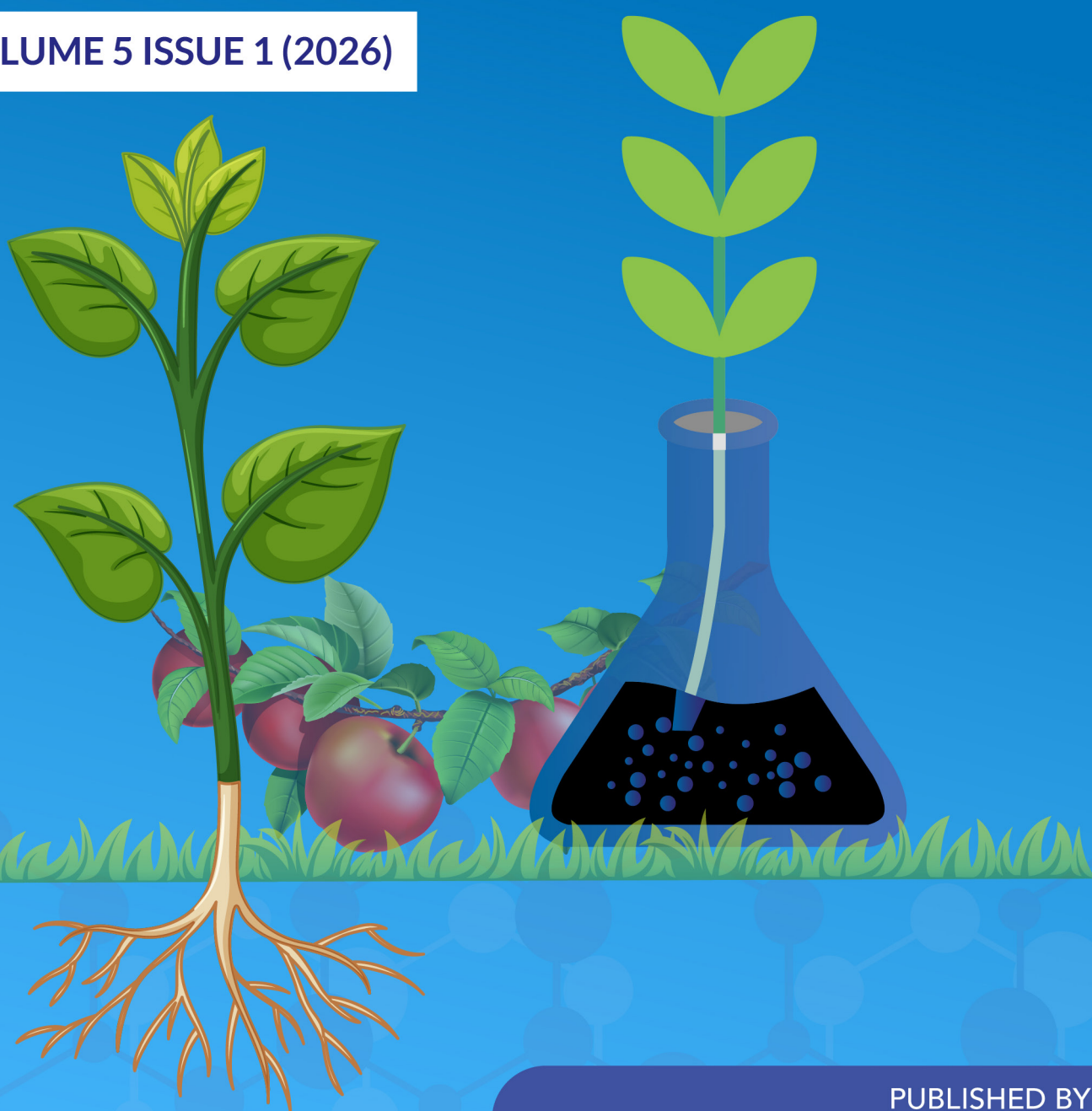




American Journal of Food Science and Technology (AJFST)

ISSN: 2834-0086 (ONLINE)

VOLUME 5 ISSUE 1 (2026)



PUBLISHED BY
E-PALLI PUBLISHERS, DELAWARE, USA

Chemical Characteristics and Quality Changes of Syrup and Massecuite Across Boiling House Stages in Raw Sugar Manufacture

