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AI-Assisted Ethnographic Reconstruction of Granulated Palm Sugar Indigenous Food Chemistry as a Contextual Resource for Chemistry Learning

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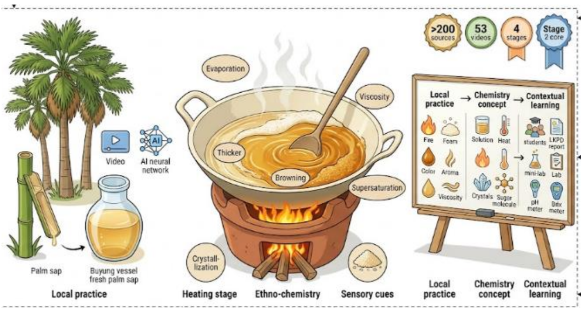
ABSTRACT



This study analyzes traditional granulated palm sugar (gula semut) production as an ethno-chemical system for contextual carbohydrate food chemistry learning through an AI-assisted applied ethnographic approach. Public YouTube videos and short online news features were treated as mediated field sites. From more than 200 sources, 53 eligible videos were selected and transcribed through a systematic data-processing workflow. Data analysis followed Miles and Huberman's interactive model and Strauss and Corbin's open–axial–selective coding, supported by a large language model to identify recurring practices and relate them to underlying chemical mechanisms. Four production stages were reconstructed, covering sap collection and initial processing, heating–concentration–early crystallization, crystallization and granulation, and drying–stabilization–packaging. The heating, concentration, and early crystallization stage emerged as the central physicochemical control window, where producers regulate fire intensity, foam behavior, evaporation, viscosity, color, and aroma to control concentration increase, boiling-point elevation, non-enzymatic browning, and the approach to supersaturation. Environmental conditions, fuel choice, cleanliness, and informal pH boundaries also function as additional control layers influencing product quality. The study generates practice-to-concept evidence maps and exemplar learning activities aligned with curriculum topics such as colligative properties, thermochemistry, reaction rates, and physical versus chemical change. These findings suggest that ethno-chemical reconstruction can support culturally grounded chemistry education by transforming local production practices into scientifically meaningful and pedagogically usable learning contexts.

Keywords: *Ethno-chemistry; Food Chemistry; Contextual Learning; Granulated Palm Sugar; AI-assisted qualitative analysis*

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INTRODUCTION

Indonesia has a rich cultural and agroecological landscape expressed through traditional practices such as food fermentation, herbal medicine, and local food production, including palm sugar processing. These practices embody empirically grounded knowledge of material properties and transformation processes and have clear nutritional, economic, and sociocultural significance [1]. However, research on indigenous products such as palm sugar has largely focused on physicochemical characteristics and market potential, with relatively little effort to translate process knowledge into frameworks that can be used directly in chemistry teaching. Classroom ready resources that convert indigenous practices into structured lesson plans, learning activities, and analytic rubrics remain limited in both the literature and school practice [2]. Without systematic documentation and educational translation, indigenous knowledge risks being treated merely as “tradition” rather than recognized as a scientific resource, even though integrating ethnoscience and ethno-chemistry into instructional design has been shown to enhance chemical literacy and student engagement [3].

Granulated palm sugar offers a particularly fertile ethno-chemical context. Its production involves a tightly ordered sequence of operations, including sap tapping, filtration, heating to evaporate water, control of foam and texture through fire regulation and stirring, and granulation, drying, and packaging. At each step, producers regulate variables such as color, aroma, viscosity, and grain size that align closely with core chemistry ideas including solution concentration, phase changes, crystallization, and heat transfer [4]. These empirically tuned operations support interdisciplinary discussion that connects organic chemistry, thermodynamics, and environmental aspects within a single context [5]. Nevertheless, the Indonesian chemistry curriculum, including *Kurikulum Merdeka*, still tends to emphasize abstract concepts with limited grounding in local food systems such as granulated palm sugar production, so opportunities to connect topics like solutions, thermochemistry, reaction rates, and chemical change to students’ everyday environments are often underused [6][7][8].

At the chemical level, granulated palm sugar production comprises transformations that map directly onto key topics in secondary chemistry. Fresh palm sap is essentially a dilute sucrose solution; progressive heating increases solute concentration and raises the boiling point, illustrating colligative properties and energy changes associated with phase transitions [9]. Continued heating drives reactions that deepen flavor and darken color, including caramelization and related browning pathways that can be linked to reaction mechanisms, thermochemistry, and structure function relationships [10]. Producers rely on experiential indicators such as viscosity, foam behavior, and color tone to judge endpoints, and these cues can be interpreted in terms of measurable properties such as concentration, temperature, and moisture content, making granulated palm sugar a concrete referent for otherwise abstract chemical concepts [11]. Yet existing studies rarely extend this potential into complete lesson designs, assessment strategies, and classroom artefacts that explicitly target common misconceptions in solution chemistry, thermochemistry, and chemical change [12][13].

