an attractive candidate for sustainable valorization in food and beverage applications. Both biological materials were handled under hygienic conditions to avoid contamination and preserve their biochemical integrity prior to processing.

Characterization of Safrari sorghum. The physicochemical characterization of the *Safrari* sorghum variety was carried out to establish baseline quality parameters relevant to brewing processes. In particular, we determined the moisture content, germination capacity, and the weight of 1,000 grains, all of which are crucial

indicators of the grain's suitability for malting and subsequent transformation into fermented beverages.

Determination of moisture and dry matter. Dry matter, also known as total solid residue, encompasses all non-volatile substances remaining after water removal from a sample. This is a critical parameter in brewing that reflects the concentration of fermentable substrates and structural components present in the grain. Dry matter was determined according to the procedure described in [22]. In this method, a mass of sorghum grains is dried in a controlled oven at a standardized temperature until a constant weight is achieved. The moisture content is then calculated by subtracting the final dry weight from the initial mass, and the dry matter percentage is obtained accordingly.

Maintaining an optimal moisture content is crucial for ensuring the stability of stored grains. Excess moisture can promote microbial growth, enzymatic degradation, and oxidative changes, while overly dry grains may become brittle and lose viability. The ideal range for storage is generally considered to be below 13%, with lower values indicating good preservation conditions and a low risk of spoilage [10]. For malting purposes, moisture levels must also be monitored to guarantee uniform germination.

Determination of germination capacity. Germination capacity, or viability, was assessed following the standardized method detailed in [22]. This parameter is essential for evaluating the enzymatic potential of the grain, which is activated during the malting process. Two random batches of 200 grains each were soaked in a hydrogen peroxide (H_2O_2) solution at a concentration of 7.5 g/L. Hydrogen peroxide was used to sterilize the grain surface and promote the germination process by facilitating oxygen diffusion.

The grains were initially soaked for 48 h at a controlled ambient temperature of 22–25°C, after which the solution was renewed to maintain chemical activity and remove metabolic by-products. Then, the grains were soaked for another 48 h (totaling four days), drained, and observed under hygienic laboratory conditions. The number of germinated grains was carefully counted, and the germination percentage was calculated for each batch. This assessment provides a clear picture of the grain's physiological readiness for malting and its responsiveness to hydration stimuli.

Determination of the weight of 1,000 grains. The 1,000-grain weight is a key indicator of the grain's size, density, and uniformity, which collectively affect the milling behavior and malt quality. The method was adapted from the reference procedure in [22]. To measure the 1,000-grain weight, we selected two representative 40-g batches of clean *Safrari* sorghum grains and removed any impurities, dust, or foreign materials prior to measurement to ensure accuracy.

Each grain in the batch was counted manually to determine the number of individual units in the sample, after which the entire batch was weighed using a precision analytical balance. The 1,000-grain weight was then calculated by extrapolating the weight of 1,000 grains based on the average mass per grain derived from the counted sample. This metric is particularly relevant in brewing since larger grains may yield higher extract values, while a uniform grain size promotes even hydration and enzymatic activation during malting.

Characterization of bark and gum extraction. ***Ash content.*** The ash content of the samples was determined using standardized analytical methods. First, the sample was dried at 105°C until it reached a constant mass, ensuring complete removal of residual moisture. Once dried, the sample was transferred to a porcelain crucible and placed in a muffle furnace (Heraeus Kendro No. 20.001.046, Germany) preheated to 550°C. The incineration process continued until white ash was obtained, indicating that all carbon had been fully combusted. After incineration, the crucibles were removed from the furnace and allowed to cool in a desiccator to prevent moisture absorption. They were then weighed with high precision. The ash content was calculated based on the mass of the ash relative to the initial dry mass of the sample, expressed as a percentage [22].

Determination of polyphenol content. Total phenolic compounds were quantified using the Folin-Ciocalteu colorimetric method, a well-established technique known for its sensitivity and reproducibility in polyphenol analysis. A 0.5-g sample of finely ground stems was added to an Erlenmeyer flask containing 70% (v/v) ethanol as an extraction solvent. The mixture was thoroughly stirred for 20 min at room temperature to maximize the extraction of phenolic compounds. Following this, the solution was filtered through Whatman No. 1 filter paper to remove any solid residues. Next, 0.5 mL of the filtrate was combined with 2 mL of a sodium carbonate solution (75 mg/mL) and 2.5 mL of a tenfold-diluted Folin-Ciocalteu reagent (1/10, v/v). The reaction mixture was then kept in the dark for 1 h at room temperature to allow the development of the characteristic blue color, which indicates the reduction of the reagent by polyphenols. Absorbance was measured at 760 nm using a spectrophotometer (Raleigh VIS-723N). The total polyphenol concentration was calculated using the regression equation derived from a calibration curve prepared with gallic acid solutions ranging from 0 to 200 mg/L. The results were expressed as milligrams of gallic acid equivalent per 100 g dry matter [23].

Determination of total sugar content. The total sugar content was assessed using the 3,5-dinitrosalicylate method, a well-established colorimetric approach for quantifying reducing sugars. For the acid hydrolysis step, 0.2 g of the sample was placed in a test tube with 5 mL of sulfuric acid (1.5 N). The mixture was heated in a water bath at 100°C for 45 min and then allowed to cool to room temperature. To neutralize and clarify the extract, we added 10 mL of 70% ethanol, 1 mL of zinc acetate (2 g/100 mL), and 1 mL of potassium ferrocyanide (10.6 g/100 mL). The solution was then filtered into a 50-mL volumetric flask, and the volume was brought up to 50 mL using distilled water. For the colo-

rimetric reaction, 0.5 mL of the extract was mixed with 1.8 mL of distilled water and 0.4 mL of the 3,5-dinitrosalicylate reagent in a test tube. A calibration curve was constructed using a 2 mg/mL glucose solution, with concentrations ranging from 0.25 to 1.5 mg/mL. The tubes were incubated in a water bath at 100°C for 5 min and then quickly cooled under running water. The absorbance of the solutions was measured at 540 nm using a UV-Visible spectrophotometer (7305-JENWAY). The total sugar concentration was calculated by interpolation based on the regression equation obtained from the calibration curve.

Extraction of gum from *T. cordifolia* bark. The preparation of *T. cordifolia* samples followed a strict protocol designed to maximize gum extraction efficiency. The stems were meticulously cleaned to eliminate any impurities and then manually stripped of their bark. The collected bark was dried in a Memmert ventilated oven (Germany) at a carefully regulated temperature of 45°C for 48 h to ensure complete removal of residual moisture and maintain the integrity of bioactive compounds. Once dried, the bark was finely ground using a laboratory mill and weighed using a high-sensitivity electronic balance (SCIENTECH ZSP 250; precision 1/1000). Gum was extracted in an aqueous medium under continuous stirring, following the procedure outlined [24, 25]. The resulting mixture was centrifuged to separate and remove any suspended solid particles. The crude extract obtained was promptly stored at 4°C under refrigeration to minimize any risk of physicochemical degradation before subsequent use.

Wort characterization. The physicochemical properties of the wort were evaluated using a range of analytical parameters. Turbidity is a critical measure of wort clarity, directly impacting its stability and overall acceptability. Color, which is influenced by natural pigments and chemical reactions during processing, has a significant effect on visual appeal. The pH level, a fundamental indicator of acidity, is crucial for maintaining microbiological and enzymatic stability. The Brix degree, which reflects the concentration of soluble solids (primarily sugars), provides valuable insights into the wort's fermentative potential. Additionally, the polyphenol content is a key factor since these bioactive compounds not only affect sensory properties such as bitterness and astringency but also contribute to the product's antioxidant capacity. Collectively, these parameters offer a comprehensive evaluation of the wort, enabling effective monitoring throughout the transformation process and optimization of clarification conditions.

Turbidity. The turbidity of the wort was assessed using a HACH 2100AN benchtop turbidimeter, a high-precision device known for its reliability in measuring suspended particles. For each test, an appropriate sample volume was carefully collected and transferred into a clean quartz cell, ensuring it was free of air bubbles to avoid any potential interference with the results. The sample was then placed in the instrument, and measurements were taken once the displayed reading stabilized. Turbidity values were recorded in European Brewery Convention units, the standard scale used to evaluate the clarity of wort and brewing products. This approach offers a precise way to quantify haze, a critical factor affecting both the visual appeal and stability of the final product. All analyses were performed under controlled conditions to ensure reproducibility and minimize variability.