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Article Information

Received: November 24, 2025

Accepted: February 16, 2026

Published: March 26, 2026

Keywords

Boiling house, Color, Crystallization, Massecuite, Purity, Syrup

ABSTRACT

The boiling house is a stage in sugar manufacture, in which clarified syrup is concentrated and crystallized into successive grades of massecuite, and sugar quality is influenced by physicochemical changes during processing. This study investigated chemical characteristics and quality changes of syrup and massecuites across major boiling house stages at Gunied Sugar Factory, Sudan, during the 2025 production season. Key parameters, including Brix, polarization (pol), purity, and color, were analyzed for syrup, A-massecuite, magma, and B- and C-massecuites to evaluate concentration behavior, crystallization efficiency, and impurity accumulation. Conversion of syrup to A-massecuite resulted in substantial increases in Brix (approximately 51.5%) and pol (approximately 52.9%), confirming effective concentration and crystallization under high-grade boiling conditions, while purity showed only a marginal change. As boiling progressed through magma and lower-grade massecuites, purity declined sharply from 89.37% in magma to 54.62% in C-massecuite, indicating progressive accumulation of non-sucrose impurities. Color intensity increased markedly from 14,516 IU in syrup to nearly 29,600 IU in C-massecuite, reflecting intensified thermal reactions and colored compound formation during repeated boiling cycles. One-way ANOVA revealed significant differences ($p < 0.01$) among stages. These findings emphasize the need for optimized pan control and real-time monitoring to enhance crystallization efficiency and sugar quality.

INTRODUCTION

The boiling house is a central operational unit in raw sugar manufacture, where clarified syrup is concentrated and crystallized into successive grades of massecuite. The efficiency of this process and the quality of the final sugar are governed by the physicochemical behavior of sucrose solutions during evaporation and crystallization. Key factors influencing this behavior include supersaturation control, viscosity, non-sucrose impurity content, and thermal reactions, all of which interact to determine crystal growth, exhaustion efficiency, and product quality (Broadfoot & Rackemann, 2023; Bubník *et al.*, 2019). As syrup progresses through the boiling house, systematic changes occur in Brix, polarization (pol), purity, and color. Increasing Brix reflects concentration of total soluble solids, while changes in pol indicate sucrose availability for crystallization. Purity, defined as the ratio of sucrose to total soluble solids, is a critical indicator of crystallization potential and typically declines across successive massecuite grades due to the accumulation of non-sucrose components in the mother liquor (Chochoowski *et al.*, 2018; Vavrincz, 2020). These changes directly influence massecuite viscosity, crystal size distribution, and centrifugal performance, ultimately affecting sugar recovery and molasses quality (Patel & Rao, 2021; Ahmed

& El Sayed, 2022). Color development is a major quality concern in modern sugar factories, particularly in lower-grade massecuites. Thermal degradation of sucrose, Maillard reactions between reducing sugars and amino compounds, and caramelization reactions intensify with increasing temperature and residence time during boiling (Singh & Kumar, 2021; Wang *et al.*, 2022). These reactions lead to the formation of high-molecular-weight colored compounds that preferentially accumulate in B and C massecuites and are resistant to crystallization (Zhao *et al.*, 2020; Rahman, 2024). Consequently, color values increase progressively across boiling stages, negatively affecting raw sugar quality and refinery performance. In recent years, advances in process modelling, soft-sensor control, and dry-substance-based pan control have improved the predictability and stability of massecuite boiling operations (El Abdien *et al.*, 2019; Lopes Fraga *et al.*, 2024). Despite these developments, empirical characterization of syrup and massecuite properties remains essential for validating control strategies, diagnosing process inefficiencies, and supporting operational decision-making in industrial sugar factories (Bubník *et al.*, 2019; Silva & Gomez, 2024). The present study investigates the chemical characteristics and quality

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changes of syrup and massecuites across different boiling house stages at Gunied Sugar Factory, Sudan. Specifically, it evaluates changes in Brix, pol, purity, and color between syrup and A-massecuite, quantifies the rate of change during this transition, and compares the properties of magma, A-, B-, and C-massecuities. The findings aim to enhance understanding of impurity accumulation, color development, and concentration dynamics across the boiling house, thereby supporting improved crystallization control and sugar quality optimization.

MATERIALS AND METHODS

Study Site and Sample Collection

The study was conducted at Gunied Sugar Factory, Sudan, in 2025, a modern sugar processing facility using multi-stage evaporation and crystallization. Syrup and massecuite samples (A, B, and C stages) were collected directly from the boiling house during routine operation. Samples were collected in clean, labeled containers and transported immediately to the laboratory for analysis (ICUMSA, 2007; Corbion *et al.*, 2023).

Brix Measurement

Total soluble solids (°Bx) were measured using a digital refractometer, calibrated before each session. Five replicates per sample were analyzed to ensure accuracy (Asikin *et al.*, 2024).

Polarization (Pol) Measurement

Sucrose content was determined using a digital polarimeter with temperature compensation following ICUMSA standard protocols (ICUMSA, 2007; Smith, 2024).