Advances in artificial intelligence offer one promising methodological pathway to address this gap. AI-assisted qualitative analysis, through automatic transcription, data scribing from video records, and natural language processing-based coding, enables researchers to work with larger and more complex datasets than would be feasible with manual analysis alone [14]. When combined with systematic coding cycles, these tools can help identify recurring themes, process variables, and chemical ideas in producers' narratives and map them transparently onto formal curriculum constructs. The present study adopts an applied ethnographic orientation enhanced by AI-assisted qualitative analysis to document granulated palm sugar production, reconstruct the chemical mechanisms implicit in local practice, and identify points of alignment with secondary chemistry. The outputs include contextual narratives, candidate learning activities on concentration changes, phase transitions, and chemical reactions, and analytic rubrics for common student difficulties [15], with the broader aim of linking empirical ethno-chemical practice to pedagogical constructs for contextualized, culturally grounded chemistry education.

METHODS

1. Research Design

This study used a qualitative descriptive approach with an applied ethnographic design supported by AI-assisted analysis to examine the ethno-chemical structure of granulated palm sugar production and reconstruct chemistry concepts for secondary education. The ethnographic component documented production sequences, local terminology, and sensory judgements, while the applied component translated these insights into contextual learning resources. Publicly available YouTube videos and online news features were treated as mediated field sites capturing visual and verbal production practices.

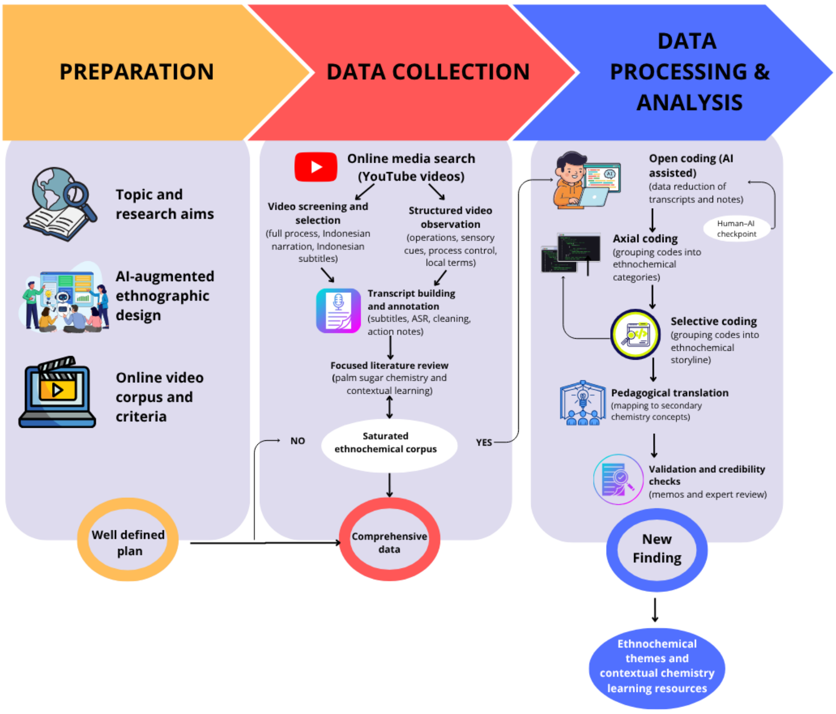

Figure 1. AI-Asisted ethnographic research design and analytic workflow for granulated palm sugar

AI tools supported transcription, segmentation, and preliminary coding through data scribing, subtitle extraction, and natural language processing, while researchers retained responsibility for data cleaning, refinement, and interpretation. Analysis followed Miles and Huberman's interactive cycle integrated with Strauss and Corbin's open–axial–selective coding, providing a transparent AI-assisted pathway from online media to ethno-chemical themes and learning materials. The overall design and analytic workflow are summarized in Figure 1.

2. Data Collection

Data were obtained exclusively from secondary sources in the form of publicly accessible online media. The dataset consisted mainly of YouTube videos on granulated palm sugar production in Indonesian contexts, complemented by short news reports and documentary clips. A structured keyword-based search (e.g., "granulated palm sugar", "making process granulated palm sugar", "granulated palm sugar traditional") initially yielded over 200 videos. Stepwise screening using predefined criteria resulted in 53 videos that constituted the empirical corpus. Analytic saturation was reached after 13 videos were fully coded, with the remaining data confirming the absence of additional process variants, local descriptors, or quality criteria. Included videos were required to document the complete production process, contain spoken narration in Bahasa Indonesia, provide Indonesian subtitles to support reliable text extraction and NLP-based analysis, and offer adequate audio-visual quality. Promotional videos, those lacking process detail, or those without subtitles were excluded. The identification and screening process is summarized in Figure 2 using a PRISMA-style flow diagram.