Color. The beer's color was assessed using a standardized spectrophotometric method, following the guidelines set by the American Society of Brewing Chemists [25]. The analysis focused on measuring the sample's absorbance at 430 nm, which corresponds to the characteristic hue of color compounds found in beer, including melanoidins and pigments produced through Maillard reactions and sugar caramelization. To convert the measured absorbance into European Brewery Convention units, it was multiplied by a factor of 25 and adjusted based on the sample's dilution coefficient. This method provided an accurate and reproducible assessment of color intensity, a critical parameter that influences the sensory perception of the final product. All measurements were carried out using a calibrated spectrophotometer to ensure the reliability and comparability of the results.

pH, Brix, and polyphenol content. The physicochemical analysis of the wort involved measuring its pH, Brix degree, and polyphenol content using validated analytical techniques. A high-precision Consort C863 pH meter was used to determine the pH, with prior calibration using reference buffer solutions to ensure accurate readings. The Brix degree, which indicates the concentration of soluble solids (mainly sugars), was assessed using a Hanna HI 96.801 optical refractometer, known for its quick and dependable measurements. The polyphenol content, a critical factor affecting the wort's sensory and antioxidant properties, was quantified following the method outlined earlier, utilizing the Folin-Ciocalteu reagent.

Malting and brewing of sorghum. The brewing process is centered on the enzymatic breakdown of macromolecules, particularly starch and proteins, transforming them into fermentable sugars and soluble peptides. The experimental protocol adopted in this mm using a manual grain mill (Victoria Grain Mill, ref. 530025) to enhance enzymatic extraction efficiency. The milled malt was then brewed in a Speidel Braumeister (20 L, Art-Nr: 47,070, Bj 2016, Prod-Nr: 471107822, 230V/50Hz/2100W/IP 42) with a malt-to-water ratio of 1:5 (1 kg of malt to 5 L of water). A total of 4 kg of ground malt was added to the Braumeister containing 20 L of water preheated to 45°C to initiate the proteolytic phase, which activates protease enzymes. This step lasted 30 min and was conducted under continuous stirring to prevent flocculation. The supernatant (16 L) was then separated, while the residual starch underwent gelatinization at 95–98°C for 40 min on a gas heating plate. After cooling to 60–65°C, amylolytic hydrolysis was carried out to convert the starch into fermentable sugars. The supernatant and gelatinized starch were reintroduced into the Braumeister at 65°C and stirred continuously for 1 h and 30 min.

The temperature was then raised to 72°C to facilitate enzymatic saccharification, which proceeded for 1 h. Once brewing was complete, the resulting wort (15 L) was separated from the spent grains and allowed to cool to room temperature. The wort clarification process was modeled mathematically and statistically to optimize the operational parameters.

Experimental design. The investigation into wort clarification employed a Box-Behnken experimental design, which incorporated three factors known to significantly influence the clarification process, as highlighted in [10, 26, 27]. The parameters included the volume of gum extract (X_1), stirring speed (X_2), and settling time (X_3). The ranges for these factors were established through preliminary laboratory experiments (Table 1).

For each experimental run, 200 mL of wort was divided into three separate containers. Varying amounts of *T. cordifolia* gum extract were added to each container, followed by agitation at controlled speeds using a mechanical stirrer. After this initial optimization phase, the same experimental setup was applied to the 15 trials generated by the experimental design, adhering to the factor levels specified in Table 1. Finally, the coded variables were converted into real variables using the methodology outlined in [28, 29], enabling easier interpretation and application of the results (Table 2).

Choice of experimental responses. The physicochemical analyses carried out in this study centered on several critical parameters, including the refractive index (expressed in Brix), pH, color, turbidity, and total polyphenol content. These measurements were taken to assess the effectiveness of the clarification process and to quantify the impact of the experimental variables examined. Specifically, we analyzed the effects of three key factors: the volume of gum extract (X_1), stirring speed (X_2), and settling time (X_3).

The statistical analysis of the data allowed for the modeling and interpretation of how these parameters influence the clarification of *Safrari* sorghum wort, revealing potential interactions among them. This methodological approach is part of an optimization effort aimed at enhancing the stability and clarity of the wort under the experimentally determined operational conditions.

Modeling and validation of mathematical models. In the optimization of the wort clarification process, a response surface methodology was applied to model the influence of the experimental factors under investigation. This approach utilizes a second-degree polynomial mathematical model, which captures interactions between independent variables and their effects on the measured responses.

The model had the following general form:

$$y = \beta_0 + \sum_{j=1}^{k} \beta_j x_j + \sum_{j=1}^{k} \beta_{jj} x_j^2 + \sum\sum_{i<j} \beta_{ij} x_i x_j \quad (1)$$

where y is the answer, x_i and x_j are the variables, β_0 is the constant term, β_i is the coefficient of linear terms, β_{jj} is the terms of the quadratic coefficient, and β_{ij} is the coefficient of the interaction terms.

Table 1 Areas of variation in factors

Factors	Actual range of variation	Coded variation domain
Volume of gum extract (X_1), mL	1.5–3.5	–1; +1
Stirring speed (X_2), rpm	30–160	–1; +1
Settling time (X_3), min	10–60	–1; +1

Table 2 Three-factor Box-Behnken experiment matrix

Real variables			Coded variables		
X_1	X_2	X_3	X_1	X_2	X_3
–1	–1	0	1.5	10	35
1	–1	0	3.5	10	35
–1	1	0	1.5	150	35
1	1	0	3.5	150	35
–1	0	–1	1.5	80	10
1	0	–1	3.5	80	10
–1	0	1	1.5	80	60
1	0	1	3.5	80	60
0	–1	–1	2.5	10	10
0	1	–1	2.5	150	10
0	–1	1	2.5	10	60
0	1	1	2.5	150	60
0	0	0	2.5	80	35
0	0	0	2.5	80	35
0	0	0	2.5	80	35

This model was employed to evaluate and predict the impact of the volume of gum extract (X_1), stirring speed (X_2), and settling time (X_3) on the physicochemical properties of the clarified wort, while considering potential interactions among these factors.

The models were evaluated and validated using several statistical criteria to ensure their robustness and reliability. The coefficient of determination (R^2) was calculated to determine how well the model fit the experimental data. Additionally, the absolute average deviation (AAD) was computed using Eq. (2) to estimate the extent of deviations between experimental and predicted values. Furthermore, the bias factor (B_f) and accuracy factor (A_f) were determined using Eq. (3) and (4), respectively. These parameters help assess the correctness and precision of the predictions generated by the statistical model.

All analyses were carried out using Microsoft Excel 2016, ensuring meticulous data handling and dependable interpretation of the results. This methodological approach confirmed the suitability of the models for describing and predicting the effects of the studied factors on *Safrari* sorghum wort clarification.

$$\mathrm{AAD} = \frac{\left[\sum_{i=1}^{N}\left(\frac{\left|Y_{i,\exp} - Y_{i,cal}\right|}{Y_{i,\exp}}\right)\right]}{N} \quad (2)$$

$$B_{fi} = 10^{\frac{1}{N}\sum_{i=0}^{N}\log\left(\frac{Y_{i,cal}}{Y_{i,\exp}}\right)} \quad (3)$$

$$A_{fi} = 10^{\frac{1}{N}\sum_{i=0}^{N}\log\left(\frac{Y_{i,cal}}{Y_{i,\exp}}\right)} \quad (4)$$

where $Y_{i,\exp}$ is the experimental response, $Y_{i,cal}$ is the computed response, and N is the number of experiments used in the calculation.

The coefficients for the different models were calculated using Minitab software, version 18 (Minitab, Ltd., Brandon Court, Unit E1-E2 Progress Way, Coventry, CV3 2TE, UK). This tool facilitated a comprehensive statistical analysis of the models, evaluating the influence of the studied factors on sorghum wort clarification. A factor was deemed statistically significant when $P \leq 0.05$, indicating a meaningful relationship between the factor and the response being analyzed.

Graphical representations were created using SigmaPlot software, version 12.5 (Systat Software, Inc., San Jose, USA), offering a clear and accurate visualization of the results. Additionally, Microsoft Excel 2016 was employed to convert the coded variables into real variables, making it easier to interpret the coefficients and observed trends. This approach ensured a meticulous analysis and dependable interpretation of the experimental findings.

Multi-response optimization. The main objective of a multi-response optimization was to find the best possible balance between different responses to enhance the quality of sorghum wort. To achieve this, specific optimal conditions were determined for each parameter analyzed. Our approach aimed to reduce turbidity, color, and polyphenol content while increasing soluble solids (Brix) to ensure a clarified wort that supports fast and efficient fermentation.

This optimization was performed using Minitab software, version 18 (Minitab, Ltd., Coventry, UK), which allowed for the application of response surface mathematical models to pinpoint the most favorable experimental conditions. The key challenge was to balance the reduction of turbidity with the preservation of bioactive compounds, particularly polyphenols, which are known for their antioxidant properties. By implementing this methodology, the clarification process was optimized, producing high-quality sorghum wort ready for fermentation.