Purity Calculation

$$\text{Purity} = \left(\frac{\text{Pol}}{\text{Brix}} \right) \times 100$$

Purity (%) was calculated using:

This assesses the proportion of sucrose relative to total soluble solids (Smith, 2024; Ergasi *et al.*, 2025).

Color Measurement

Color intensity (IU) was measured using an ICUMSA colorimeter at standardized wavelengths. Higher values indicate thermal effects and accumulation of non-sugar impurities during boiling (Smith, 2024; Corbion *et al.*, 2023).

Statistical Analysis

Data were analyzed using one-way ANOVA to evaluate differences between syrup and massecuite samples, as well as among boiling house stages. Post hoc comparisons were performed using Duncan's multiple range test at $p > 0.05$.

Table 1: Chemical properties of syrup and (A) massecuite in boiling house

Parameter	Brix (°Bx)	Pol (%)	Purity (%)	Color (IU)
Syrup	60.96 ± 1.80 ^b	51.80 ± 2.20 ^b	84.98 ± 0.63 ^b	14516 ^b
A-massecuite	91.94 ± 0.63 ^a	79.20 ± 0.55 ^a	85.22 ± 0.22 ^a	18180.4 ± 2.91 ^a

Values in the same row with different superscript letters differ significantly ($p \leq 0.05$). Values sharing the same letter are not significantly different ($p > 0.05$).

RESULTS AND DISCUSSION

The chemical properties of syrup and A-massecuite are presented in Table 1. A-massecuite exhibited significantly higher Brix (91.94 °Bx) and Pol (79.20%) compared with syrup (60.96 °Bx and 51.80%, respectively). This increase reflects the strong concentration of soluble solids during the pan boiling process and the establishment of supersaturation conditions required for sucrose crystallization. The marked increase in Brix confirms the progressive evaporation of water and accumulation of dissolved solids, which is essential for stable nucleation and crystal growth. Similarly, the increase in polarization indicates a higher proportion of crystallizable sucrose in the massecuite phase. Efficient crystallization at this stage suggests proper control of supersaturation and effective separation of crystals from the mother liquor during pan boiling. Maintaining suitable dry substance levels is important for achieving efficient crystallization while preventing excessive viscosity that may hinder mass transfer during boiling operations (Vavrinecz, 2020; Lopes Fraga *et al.*, 2024). Purity showed only a slight increase from 84.98% in syrup to 85.22% in

A-massecuite, indicating that sucrose crystallization occurred with minimal incorporation of non-sucrose impurities into the crystal lattice. Such behavior is typical of high-grade boiling where careful control of feed quality and supersaturation limits impurity inclusion (Ibrahim, 2021; Broadfoot & Fraga, 2023). In contrast, the color value increased markedly from 14516 IU to 18180.4 IU, suggesting the beginning of color formation during thermal processing. This increase is associated with heat-induced reactions such as sucrose degradation and early Maillard reactions

The rate of change between syrup and A-massecuite is presented in Table 2. The results show that Brix and Pol increased by approximately 51.5% and 52.9%, respectively. These increases confirm the substantial concentration of sucrose during the transformation of syrup into massecuite. The rise in Brix reflects a higher dry-substance content, while the increase in Pol indicates greater availability of crystallizable sucrose within the system. Such changes are characteristic of the first boiling stage where efficient crystallization occurs under controlled supersaturation conditions. In

Table 2: The rate of change between syrup and (A) massecuite in boiling house

Parameter	Syrup	A-massecuite	Change (%)
Brix (°Bx)	60.69 ± 1.80	91.94 ± 0.63	51.50
Pol (%)	51.80 ± 2.20	79.20 ± 0.55	52.90
Purity (%)	84.98 ± 0.63	85.92 ± 0.22	0.07
Color (IU)	14516	18180.4 ± 2.91	25.25

contrast, purity showed only a minimal increase (0.07%), suggesting that most non-sucrose impurities remained in the mother liquor rather than being incorporated into the growing sugar crystals. This indicates effective impurity exclusion during high-grade crystallization. However, color increased by approximately 25.25%, indicating

the formation of colored compounds during the concentration process. Thermal reactions such as sucrose inversion, caramelization, and Maillard reactions intensify as temperature and concentration increase, contributing to the development of colored substances in the boiling house system (Wang *et al.*, 2022).

Table 3: Chemical characteristics of boiling house products at different stages

Parameter	Brix (°Bx)	Pol (%)	Purity (%)	Color (IU)
Magma	91.26 ^b	81.55 ^a	89.37 ^d	17579.4 ^c
A-massecuite	91.94 ^b	79.20 ^a	85.92 ^a	18180.4 ^c
B-massecuite	94.32 ^a	69.75 ^b	73.20 ^b	23761.9 ^b
C-massecuite	99.57 ^c	54.39 ^c	54.62 ^c	29571.6 ^d

Values in the same row with different superscript letters differ significantly ($p \leq 0.05$). Values sharing the same letter are not significantly different ($p > 0.05$).