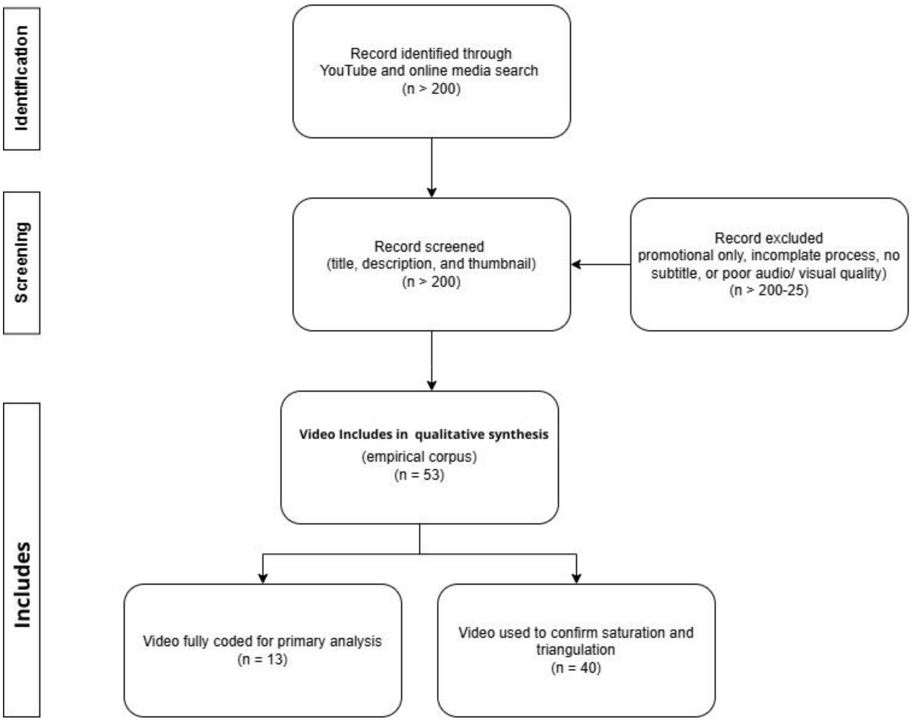

Figure 2. PRISMA flow diagram of video identification and selection

Only videos presenting the complete granulated palm sugar workflow from sap tapping to final packaging were included. Each video was analyzed through structured observation, generating time-stamped notes on process sequences, narrated sensory cues (aroma, color, viscosity, foam), process-control indicators (fire regulation, stirring, pan changes, end-point decisions), and local terminology. Screenshots were captured as needed to document equipment, fuel, and product characteristics, with each video treated as a mediated field site conveying tacit process knowledge. Spoken narration and subtitles were merged into a single transcript using a data-scribing pipeline, with subtitle files serving as the base layer and automatic speech recognition used for verification and gap filling. Transcripts were cleaned to correct errors, remove irrelevant content, standardise key terms, and annotate essential non-verbal actions, producing a linear corpus for qualitative coding. A focused review of palm sugar chemistry, non-enzymatic browning, colligative properties, and contextual chemistry learning provided theoretical support. Data saturation was reached when additional eligible videos yielded no new process variants or quality indicators.

3. Data Analysis Procedure

The analysis combined Miles and Huberman’s cycle of data reduction, data display, and conclusion drawing with Strauss and Corbin’s open–axial–selective coding to ensure a coherent analytic pathway [16]. Open coding segmented transcripts and observation notes into first-order codes on materials, operations, process conditions, and evaluative expressions. To handle the high volume of textual data, this initial segmentation was supported by a Large Language Model (specifically, OpenAI's GPT via a custom Python/Colab pipeline) acting as a qualitative data processing tool. The model was prompted strictly to extract and group verbatim observational descriptions (e.g., sensory cues, physical actions) without generating independent chemical interpretations. To mitigate hallucination risks and ensure trustworthiness, a strict human-in-the-loop verification protocol was enforced: the primary researcher manually reviewed 100% of the AI-generated tentative labels against the original video timestamps and cleaned transcripts. Any labels that lacked direct empirical backing from the videos were discarded or refined. This human-AI checkpoint established a stable and reliable code set before advancing to axial coding.