RESULTS AND DISCUSSION

Characteristics of *Safrari* sorghum and *Triumpheta cordifolia* A. Rich. bark. The physicochemical properties of *Safrari* sorghum before malting are presented in Table 3. The moisture content (9.320 ± 0.091%) falls well within the recommended range for grain storage, which should not exceed 13% [10]. This low moisture level indicates that the grains were properly dried and stored to minimize the risk of microbial degradation and preserve their quality for malting and brewing.

The germination energy, a critical parameter for assessing malt quality, was evaluated at two different volumes (4 and 8 mL) of the hydrogen peroxide solution, yielding values of 99.50 ± 0.71 and 98 ± 1%, respectively. These results comply with the stringent standards set by [22], confirming high viability and uniformity of the grains. Such high germination rates are essential to ensure consistent enzymatic activity during malting, which directly impacts the efficiency of starch conversion and sugar extraction during brewing.

The weight of 1,000 grains, a key indicator of the grain size and density, was measured at 21.78 ± 0.69 g. This value aligns with the typical range reported in the literature for sorghum varieties, which spans from 7 to 61 g depending on genetic and environmental factors [30]. The consistency in grain weight suggests uniformity in size, which is advantageous for milling and subsequent processing. These findings are corroborated by other studies [10, 31], which have demonstrated that *Safrari* sorghum exhibits favorable malting characteristics, including high extract yields and robust enzymatic profiles. The combination of low moisture, high germination energy, and uniform grain size underscores the suitability of *Safrari* sorghum for brewing applications, particularly in the production of traditional African beers where sorghum serves as the primary raw material.

The physicochemical properties of *T. cordifolia* bark reveal a total sugar content of 77.00 ± 2.00 g/100 g of dry matter, a polyphenol content of 12.25 g/100 g dry matter, and an ash content of 11.00 g/100 g of dry matter (Table 3). These values are consistent with those generally reported for mucilaginous plant materials, although variations may occur depending on sampling periods and environmental conditions [32]. The high sugar content is attributed to the presence of polysaccharides, which are the primary functional components of the gum. These polysaccharides exhibit unique rheological properties, such as high viscosity and water-binding capacity, making them effective as flocculating or stabilizing agents in clarification processes [33, 34].

The polyphenol content of *T. cordifolia* bark is particularly noteworthy, as phenolic compounds are known for their antioxidant properties and ability to interact with proteins and other macromolecules. This interaction can influence the clarity and stability of beverages by forming complexes that either precipitate or remain suspended, depending on the processing conditions. The ash content, representing inorganic residue after combustion, provides insights into the mineral composition of the bark.

Table 3 Physicochemical characteristics of *Safrari* sorghum and *Triumpheta cordifolia* bark

Characteristics	*Safrari* sorghum	*Triumpheta cordifolia* bark
Total sugars, g/100 dry matter	–	77.00 ± 2.00
Polyphenols, g/100 dry matter	–	12.25 ± 2.00
Ash, g/100 g dry matter	–	11.00 ± 0.50
Moisture, %	9.32 ± 0.09	10.00 ± 0.09
Germination energy (8 mL), %	98.00 ± 1.00	–
1,000 grains weight, g	21.78 ± 0.69	–
Germination energy (4 mL), %	99.50 ± 0.71	–
Germination capacity, %	95.00 ±1.41	–

The relatively high ash content (11.00 g/100 g dry matter) suggests the presence of significant amounts of minerals, which could contribute to the nutritional profile of the gum and its potential health benefits. The moisture content of the bark was measured at 10.00 ± 0.09%, indicating proper drying and storage conditions, which are critical for preserving the functional properties of the gum.

The combination of these physicochemical characteristics highlights the potential of *T. cordifolia* gum as a natural clarifying agent and a sustainable alternative to synthetic additives in the brewing industry.

Impact of various factors on some physicochemical properties of *Safrari* sorghum wort. The responses were analyzed using statistical mathematical modeling. Each response was represented by a model, with its coefficients indicating the influence of different factors and their interactions on the response. Table 4 displays the average raw results from the physicochemical analyses of clarified *Safrari* sorghum wort, alongside the predicted results generated by Minitab. The responses included turbidity, European Brewery Convention units (EBC); color, EBC; Brix, pH; and polyphenol content, mg/mL. Their coded variables can be seen in Table 5. These models were multivariate polynomial equations, specifically second-order models with interaction terms. The factors in the models included linear or quadratic terms (X_1, X_2, and X_3), quadratic terms (X_1X_1, X_2X_2, and X_3X_3), and interaction terms (X_1X_2, X_1X_3, and X_2X_3). All the models were validated following established literature [35–38].

Table 6 presents the coefficients and probabilities of different factors for the responses. The coefficient values represent the strength of the effect, while their sign indicates whether the effect on the corresponding response is positive or negative. The associated probability test helped determine whether a factor or interaction had a significant impact on the response. Factors with a probability of $P \leq 0.05$ were considered statistically significant for the studied responses.

Impact of T. cordifolia gum extract volume on turbidity, polyphenol content, pH, Brix, and color. The gum extract volume (X_1) had a significant influence on turbidity, pH, Brix degree, and polyphenol content ($p < 0.05$), whereas its effect on color was not statistically significant ($p > 0.05$, Table 6). These responses were analyzed under fixed conditions, including an agitation speed of 120 rpm and a settling time of 35 min. Figure 1 illustrates variations in the parameters depending on the gum extract volume.

Effect of T. cordifolia gum extract volume on turbidity. The volume of the gum extract (X_1) demonstrated a significant impact on turbidity ($p = 0.005$, Table 6), initially contributing to a decrease in this parameter, as shown in Fig. 1. Specifically, turbidity decreased from 2.95 EBC at a gum extract volume of 1.5 mL to 7 EBC at 2.5 mL, followed by an increase to 9.5 EBC at 3.5 mL. This increase is attributed to the quadratic effect of the factor (X_1X_1), which is statistically significant for turbidity ($p = 0.000$, Table 6).

The decrease in turbidity observed at lower gum extract volumes was due to its role as a flocculating and settling agent. This organic polymer helps particles come together through two main mechanisms: reducing their surface electrical charges [39] and creating molecular bridges between suspended particles [40]. The way in which the polymer interacts with colloids depends on electrostatic forces, especially when their charges are opposite. Alternatively, it may depend on the secondary forces such as hydrogen bonding, ion exchange, and Van der Waals interactions when their charges are similar [41]. As a result, flocs form and settle under gravity [42]. However, if the polymer folds onto itself instead of binding

Table 4 Experimental design

Factors			Responses									
X_1	X_2	X_3	Turbidity, EBC		Color, EBC		pH		Brix		Polyphenol content, mg/mL	
			Exp.	Pred.	Exp.	Pred.	Exp.	Pred.	Exp.	Pred.	Exp.	Pred.
–1	–1	0	14.39	14.15	24.00	24.40	5.20	5.23	4.0	4.31	20.00	20.03
1	–1	0	7.48	7.20	19.13	17.49	4.97	5.01	7.0	6.94	25.13	24.81
–1	1	0	18.04	18.32	26.40	28.04	5.25	5.21	4.0	4.06	22.40	22.72
1	1	0	19.40	19.64	29.40	29.00	4.97	4.94	7.0	6.69	25.40	25.37
–1	0	–1	10.85	11.43	20.85	20.97	5.20	5.21	4.0	3.88	16.85	16.34
1	0	–1	10.19	10.81	18.04	20.20	4.97	4.96	6.5	6.75	20.42	20.26
–1	0	1	10.20	9.58	22.36	20.20	5.15	5.16	4.0	3.75	21.99	22.16
1	0	1	5.15	4.57	15.15	15.03	4.92	4.91	6.0	6.13	25.15	25.67
0	–1	–1	7.26	6.92	17.26	16.74	5.14	5.10	6.5	6.31	16.11	16.60
0	1	–1	14.62	13.76	24.62	22.86	5.00	5.04	5.5	5.56	20.62	20.82
0	–1	1	0.55	1.41	10.55	12.31	5.07	5.03	5.5	5.44	25.00	24.81
0	1	1	10.84	11.18	20.84	21.36	4.97	5.01	5.5	5.69	24.32	23.84
0	0	0	7.00	7.11	18.00	17.78	5.04	5.04	5.5	5.50	23.00	23.33
0	0	0	7.33	7.11	17.33	17.78	5.05	5.04	5.5	5.50	24.00	23.33
0	0	0	7.00	7.11	18.00	17.78	5.04	5.04	5.5	5.50	23.00	23.33