The chemical characteristics of boiling house products at different processing stages are shown in Table 3. Brix increased progressively from magma (91.26 °Bx) to C-massecuite (99.57 °Bx), reflecting the continued concentration of solids as boiling proceeds. This increase indicates the gradual removal of water and the accumulation of dissolved solids during successive crystallization cycles. In contrast, both Pol and purity decreased significantly across the same stages. Purity declined from 89.37% in magma to 54.62% in C-massecuite, demonstrating the progressive accumulation of non-sucrose impurities in the mother liquor as sucrose crystals are removed during centrifugation. Non-sugar compounds such as ash, dextrans, reducing sugars, and organic acids become increasingly concentrated in lower-grade massecuites, reducing the crystallization efficiency and increasing viscosity (Torres *et al.*, 2020; Patel & Rao, 2021). Color intensity also increased substantially from 17579.4 IU in magma to 29571.6 IU in C-massecuite. This progressive increase is attributed to repeated thermal exposure and the recycling of colored mother liquor during successive boiling operations. High-molecular-weight colored compounds, including melanoidins formed during Maillard reactions, accumulate in lower-grade massecuites and are difficult to remove during crystallization (Zhao *et al.*, 2020; Brown & Kelly, 2022). Consequently, the high color values observed in C-massecuite reflect the cumulative effect of thermal reactions and impurity concentration during industrial sugar processing.

As seen in Fig 1. The purity of sugar streams decreased gradually from magma to C-massecuite. This decline

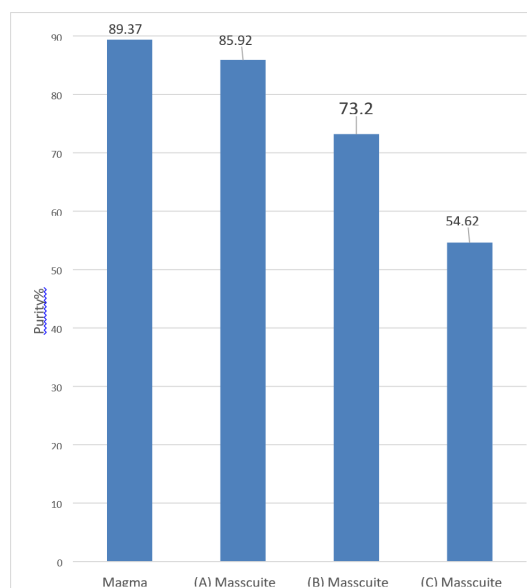


Figure1: The purity in difference stages of boiling house was decreased gradually.

reflects the progressive accumulation of non-sucrose impurities in the mother liquor as sucrose is removed through crystallization. Lower purity values in later stages indicate reduced crystallization efficiency and higher impurity concentrations in the residual liquor.

Figure 2 : Color values increased progressively from magma to C-massecuite. The increase in color intensity is attributed to thermal degradation of sucrose, Maillard reactions, and caramelization processes occurring during repeated boiling cycles. These reactions generate colored

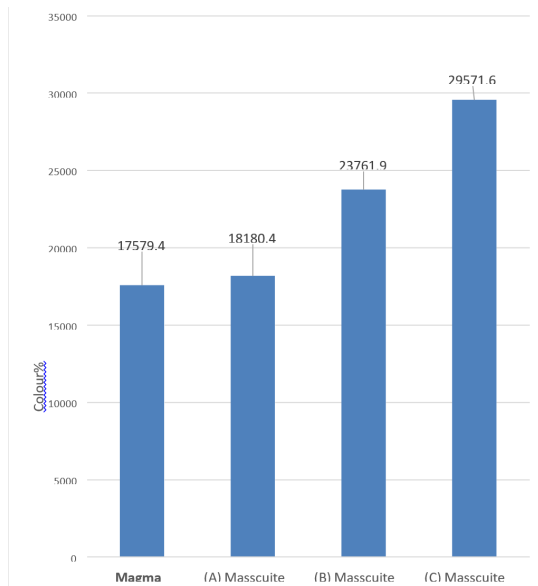


Figure 2: The color value in difference stages of boiling house was increased gradually.

compounds that accumulate in lower-grade masscuites and contribute to reduced raw sugar quality.

CONCLUSION

The study confirms that syrup concentration, crystallization, and impurity accumulation significantly influence the chemical characteristics of masscuites across the boiling house. Purity declines and color increases progressively from magma to C masscuite, reflecting the accumulation of non sucrose impurities and thermal reaction products. These findings highlight the need for improved pan control strategies and real time monitoring to enhance sugar quality and process efficiency.

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