Axial coding used source × time × theme matrices and practice–to–concept maps to relate codes and consolidate them into categories such as boiling and concentration dynamics, heat management, granulation indicators, and local quality criteria. Selective coding integrated these categories into a narrative linking production practices with underlying chemical mechanisms. The analysis focused on three themes physicochemical transformations, sensory-based process indicators, and pedagogical translation to secondary chemistry concepts, including colligative properties, thermochemistry, reaction rate, and physical–chemical change. Memoing, diagramming, and a versioned codebook supported analytic transparency. From over 200 identified videos, 53 met inclusion criteria; saturation was reached after 13 were fully coded, with remaining videos confirming stability. Triangulation and expert debriefing strengthened analytic credibility and curricular relevance. Figure 3 summarizes the AI-assisted coding workflow.

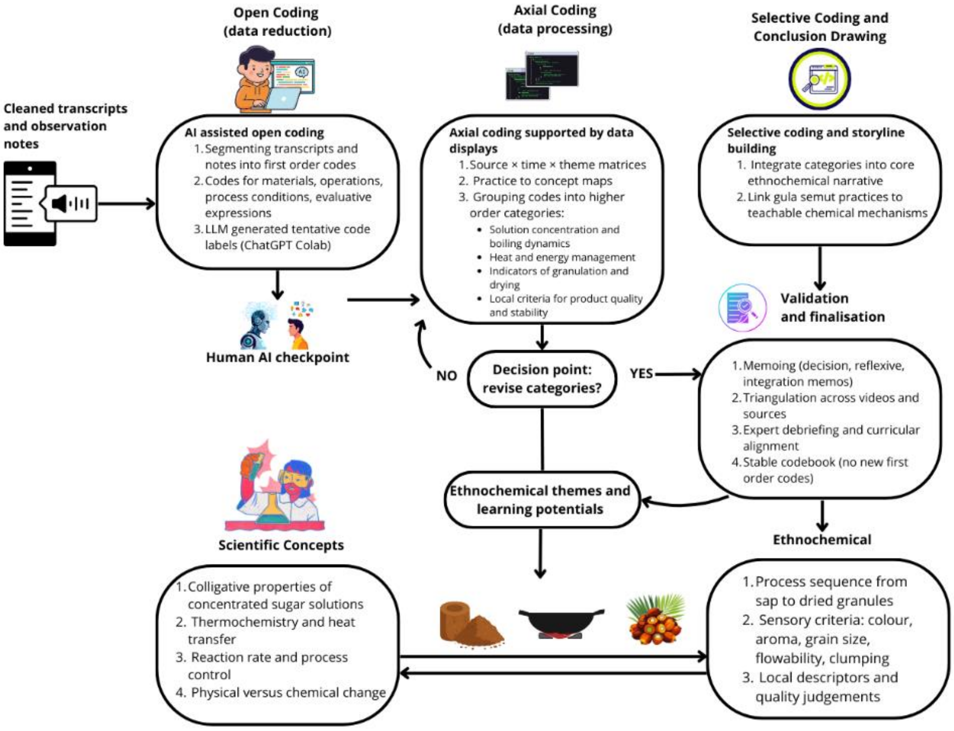

Figure 3. AI-assisted data analysis process for ethno-chemical reconstruction of granulated palm sugar

RESULT AND DISCUSSION

Integrated analysis of structured observations, linearized transcripts, and AI-assisted coding produced a coherent four-stage reconstruction of traditional granulated palm sugar production: (1) sap collection and initial processing, (2) heating, concentration, and early crystallization, (3) crystallization and granulation, and (4) drying, stabilization, and packaging. Video observations clarified action sequences and fire management, transcripts captured tacit descriptors of color, aroma, and texture, and AI-assisted coding consolidated recurring patterns into chemistry-relevant themes. While each stage is interconnected, the concentration and heating stage contained the richest cluster of chemical ideas especially fire adjustment, foam and evaporation control, color and viscosity cues, and end-point decisions. Accordingly, the next subsection elaborates Stage 2 as the main gateway for contextual chemistry learning.

1. Stages of Granulated Palm Sugar Production and Local Practices

Reanalysis of video data organized traditional granulated palm sugar production into four stages: (1) sap collection and initial processing, (2) heating, concentration, and early crystallization, (3) crystallization and granulation, and (4) drying, stabilization, and packaging. The first stage prepares fresh sap as the starting sugar solution, the third captures the shift from concentrated syrup to granules, and the fourth stabilizes the product through drying, sieving, and packaging. In this stage, filtered sap is boiled in wide pans over adjustable fires, with producers regulating flame intensity, shifting pans across heat zones, and varying stirring to manage boiling onset, foam behavior, and progressive thickening. This physical workflow demonstrates a transition from a simple dilute solution to a complex, high-viscosity system. The sequence of pan changes and fire adjustments serves as the primary mechanism for managing the mass transfer of water vapor, ensuring the syrup reaches the necessary threshold for subsequent granulation. Figure 4 illustrates the integrated operational and physicochemical dynamics of this phase.