Exp. – experimental; Pred. – predicted

Table 5 Validation criteria for different mathematical models

Validation criteria	Mathematical models	R^2	AAD	A_f	B_f	Decision
Turbidity	$Y = 7{,}110 - 1{,}407\ X_1 + 4{,}152\ X_2 - 2{,}023\ X_3 + 4{,}249\ X_1 \times X_1 + 3{,}469\ X_2 \times \times X_2 - 2{,}261\ X_3 \times X_3 + 2{,}067\ X_1 \times X_2 - 1{,}097\ X_1 \times X_3 + 0.732\ X_2 \times X_3$	98.99	0.142	1,052	1,107	Validated
Color	$Y = 17.78 - 1{,}486\ X_1 + 3{,}790\ X_2 - 1{,}484\ X_3 + 3.87\ X_1 \times X_1 + 3.09\ X_2 \times X_2 - - 2.55\ X_3 \times X_3 + 1.97\ X_1 \times X_2 - 1.10\ X_1 \times X_3 + 0.73\ X_2 \times X_3$	92.96	0.050	1,004	1,051	Validated
pH	$Y = 5.0433 - 0{,}1213\ X_1 - 0.0238\ X_2 - 0{,}0250\ X_3 - 0.0346\ X_1 \times X_1 + 0.0196\ X_2 \times X_2 - 0{,}0179\ X_3 \times X_3 - 0.0125\ X_1 \times X_2 + 0\ X_1 \times X_3 + 0.0100\ X_2 \times X_3$	92.55	0.004	1,000	1,004	Validated
Brix	$Y = 5{,}500 + 1{,}313\ X_1 - 0.125\ X_2 - 0.188\ X_3 - 0.313\ X_1 \times X_1 + 0.313\ X_2 \times X_2 - - 0.062\ X_3 \times X_3 + 0\ X_1 \times X_2 - 0.125\ X_1 \times X_3 + 0.250\ X_2 \times X_3$	97.22	0.026	1,000	1,026	Validated
Polyphenol content	$Y = 23{,}333 + 1{,}858\ X_1 + 0.813\ X_2 - 2{,}807\ X_3 - 0.255\ X_1 \times X_1 + 0.155\ X_2 \times \times X_2 - 1{,}975\ X_3 \times X_3 - 0.532\ X_1 \times X_2 - 0.103\ X_1 \times X_3 - 1{,}298\ X_2 \times X_3$	98.34	0.049	1,034	1,045	Validated
Standard values		100%	0	1	1	

Table 6 Probability and coefficients of factors for different responses

Terms	Turbidity		Color		pH		Brix		Polyphenol content	
	Coefficient	*P*-value	Coefficient	*P*-value	Coefficient	*P*-value	Coefficient	*P*-value	Coefficient	*P*-value
Constant	7.110	0.000	17.780	0.000	5.0433	0.000	5.500	0.000	23,333	0.000
X_1	–1,407	0.005	–1,486	0.102	–0.1213	0.001	1,313	0.000	1,858	0.000
X_2	4,152	0.000	3.790	0.004	–0.0238	0.210	–0.125	0.286	0.813	0.017
X_3	–2,023	0.001	–1,484	0.102	–0.025	0.190	–0.188	0.133	2,807	0.000
$X_1 \times X_1$	4,249	0.000	3.870	0.017	–0.0346	0.214	–0.313	0.098	–0.300	0.473
$X_2 \times X_2$	3,469	0.001	3.090	0.037	0.0196	0.457	0.313	0.098	0.155	0.659
$X_3 \times X_3$	–2,261	0.003	–2.550	0.067	–0.0179	0.494	–0.062	0.702	–1,975	0.002
$X_1 \times X_2$	2,067	0.004	1.970	0.120	–0.0125	0.615	0.000	1.000	–0.532	0.153
$X_1 \times X_3$	–1,097	0.047	–1.100	0.343	0.0000	1.000	–0.125	0.437	–0.103	0.759
$X_2 \times X_3$	0.732	0.140	0.730	0.517	0.0100	0.686	0.250	0.152	–1,298	0.001

with other particles, it can actually stabilize them and prevent flocculation [43].

The increase in turbidity at the extract volumes above 2.5 mL could be due to a phenomenon called restabilization. Several studies suggest that when too much polymer is added to the system, it can reverse the surface charges of the particles, making coagulation less effective [44, 45]. This is a common issue in colloidal systems, highlighting the importance of finding the right balance in flocculant concentration to get the best clarification results. These observations show why it is crucial to carefully control the clarification process, especially the gum extract concentration, to minimize turbidity. Optimizing this step is key to ensuring the final product's quality and stability in industrial applications.

Effect of T. cordifolia gum extract volume on polyphenol content. The polyphenol content increased significantly ($p = 0.00$, Table 6) in direct correlation with the rise in the gum extract volume (X_1), as illustrated in Fig. 1. This content rose from 21 mg/L at an extract volume of 1.5 mL to 25 mg/L at a volume of 3.5 mL. This increase can be attributed to the natural presence of polyphenols in *T. cordifolia* bark, as evidenced by the physicochemical analyses (Table 3) and supported by a recent study [46]. These phenolic compounds, which are soluble in aqueous media [47], are extracted during the gum extraction process from *T. cordifolia*. Therefore, increasing the volume of the gum extract added to the wort leads to a greater release of these molecules, resulting in a proportional rise in polyphenols in the medium. These findings suggest that *T. cordifolia* gum extract is a potential source of polyphenols, and its incorporation into the wort could enhance its antioxidant and nutritional properties.

Effect of T. cordifolia gum extract volume on pH. The influence of the gum extract volume on pH is illustrated in Fig. 1. As can be seen, the pH significantly decreased ($p = 0.001$, Table 6) as the extract volume increased. Specifically, the pH dropped from 5.15 at an extract volume of 1.3 mL to 4.85 at a volume of 3.5 mL. This gradual acidification of the medium can be attributed to the presence of organic acids in the gum's composition, as noted in [48]. Increasing the volume of the extract introduced into the medium leads to a greater release of these acidic compounds, which could explain the observed drop in pH. These results highlight the role of the gum as a natural source of acidifying compounds, whose effect on the acid-base balance of the medium is directly proportional to the concentration used.

Effect of T. cordifolia gum extract volume on Brix. The influence of the gum extract volume on Brix is illus-

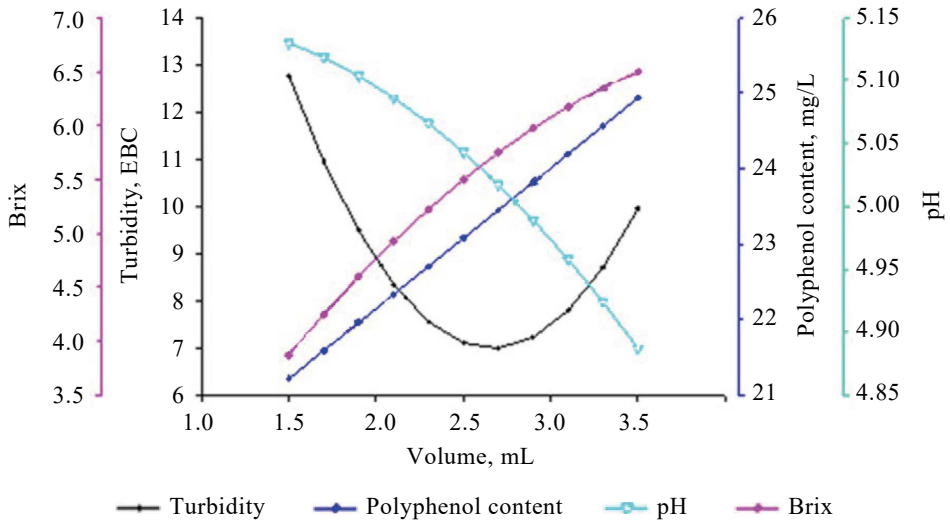

Figure 1 Impact of *Triumpheta cordifolia* gum extract volume on Brix, soluble protein content, turbidity, viscosity, pH, and polyphenol content

trated in Fig. 1. The results show a significant increase in Brix, rising from 3.8 at an extract volume of 1.5 mL to 6 at a volume of 3.5 mL. This rise can be attributed to the presence of soluble compounds such as polysaccharides, proteins, and polyphenols in *T. cordifolia* bark, as demonstrated in [49] and the analyses reported in Table 3. These molecules, extracted in an aqueous medium during gum preparation, are present in the extract and contribute to the increase in soluble solids when introduced into the wort. Specifically, polysaccharides are known for their ability to increase viscosity and dissolved solids concentration, while proteins and polyphenols also add to the total soluble mass. Thus, the gradual addition of the gum extract to the wort leads to a proportional increase in Brix, reflecting a higher concentration of soluble compounds. These results highlight the potential of *T. cordifolia* gum extract as an enriching agent for soluble solids, which could have significant implications during the wort fermentation process.

Effect of T. cordifolia gum extract volume on the wort color. The gum extract volume did not show a significant impact on color ($p = 0.102$, Table 6), although its quadratic effect contributed to a slight increase in color ($p = 0.017$, Table 6). This increase can be explained by the presence of polyphenols in the gum's composition (Table 3). Polyphenols, known for their chromogenic properties, are partially responsible for the coloration of the media in which they are solubilized [50]. Thus, introducing a higher quantity of the gum extract into the wort leads to a greater release of these phenolic compounds. However, the absence of a significant linear effect suggests that other factors, such as interactions between polyphenols and other compounds in the medium (e. g., proteins or sugars), might be responsible for this effect [51, 52].

Effect of the stirring speed on the responses. The gum extract volume had a significant impact on turbidity, color, and polyphenol content, with probability values of 0, 0.004, and 0.017, respectively. However, its influence on Brix, pH, and viscosity was not statistically significant ($p > 0.05$, Table 6). Figure 2 illustrates the effect of the extract volume on these responses after fixing the ratio at 2.5 and the stabilization time at 35 min. Figure 2 allows for an analysis of parameter variations under the experimental conditions.

Effect of the stirring speed on turbidity. The influence of the stirring speed on turbidity is shown in Fig. 2. As can be observed, turbidity increased significantly with higher stirring speeds. Specifically, turbidity rose from 6.5 EBC at 30 rpm to 16 EBC at 160 rpm. This increase can be explained by the fact that mechanical agitation promotes homogenization of the medium, preventing the sedimentation of suspended particles. Indeed, more intense agitation keeps colloidal particles in suspension and can even resuspend those that have settled due to gravity, leading to an increase in measured turbidity. This phenomenon aligns with the physicochemical principles governing colloidal systems, where the mechanical energy provided by agitation counteracts sedimentation forces [53]. These results highlight the importance of controlling the stirring speed in clarification processes, as excessive agitation can compromise sedimentation efficiency and increase the turbidity of the medium.

Effect of the stirring speed on the wort color. The influence of the stirring speed on the wort color is illustrated in Fig. 2. As can be seen, the color decreased (from 24.5 to 21.5 EBC) at low stirring speeds (10 to 70 rpm), but increased at significantly higher stirring speeds. The reduction could be explained by the fact that low stirring speeds promote the bridging of color-causing particles, such as polyphenols [50], with the polysaccharides present in the *T. cordifolia* gum extract already in the wort [51, 52]. These aggregates, due to their size and mass, may precipitate under the influence of gravity [42]. This precipitation reduces the concentra-

tion of coloring compounds in the solution, leading to a decrease in measured color.

On the other hand, the increase in color at higher stirring speeds is likely due to the shear effect induced by agitation, which promotes the redispersion and dissolution of deposited particles [53], thereby increasing the concentration of coloring compounds in the solution.

Effect of the stirring speed on polyphenol content. The influence of the stirring speed on the polyphenol content is illustrated in Fig. 2. Figure 2 reveals a significant increase in polyphenols from 22.4 to 24.4 mg/L as the stirring speed increased from 10 to 160 rpm. This gradual rise suggests that this parameter plays a key role in the extraction and release of phenolic compounds into the wort. Indeed, a recent study has shown that *T. cordifolia* bark contains a substantial amount of phenolic compounds [46]. Naturally present in the bark, they are released more effectively into the wort under mechanical agitation. Specifically, agitation enhances the interaction between solid gum particles and the liquid medium, optimizing the transfer of phenolic compounds into the solution. This observation aligns perfectly with the work of [54], who demonstrated that stirring the medium at around 150 rpm achieves optimal extraction of phenolic compounds. In this study, agitation at 160 rpm promoted a greater release of these compounds.

Effect of the settling time on turbidity and polyphenol content. The settling time had a significant influence on certain wort parameters, particularly turbidity and polyphenol content, as evidenced by the statistical results ($p < 0.05$, Table 6). However, its impact on other properties, such as pH, Brix, and color, was not significant ($p > 0.05$).

Figure 3 illustrates the effect of the settling time on turbidity after adjusting the extract volume to 2.5 mL and the stirring speed to 135 rpm. The results revealed a non-linear evolution of turbidity with the settling time. Initially, turbidity increased from 7 to 8 EBC at the settling times between 10 and 25 min, followed by a marked decrease to 3 EBC units at a settling time of

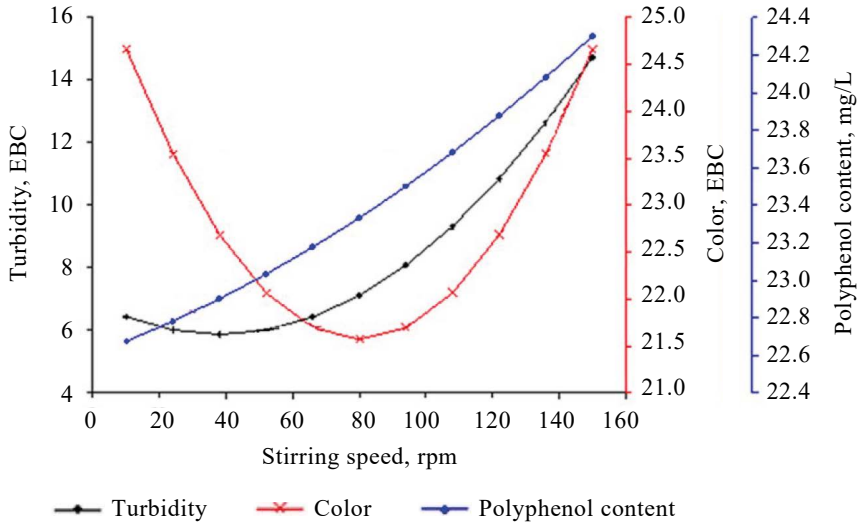

Figure 2 Impact of stirring speed on turbidity, color, and polyphenol content

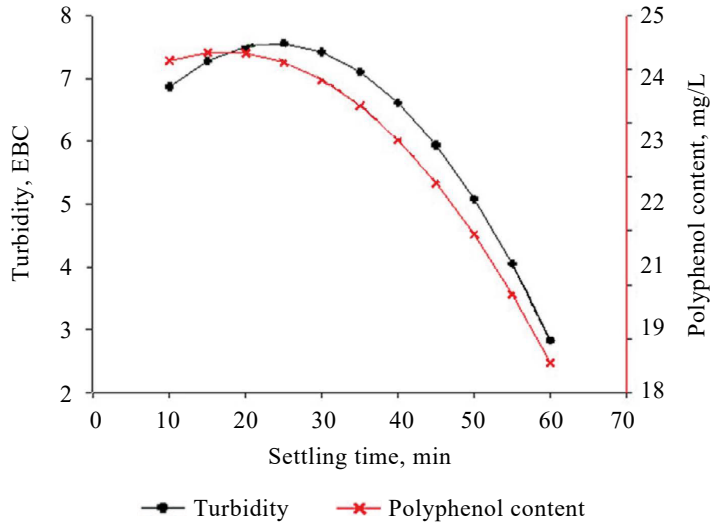

Figure 3 Impact of settling time on soluble protein content, turbidity, and polyphenol content

60 min. At the same time, the polyphenol content gradually reduced as the settling time increased.

This trend in turbidity and polyphenol content can be explained by complex interactions between polyphenols and proteins in the wort. Indeed, studies [55, 56] have demonstrated that polyphenols can react with proteins to form polyphenol-protein complexes. These complexes, due to their large size and high molecular weight, initially contribute to an increase in wort turbidity. However, with prolonged settling time, these insoluble complexes can gradually sediment under the influence of gravity, leading to a decrease in their concentration in the wort and, consequently, a reduction in measured turbidity. At the same time, the sedimentation of these polyphenol-protein complexes can explain the observed decrease in the polyphenol content. By binding to proteins to form insoluble complexes, polyphenols are progressively removed from the liquid phase, resulting in their reduced concentration in the wort after extended settling. Thus, these results highlight the crucial role of the settling time in modulating turbidity.

Effect of interactions X_1X_2, X_2X_3, and X_1X_3 on different responses. The interactions between the gum extract volume and the stirring speed (X_1X_2), as well as between the stirring speed and the settling time (X_2X_3), had a statistically significant influence on turbidity ($p < 0.05$). However, the same interactions did not show a significant effect on the other responses (color, pH, Brix, and polyphenol content, $p > 0.05$). Figures 4 and 5 provide a clear visualization of complex relationships between the experimental variables and the measured responses.