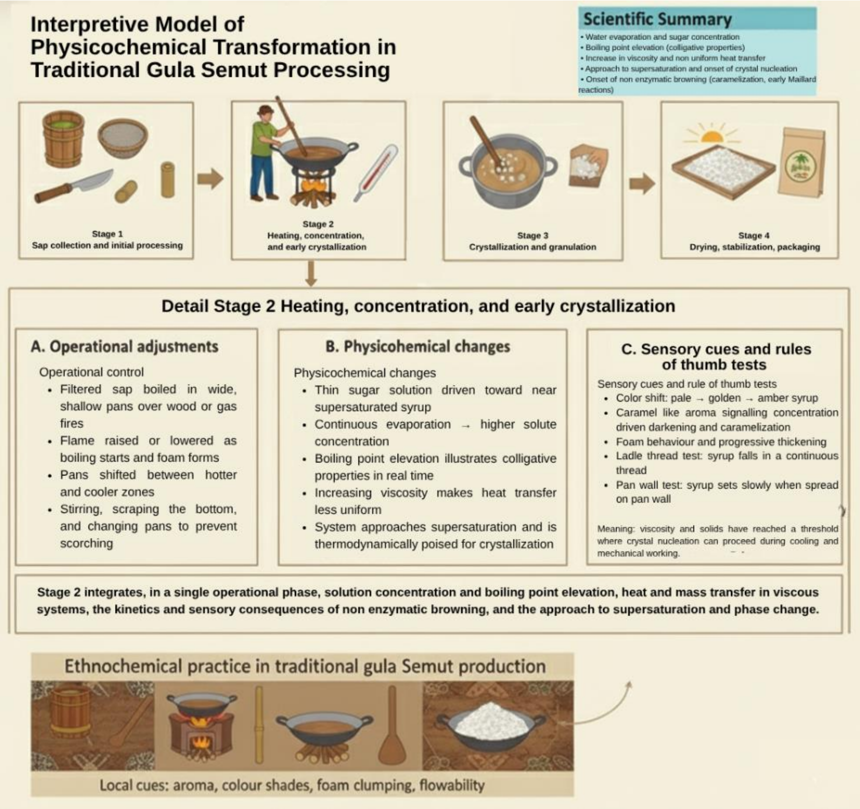

Figure 4. Detail of the heating, concentration, and early crystallization window (Stage 2) in traditional granulated palm sugar processing.

2. Sensory Characteristics and Local Preferences

Throughout production, producers assess granulated palm sugar quality largely through sensory cues, with the most decisive changes in flavor, color, and texture occurring during the heating and concentration of sap. Early checks of fresh sap focus on clarity, aroma, and sweetness as indicators of raw material suitability, while later stages emphasize granule size, flowability, and clumping as markers of stability. The sensory profile recognized as "good" granulated palm sugar is shaped mainly during boiling: deeper sweetness, slight bitterness, and a warm caramel-like aroma are attributed to the duration and intensity of heating. These sensory benchmarks-specifically the transition to amber tones and the development of a 'heavy' syrup feel-act as experiential proxies for measuring supersaturation. By relying on these indicators, producers execute precisely timed interventions, such as heat reduction, which are critical for achieving the desired sandy texture without the use of industrial thermometers. Final texture preferences also depend on this phase syrups left insufficiently thick often produce sticky, clumping granules, whereas syrups boiled to the right consistency yield free flowing, sandy sugar. In practice, color, aroma, viscosity, and simple thread tests guide decisions to stop boiling, making the heating concentration stage the central sensory and chemical control point of the entire process.

3. Coding-Derived Evidence Map for the Heating Concentration and Early Crystallization Phase

. Open–axial–selective coding of the heating, concentration, and early crystallization phase revealed four practice–to–concept links that show how local sugar-processing knowledge functions as an ethno-chemical control system. Heating control supports EC-P2, where careful regulation of fire intensity prevents excessive caramelization, scorching, and degradation of the sugar matrix. This practice indicates that local practitioners actively manage thermal input rather than merely applying heat. Foam and evaporation management supports EC-P3, showing that reducing the flame and stirring continuously during vigorous boiling help control heat input, surface boiling behavior, overflow risk, and uneven evaporation. These actions also help maintain product consistency by distributing heat more evenly, reducing localized overheating, and preventing material loss caused by excessive foaming.

Sensory and empirical indicators further guide the transition from concentration to crystallization. The thread test supports EC-P4, showing that continuous thread formation indicates increased solids content, higher viscosity, and near-supersaturation suitable for crystallization. Color and aroma changes support EC-P5, where a stable golden-brown color and caramel-like aroma indicate the desired endpoint of concentration and non-enzymatic browning. Together, the practices recorded in V11, V19, V27, and V31 demonstrate that fire regulation, foam control, thread testing, and sensory monitoring form an integrated local knowledge system for managing thermal conditions, evaporation, supersaturation, crystallization readiness, and flavor development in concentrated sugar solutions. These findings illustrate how everyday local practices can be translated into chemical concepts such as heat transfer, evaporation, caramelization, viscosity, supersaturation, and crystallization. Table 1 summarizes the exemplar quotations, coding structure, selective propositions, and ethno-chemical concepts underlying these practice–to–concept links.