Impact of the gum extract volume and stirring speed ($X_1X_{2)}$ on turbidity. Figure 4 shows the influence of the interaction between the gum extract volume and the stirring speed (X_1X_2) on turbidity at a settling time (X_3) of 35 min. Figure 4 reveals a gradual decrease in turbidity (from 12 to 4 EBC) at low stirring speeds and low gum extract volumes (10 rpm and 1.5 mL, respectively). However, beyond a certain threshold, turbidity increased (from 8 to 18 EBC) at a gum extract volume of 3.5 mL and a stirring speed of 160 rpm.

This reduction in turbidity can be explained by the fact that low stirring speeds promote the formation of chemical bridges between polysaccharides in the gum extract and suspended particles in the solution. These chemical bridges contribute to particle aggregation, facilitating their sedimentation under the influence of gravity [42], which results in lower measured turbidity. On the other hand, the increase in turbidity observed beyond a certain threshold was due to an overdose of the gum. When added in excess, polysaccharide chains saturate the surfaces of colloidal particles preventing the formation of new polymer bridges. This saturation of available sites on the particles restabilizes colloids, resulting in higher turbidity.

Additionally, excessive or prolonged stirring could also play a role in this dynamic. Indeed, excessive agitation can break the polymer bridges already formed and restabilize the particles increasing turbidity. This phenomenon has been documented in [41], who highlighted the impact of mixing conditions and dosage on the stability of colloidal suspensions. Thus, optimizing the operational parameters, such as the stirring speed, gum extract volume, and settling time, is key to effectively controlling turbidity in this system.

Impact of the stirring speed and settling time on the polyphenol content. Figure 5 shows the effect of the interaction between the stirring speed and the settling time (X_2X_3) on the polyphenol content at a gum extract volume (X_1) of 1.5 mL. A decrease in the polyphenol content was observed as both the stirring speed and the settling time increased. This reduction can be attributed to the formation of high-molecular-weight polyphenol-protein complexes, which tend to precipitate over time, particularly under the combined effect of mechanical agitation and prolonged settling. The precipitation of

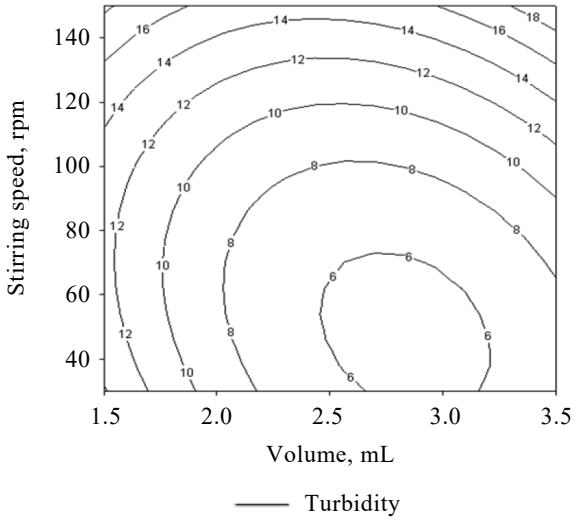

Figure 4 Effect of gum extract volume and settling time on turbidity

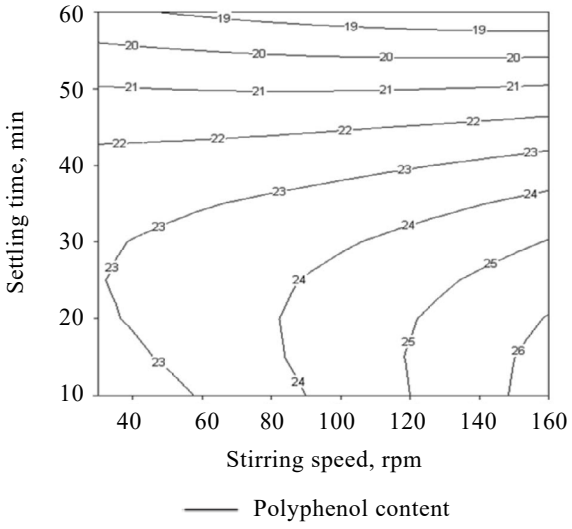

Figure 5 Effect of stirring speed and settling time on polyphenol content

Table 7 Optimal values of physicochemical parameters

	Turbidity, EBC	pH	Color, EBC	Brix	Polyphenols, Mg/L
Theoretical values (provided by software)	6.67	5.04	16.43	6.88	18.19
Experimental values	6.70 ± 0.20	4.98 ± 0.21	17.02 ± 1	7.20 ± 0.3	21.24 ± 0.97

these complexes lowers the concentration of free polyphenols in the solution, explaining the observed decline [51, 57, 58].

Thus, increasing the stirring speed and the settling time promotes the formation and precipitation of polyphenol-protein complexes, thereby reducing the content of polyphenols available in the medium. This mechanism highlights the importance of controlling the operational parameters, such as the stirring speed and the settling time, to optimize the polyphenol content in the systems where these compounds play a critical role, whether from a nutritional, functional, or technological perspective.

Impact of the gum extract volume and the settling time on turbidity. Figure 4 illustrates the influence of the interaction between the gum extract volume and the stirring speed at a settling time of 35 min. Figure 5 shows a significant reduction in turbidity ($p = 0.047$, Table 7) as both the gum extract volume and the settling time increased. Specifically, turbidity decreased from an initial value of 12 EBC, corresponding to a gum extract volume of 1.5 mL and a settling time of 10 min, to a final value of 4 EBC at a gum extract volume of 3.5 mL and a settling time of 60 min.

This reduction in turbidity can be attributed to the coagulating and flocculating properties of the gum extract [39, 59]. The gum extract acts by destabilizing suspended particles in the solution, initiating a process of trapping and sedimentation. This mechanism involves the formation of a precipitate that encapsulates colloidal particles, promoting their agglomeration and sedimentation. As a result, the particles are removed from the liquid phase, leading to a significant reduction in turbidity. This phenomenon aligns with the observations in [41], who highlighted the role of coagulating and flocculating agents in destabilizing colloidal suspensions.

Optimization results. The optimization of operating conditions was undertaken to identify a combination of parameters capable of producing a clarified wort that meets the predefined physicochemical criteria. The application of Minitab 18 software led to the determination of the following optimal conditions: a gum extract volume (X_1) of 2.4 mL, a stirring speed (X_2) of 85.15 rpm, and a settling time (X_3) of 60 min.

The validity of the predictive model was assessed by conducting an experimental clarification test under the optimized conditions, followed by physicochemical analyses of the resulting wort. The results (Table 7) show a good agreement between predicted and experimental values, particularly for turbidity (6.70 ± 0.20 EBC compared to the theoretical value of 6.67 EBC), suggesting an overall adequacy of the model. The discrepancies observed for certain secondary parameters may be attributed to the intrinsic limitations of statistical modeling, especially in accounting for complex interactions and unmodeled experimental variability.

In this study, turbidity was selected as the primary indicator of clarification performance. In this regard, the work of Man-Ikri & Desobgo Zangué [10], which focused on the clarification of Mbayeri sorghum wort using Grewia mollis bark powder, provides a relevant comparative framework. Using a Box–Behnken experimental design, these authors demonstrated the effectiveness of plant-based biocoagulants by optimizing similar variables, including the wort-to-coagulant ratio, stirring speed, and treatment duration.

In light of these findings, the performance achieved with Triumfetta cordifolia gum, yielding a final turbidity of 6.70 EBC (≈ 16.7 NTU), highlights its potential as a highly efficient bio-clarifying agent. These results support the relevance of plant-derived biomaterials as sustainable alternatives to conventional clarification processes and open perspectives for their application in environmentally friendly brewing process optimization.

CONCLUSION

In this study, we successfully optimized the clarification of *Safrari* sorghum wort using *Triumpheta cordifolia* A. Rich. gum extract. For this, we employed the response surface methodology to systematically evaluate the effects of the gum volume, stirring speed, and settling time. The physicochemical properties of *Safrari* sorghum (low moisture content, high germination energy, and uniform grain size) confirmed its suitability for brewing applications. In addition, the gum extract, which is rich in polysaccharides and polyphenols, proved highly effective in reducing turbidity while enhancing the overall wort quality. The Box-Behnken experimental design revealed significant interactions among the studied factors, thereby enabling us to identify optimal clarification conditions: a gum extract volume of 2.4 mL, stirring speed of 85.15 rpm, and settling time of 60 min. These conditions produced a wort with low turbidity (6.70 European Brewery Convention units), balanced pH (4.98), and moderate polyphenol content (21.24 mg/L), which closely aligned with the theoretical predictions, thus validating the robustness of the model.

These findings underscore the potential of *T. cordifolia* gum as a sustainable alternative to synthetic clarifiers in the brewing industry. Future research could explore the scalability of this process and assess the long-term stability of clarified wort under industrial conditions. In addition, the nutritional and antioxidant benefits of polyphenols in the gum could be further

investigated to enhance the health-promoting properties of sorghum-based beverages.

In conclusion, our study provides a robust and scientifically grounded framework for optimizing wort clarification using natural gums. It therefore contributes significantly to the valorization of local resources and the advancement of sustainable brewing practices in sub-Saharan Africa.

CONTRIBUTION

Z.C. Bassa: investigation (laboratory sample analysis), formal analysis (statistical data analysis), writing – original draft, writing – review & editing. S.C. Desobgo Zangué: supervision, validation, methodology, formal analysis (statistical data analysis), writing – review & editing. E.J. Nso: supervision, validation, methodology, project administration, writing – review & editing.

CONFLICT OF INTEREST

The authors state that there is no conflict of interest.

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DECLARATION OF AI

Everything written here was authored by the writers themselves in French, as all the authors are native French speakers. We used AI tools (ChatGPT-3.5 and DeepSeek-V3) solely for translation purposes, and we ensured that no substantive information was altered or modified during the translation process. Therefore, we can confirm that the manuscript in its current state truly reflects the spirit of our research work.

REFERENCES

1. Kazungu FK, Muindi EM, Mulinge JM. Overview of sorghum (*Sorghum bicolor*. L), its economic importance, ecological requirements and production constraints in Kenya. International Journal of Plant & Soil Science. 2023; 31(1):62–71. https://doi.org/10.9734/IJPSS/2023/v35i12744
2. Sanchez VCC, da Silva JCR, Lima VS. Beer production using saccharine sorghum (*Sorghum bicolor*): Potential and possibilities. Revista Scientia Vitae. 2023;14(39):1–10.
3. Sawadogo-Lingani H, Owusu-Kwarteng J, Glover R, Diawara B, Jakobsen M, *et al*. Sustainable production of African traditional beers with focus on *Dolo*, a West African sorghum-based alcoholic beverage. Frontiers in Sustainable Food Systems. 2021;5:672410. https://doi.org/10.3389/fsufs.2021.672410
4. Touwang C, Nso EJ, Ndjouenkeu R. Technical production system of «bili-bili», a traditional sorghum beer: Territorial variability of practices and valorization perspectives. International Journal of Innovation and Applied Studies. 2021;34(2):343–353. (In French)
5. Dabija A, Ciocan ME, Chetrariu A, Codină GG. Maize and sorghum as raw materials for brewing, a review. Applied Sciences. 2021;11(7):3139. https://doi.org/10.3390/app11073139
6. Davana TV, Revanna ML. Development of beer from malted sorghum (*Sorghum bicolor*). Peer Reviewed Journal. 2021;9(1):330–334. https://doi.org/10.22271/chemi.2021.v9.i1e.11248
7. Djida AK, Wassouo FA, Yougouda H, Gnapou D, Djaowe A. Adaptability of four improved varieties of dual-purpose rainfed sorghum [*Sorghum bicolor* (L.) Moench.] to the climatic conditions of the Guinean high savannah zone of Cameroon. 2024;25(1):131–140. (In French)
8. Bakari H, Djomdi, Ruben ZF, Roger DD, Cedric D, *et al*. Sorghum (*Sorghum bicolor* L. Moench) and its main parts (by-products) as promising sustainable sources of value-added ingredients. Waste and Biomass Valorization. 2023;14:1023–1044. https://doi.org/10.1007/s12649-022-01992-7
9. Lyumugabe Loshima F. Characterisation and improvement of the quality of Rwandese traditional beer « ikigage » made from sorghum. ULiège – Université de Liège. 2013.
10. Man-Ikri B, Desobgo Zangué SC. *Grewia mollis* bark powder impact on the clarification of *Mbayeri* sorghum wort. Applied Food Research. 2023;3(1):100243. https://doi.org/10.1016/j.afres.2022.100243
11. Sanga PR, Kalera AN. Improvement of the physico-chemical and microbiological characteristics of a traditional beer based on sorghum flour called “Musururu” produced in the province of North Kivu in the DRC. Annales de l’Université de Goma. 2020;10(1):61–76. (In French)
12. Desobgo Zangué S, Nso JE, Tenin D. Use of the response surface methodology for optimizing the action of mashing enzymes on wort reducing sugars of the *Madjeru sorghum* cultivar. African Journal of Food Science 2011;5(2):91–99.
13. Bouchareb R, Derbal K, Benalia A. Optimization of active coagulant agent extraction method from *Moringa Oleifera* seeds for municipal wastewater treatment. Water Science & Technology. 2021:84(2):393–403. https://doi.org/10.2166/wst.2021.234

14. Shirvani A, Mirzaaghaei M, Goli SAH. Application of natural fining agents to clarify fruit juices. Comprehensive Reviews in Food Science and Food Safety. 2023;22(6):4190–4216. https://doi.org/10.1111/1541-4337.13207
15. Adesina OA, Taiwo AE, Akindele O, Igbafe A. Process parametric studies for decolouration of dye from local 'tie and dye' industrial effluent using *Moringa oleifera* seed. South African Journal of Chemical Engineering. 2021;37:23–30. https://doi.org/10.1016/j.sajce.2021.03.005
16. Hartal O, Madinzi A, Rifi SK, Haddaji C, Kurniawan TA, *et al*. Optimization of coagulation-flocculation process for wastewater treatment from vegetable oil refineries using chitosan as a natural flocculant. Environmental Nanotechnology, Monitoring & Management. 2024;22:100957. https://doi.org/10.1016/j.enmm.2024.100957
17. Venkatesh T, Alphonsa G, Rishi KS, Sajeev SM, Kothakota A. Plant-based hydrocolloids for efficient clarification of cane juices: Rheological analysis and solidification studies. Food Function. 2024;15(4):1977–1993. https://doi.org/10.1039/D3FO05029G
18. Cerqueira UMFM, Bezerra MA, Ferreira SLC, de Jesus Araújo R, da Silva BN, *et al*. Doehlert design in the optimization of procedures aiming food analysis – A review. Food Chemistry. 2021;364:130429. https://doi.org/10.1016/j.foodchem.2021.130429
19. Shekhar S, Prakash P, Singha P, Prasad K, Singh SK. Modeling and optimization of ultrasound-assisted extraction of bioactive compounds from *Allium sativum* leaves using response surface methodology and artificial neural network coupled with genetic algorithm. Foods. 2023;12(9):1925. https://doi.org/10.3390/foods12091925
20. Torres JD, Alvis A, Acevedo D, Montero PM, Tirado DF. Optimization of vacuum frying conditions of eggplant (*Solanum melongena* L.) slices by response surface methodology. Interciencia. 2017;42(10):683–691.
21. Sopacua E, Dirpan A, Syarifuddin A. Literature review on response surface methodology (RSM) application in the fermentation of food products. Proceedings of the 1st UNHAS Intern. Conf. on Agricult. Technol. (UICAT 2021). Makassar, 2023;2596(1):050007. https://doi.org/10.1063/5.0119602
22. European Brewery Convention. The European reference methods for breweries by EBC. Analytica-EBC. Nuremberg: Fachverlag Hans Carl; 1998. (In German)
23. Jung JY, Ha SY, Yang JK. Response surface methodology optimization of phenolic compounds extraction from steam-treated oak (*Quercus mongolica*) wood. Journal of the Korean Wood Science and Technology. 2017;45(6):809–827. https://doi.org/10.5658/WOOD.2017.45.6.809
24. Saidou C, Ndjouenkeu R, Roux D, Tchatchueng JB, Heyraud A, *et al*. Effect of drying conditions on rheological properties of hydrocolloids gums from *Triumfetta cordifolia* and *Bridelia thermifolia* Barks. Food and Nutrition Sciences. 2013;4(6):626–631. http://doi.org/10.4236/fns.2013.46080
25. American Society of Brewing Chemists. ASBC methods of analysis. NY: American Society of Brewing Chemists. 2009.
26. Sin HN, Yusof S, Hamid NSA, Rahman RA. Optimization of enzymatic clarification of sapodilla juice using response surface methodology. Journal of Food Engineering. 2006;73(4):313–319. https://doi.org/10.1016/j.jfoodeng.2005.01.031
27. Liew Abdullah AG, Sulaiman NM, Aroua MK, Noor MJMM. Response surface optimization of conditions for clarification of carambola fruit juice using a commercial enzyme. Journal of Food Engineering. 2007;81(1):65–71. https://doi.org/10.1016/j.jfoodeng.2006.10.013
28. Adebo OA, Njobeh PB, Mulaba-Bafubiandi AF, Adebiyi JA, Desobgo Zangué SC, *et al*. Optimization of fermentation conditions for ting production using response surface methodology. Journal of Food Processing and Preservation. 2018;42:e13381 https://doi.org/10.1111/jfpp.13381
29. Manga JAM, Desobgo Zangué SC, Tatsadjeu LN, Zargar M, Albert E, *et al*. Producing probiotic beverage based on raffia sap fermented by *Lactobacillus fermentum* and *Bifidobacterium bifidum*. Research on Crops. 2019;20(3):629–634.
30. Touwang C, Nso EJ, Ndjouenkeu R. Production du Bili-Bili, biere traditionnelle de sorgho du nord cameroun: Diversité des procédés de production et qualité des produits. European Scientific Journal. 2018;14(36):207–224. (In French) https://doi.org/10.19044/esj.2018.v14n36p207
31. Desobgo Zangué SC, Naponni FY. Caractérisation des moûts et bières du sorgho Safrari houblonnés avec *Vernonia amygdalina* et *Nauclea diderrichii*. International Journal of Innovation and Applied Studies. 2013;2(1):83–91.
32. Choy SY, Prasad KMN, Wu TY, Ramanan RN. A review on common vegetables and legumes as promising plant-based natural coagulants in water clarification. International Journal of Environmental Science and Technology. 2015;12:367–390. https://doi.org/10.1007/s13762-013-0446-2
33. Chen H, Chen Y, Ye X, Liu D, Chen J. Turbidity, antioxidant compounds, color, and dynamics of clarification of bayberry juice using various polysaccharide-based clarifying agents. Journal of Food Processing and Preservation. 2019;43:e13980. https://doi.org/10.1111/jfpp.13980