Table 1. Mapping Heating Concentration and Early Crystallization Practices to Ethno-chemical Concepts in Granulated Palm Sugar Production

Quote (ID)	Open Code	Axial Theme (Cause, Context, Strategy, Consequence)	Selective Proposition (EC-Px; If/Then/Because)	Ethnochemical Concept	Local Practice (EN)	Factor Type
“*Pemanasan harus dilakukan dengan hati-hati agar tidak gosong*.” (V11)	Heating control	Cause: excessive heat causes scorching and over-caramelization; Context: Stage 2, mid-heating, Strategy: moderate and adjust fire intensity, Consequence: preserve desired flavor and texture	EC-P2: If heating is controlled carefully, then excessive caramelization and burning are avoided because the temperature stays within a suitable range for concentration without degradation.	Thermal control in concentrated sugar systems	Controlled heating to avoid burning	Process or Operational
“*Kalau busa sudah naik tinggi, api dikecilkan dan diaduk terus supaya tidak meluap*.” (V19)	Foam and evaporation management	Cause: vigorous boiling and foam formation increase overflow risk, Context: Stage 2, vigorous boiling, Strategy: reduce fire and increase stirring; Consequence: prevent loss of material and ensure even evaporation	EC-P3: If foam rise during vigorous boiling is managed by lowering the fire and stirring continuously, then overflow and uneven evaporation are reduced because heat input and surface behavior are kept under control.	Evaporation rate and surface boiling behavior	Lowering the fire and stirring when foam rises	Process or Operational
“Saat nira sudah berat dan bisa ditarik jadi benang, berarti sudah cukup kental.” (V27)	Thread test and viscosity	Cause: high solids content increases viscosity, Context: Stage 2, late concentration, Strategy: use thread formation as endpoint test, Consequence: syrup reaches supersaturated state ready for crystallisation	EC-P4: If the concentrated syrup can form a continuous thread when lifted, then the solids content is high enough for crystallizationbecause viscosity indicates a near-supersaturated sugar solution.	Supersaturation, viscosity, and crystallizationreadiness	Using thread formation of syrup as readiness indicator	Sensory or Empirical
“*Warna gula berubah jadi coklat keemasan dan aromanya seperti karamel, itu tandanya sudah pas.*” (V31)	Color and aroma change	Cause: progressive caramelization and concentration, Context: Stage 2, final heating, Strategy, monitor golden-brown color and caramel aroma, Consequence: optimal flavor and color before entering granulation	EC-P5: If the syrup reaches a stable golden-brown color with a distinct caramel aroma, then it is ready to leave the heating stage because browning and concentration have progressed to the desired level.	Non-enzymatic browning (caramelization) and flavor development	Using golden-brown color and caramel aroma as final heating cue	Sensory or Empirical

4. Environmental and Cultural Controls During Heating and Concentration

During the heating, concentration, and early crystallization phase, producers treat the environment as an active variable that must be managed. Boiling commonly occurs in semi-open kitchens or simple sheds that release steam while protecting the pans from wind, dust, and sudden rain. Humid or rainy conditions are believed to increase the risk of sticky, clumping sugar, prompting makers to lengthen heating time, stabilize the flame, or delay boiling. Firewood choice and stove positioning also serve as controls: evenly burning fuel and pan placement that prevents flames from climbing the sides help minimize scorching and uneven color. Simple social rules reinforce these physical adjustments keeping pans away from foot traffic, discouraging children from approaching the fire, and routinely wiping utensils to prevent contamination. The management of the microclimate around the cooking area, combined with cultural rules regarding kitchen traffic and utensil cleanliness, constitutes an informal quality-control system. These practices mitigate risks of acid-catalyzed sucrose inversion and contamination, which are vital for maintaining the chemical stability of the final granulated product.

5. Synthesis of findings

The scientific coherence of traditional granulated palm sugar processing can be understood through the molecular and physicochemical transformations occurring during the heating, concentration, and early crystallization stage. This phase represents the core transformation window in which dilute palm sap is gradually converted into a thick, near-supersaturated sucrose matrix. Continuous heating removes water, increases solute concentration, raises the boiling point, and promotes viscosity development, thereby illustrating colligative behavior and heat–mass transfer in a viscous sugar system [17]. Supported by established food chemistry models, it can be inferred that under these elevated temperatures and mildly acidic conditions, sucrose undergoes hydrolysis into glucose and fructose ($C_{12}H_{22}O_{11} \rightarrow C_6H_{12}O_6 + C_6H_{12}O_6$), enhancing sweetness and initiating non-enzymatic browning and crystallization pathways [18][19]. Although interpretive rather than instrument-based, this reconstruction is consistent with established models of traditional palm sugar processing, as summarized in Figure 5.

Within this phase, thermal control becomes the primary operational focus. Producers adjust fire intensity, pan position, and stirring to drive concentration while preventing excessive sucrose degradation. Literature indicates that temperatures around 115–120 °C are typically sufficient to achieve high solids content and controlled caramelization, creating favorable conditions for crystallization [20][21]. These targets are achieved through sensory heuristics rather than instruments: the syrup remains thick yet workable, foam is stabilized, and color settles at a golden amber tone before heat reduction, reflecting scientific requirements for limiting temperature gradients and local overheating in viscous sugar systems.

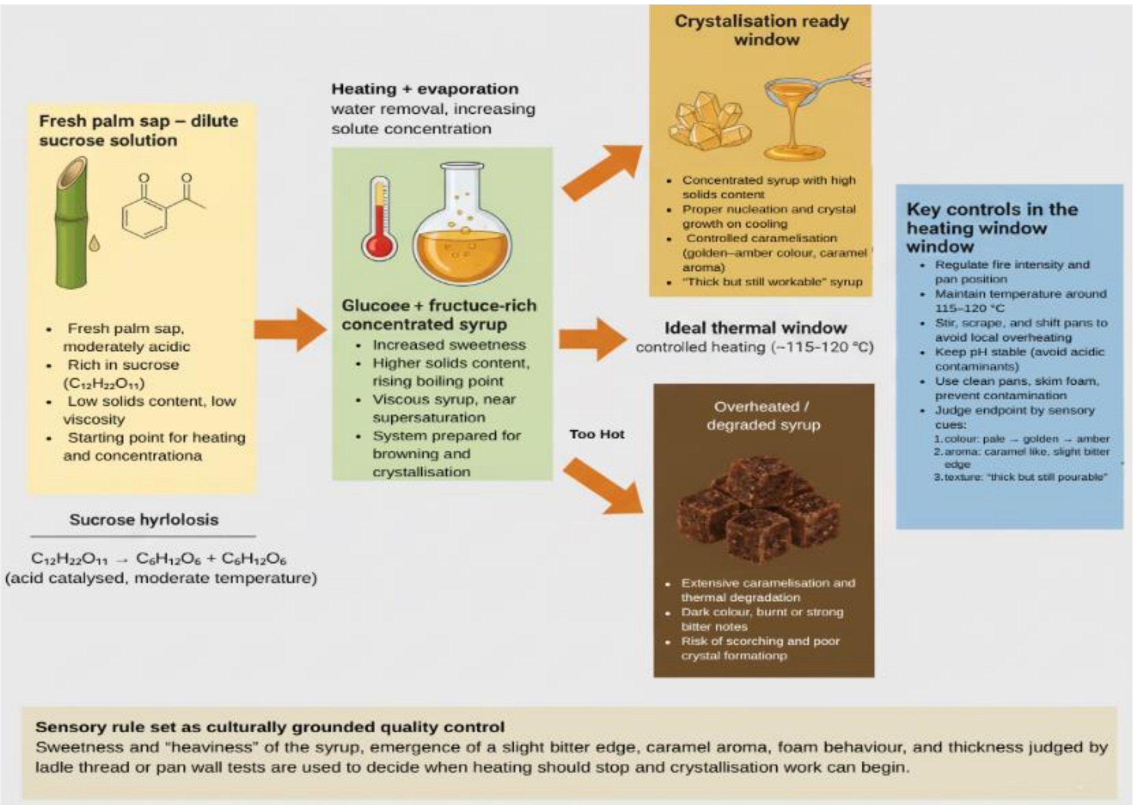

Figure 5. Heating, concentration, and early crystallization window in traditional granulated palm sugar processing

Sensory cues function as a culturally grounded quality-control system. Changes in sweetness and viscosity, the onset of slight bitterness, and the emergence of a caramel-like aroma indicate process progression and endpoint readiness [22], which literature suggests correspond to measurable variables such as °Brix and pH [23]. Supporting hygiene practices clean equipment, foam skimming, and avoidance of acidic utensils reinforce pH stability and contamination control [24][25]. Together, thermal regulation, sensory monitoring, and the inferred reaction pathway in Figure 5 integrate key food chemistry concepts, including solution behavior, thermochemistry, non-enzymatic browning, and crystallization, while demonstrating the scientific coherence of indigenous palm sugar production practices [26].