34. Lachowicz S, Oszmiański J, Kalisz S. Effects of various polysaccharide clarification agents and reaction time on content of polyphenolic compound, antioxidant activity, turbidity and colour of chokeberry juice. LWT. 2018;92: 347–360. https://doi.org/10.1016/j.lwt.2018.02.054

35. Baranyi J, Pin C, Ross T. Validating and comparing predictive models. International Journal of Food Microbiology. 1999;48(3):159–166. https://doi.org/10.1016/s0168-1605(99)00035-5

36. Baş D, Boyacı İH. Modeling and optimization I: Usability of response surface methodology. Journal of Food Engineering. 2007;78(3):836–845. https://doi.org/10.1016/j.jfoodeng.2005.11.024

37. Dalgaard P, Jørgensen VL. Predicted and observed growth of *Listeria monocytogenes* in seafood challenge tests and in naturally contaminated cold-smoked salmon. International Journal of Food Microbiology. 1998;40(1–2):105–115. https://doi.org/10.1016/s0168-1605(98)00019-1

38. Goupy J, Creighton L. Introduction to the plans of experiments. Boston, MA: Hachette; 2006.

39. Benalia A, Derbal K, Amrouci Z, Baatache O, Khalfaoui A, *et al*. Application of plant-based coagulants and their mechanisms in water treatment: A review. Journal of Renewable Materials. 2024;12(4):1–10. https://doi.org/10.32604/jrm.2024.048306

40. Assaad E, Azzouz A, Nistor D, Ursu AV, Sajin T, *et al*. Metal removal through synergic coagulation–flocculation using an optimized chitosan–montmorillonite system. Applied Clay Science. 2007;37(3–4):258–274. https://doi.org/10.1016/j.clay.2007.02.007

41. Benefield LD, Judkins JF, Weand BL. Process chemistry for water and wastewater treatment. Hoboken: Prentice-Hall; 1982, 212 p.

42. Das N, Ojha N, Mandal SK. Wastewater treatment using plant-derived bioflocculants: Green chemistry approach for safe environment. Water Sciense & Technology. 2021;83(8):1797–1812. https://doi.org/10.2166/wst.2021.100

43. Teramoto T. Deep ocean circulation: Physical and chemical aspects. Amsterdam: Elsevier; 1993, 382 p.

44. Ferasat Z, Panahi R, Mokhtarani B. Natural polymer matrix as safe flocculant to remove turbidity from kaolin suspension: Performance and governing mechanism. Journal of Environmental Management. 2020;255:109939. https://doi.org/10.1016/j.jenvman.2019.109939

45. Konkobo FA, Diao M, Roamba NE, Savadogo PW, Dicko MH. Optimization of the purification capacity of Moringa oleifera seeds in the water purification process in Burkina Faso. Sciences Naturelles Et Appliquées. 2024;42(1): 89–108. (In French)

46. Tautua BMA, Ajoko IT, Oyaseiye PE. Phytochemical screening and antioxidant potential of methanol extract of *Triumfetta cordifolia* A. Rich. (Malvaceae) leaves. Scholars International Journal of Traditional and Complementary Medicine. 2024;7(1):1–7. https://doi.org/10.36348/sijtcm.2024.v07i01.001

47. Lampakis D, Skenderidis P, Leontopoulos S. Technologies and extraction methods of polyphenolic compounds derived from pomegranate (*Punica granatum*) peels. A mini review. Processes. 2021;9(2):236. https://doi.org/10.3390/pr9020236

48. Fanwa MN, Malhiac C, Hucher N, Cheumani AMY, Ndikontar MK, *et al*. *Triumfetta cordifolia* gum as a promising bio-ingredient to stabilize emulsions with potentials in cosmetics. Polymers. 2023;15(13):2828. https://doi.org/10.3390/polym15132828

49. Ajoko IT, Amos-Tautua BMW, Bamgbade EO. HPLC analysis and anti-inflammatory effect of methanol extract of the leaves of *Triumfetta cordifolia* A. Rich. (Malvaceae) Available in Bayelsa State, Nigeria. Scholars International Journal of Chemistry and Material Sciences 2023;6(6):115–125. https://doi.org/10.36348/sijcms.2023.v06i06.001

50. Ducasse MA, Canal-Llauberes RM, de Lumley M, Williams P, Souquet JM, *et al*. Effect of macerating enzyme treatment on the polyphenol and polysaccharide composition of red wines. Food Chemistry. 2010;118(2):369–376. https://doi.org/10.1016/j.foodchem.2009.04.130

51. Bauduin R, Poupard P, Cottereau P, Charrier F, Meistermann E, *et al*. Colloidal destabilization of clear beverages: Research on the mechanisms involved and development of technological prevention routes. Innovations Agronomiques. 2020;79:49–59. (In French)

52. Zhao H, Sun-Waterhouse D. Interactions between proteins and polyphenols in beer. In: Melton L, Shahidi F, Varelis P, editors. Encyclopedia of Food Chemistry. Oxford: Academic Press; 2019, pp. 550–553. https://doi.org/10.1016/B978-0-08-100596-5.21487-X

53. Li T, Zhu Z, Wang D, Yao J, Tang N. Characterization of floc size, strength and structure under various coagulation mechanisms. Powder Technology. 2006;168(2):104–110. https://doi.org/10.1016/j.powtec.2006.07.003

54. Sushma R, Dharini H, Tabassum S, Murthy KTP, Bhavya SG, *et al*. Extraction of polyphenols from *Decalepis hamiltonii* root: Optimization of batch extraction process parameters. 2014;5(4):624–632.

55. Jongberg S, Andersen ML, Lund MN. Covalent protein-polyphenol bonding as initial steps of haze formation in beer. Journal of the American Society of Brewing Chemists. 2020;78(2):153–164. https://doi.org/10.1080/03610470.2019.1705045

56. Wang Y, Ye L. Haze in beer: Its formation and alleviating strategies, from a protein–polyphenol complex angle. Foods. 2021;10(12):3114. https://doi.org/10.3390/foods10123114

57. Haslam E, Lilley TH, Butler LG. Natural astringency in foodstuffs – A molecular interpretation. Critical Reviews in Food Science and Nutrition. 1988;27(1):1–40. https://doi.org/10.1080/10408398809527476

58. Siebert KJ, Carrasco A, Lynn PY. Formation of protein−polyphenol haze in beverages. Journal of Agricultural and Food Chemistry. 1996;44(8):1997–2005. https://doi.org/10.1021/jf950716r

59. Chevassus-Agnès S, Favier JC, Joseph A. Traditional technology and nutritional value of Sorghum “beers” from Cameroon. Cahiers de l’ONAREST. 1979;2(3):83–112. (In French)

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