6. Environment and Culture as Controls in the Heating Concentration Phase

In traditional granulated palm sugar production, environmental and cultural controls converge most strongly during the heating and concentration phase, when filtered sap is boiled toward a supersaturated syrup. Rapid changes in water activity, viscosity, and supersaturation make humidity and weather critical; humid or rainy conditions are associated with slower drying and sticky, partially crystallized sugar, rendering this phase the most failure-sensitive [27]. To stabilize it, producers apply culturally embedded practices aligned with food chemistry principles, including cooling fresh sap to slow acid-catalyzed sucrose inversion [28], storing sap and partially heated syrup in sealed or semi-sealed containers to limit contamination and temperature humidity fluctuations [29], and avoiding acidic materials as an informal pH-control strategy that supports controlled browning [30]. Sensory cues-enhanced sweetness, emerging bitterness, increased viscosity, and caramel-like aroma-function as a culturally grounded quality-control system and correspond closely to measurable indicators such as °Brix and pH [31]. Together, environmental regulation, process rules, and sensory monitoring position the heating and concentration phase as a key context for learning about temperature control, water removal, sucrose inversion, non-enzymatic browning, and crystallization, as summarized in Figure 6.

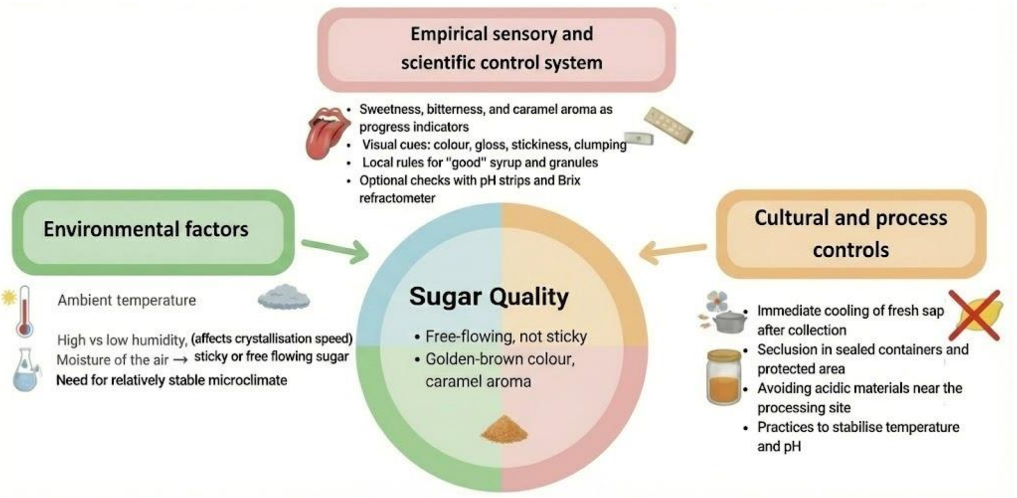

Figure 6. Convergence of environmental, cultural, and sensory controls on sugar quality during the intensive heating and concentration phase in traditional granulated palm sugar production

7. Educational Mapping and Safety

The heating, concentration, and early crystallization phase in granulated palm sugar production represents a high-yield entry point for contextual food chemistry education because it contains observable local practices that can be directly connected to core chemical principles. Producers regulate fire intensity, manage foam and evaporation, monitor color transition, and assess syrup thickness through thread tests and perceived "heaviness." These practices reflect embodied chemical reasoning related to heat transfer, evaporation, boiling-point elevation, viscosity change, supersaturation, caramelization, and controlled crystallization [32][33]. Fire regulation shows an effort to maintain a practical thermal window that supports water removal without excessive browning or burning, while foam control through lowering the flame and continuous stirring demonstrates practical understanding of surface boiling behavior, heat distribution, and material loss prevention. Thread formation, increasing syrup heaviness, golden-brown color, and caramel-like aroma further indicate that producers use sensory and empirical cues to judge concentration, flow behavior, browning development, and crystallization readiness.

Table 2. Mapping Heating Concentration Practices in Granulated Palm Sugar Production to Chemical Concepts and Learning Activities

Local Practice	Informant Quotation	Reconstructed Chemical Concept	Potential Contextual Learning Activity
Regulating fire to avoid burning	"Heating must be done carefully so that it does not burn." (V11)	Thermal control in concentrated sugar systems; balance between concentration and thermal degradation	Heat model sucrose solutions at different burner settings, record time to reach a target °Brix and the onset of scorching, and discuss heat transfer and practical temperature windows for safe concentration.
Managing foam during vigorous boiling	"When the foam rises high, the fire is reduced and the syrup is stirred continuously so it does not overflow." (V19)	Evaporation rate, surface boiling behavior, and mass transfer at the liquid–air interface	Boil sugar solutions while varying heat input and stirring frequency, measure mass loss from evaporation, document foam height, and relate observations to control of surface phenomena during concentration.
Using the thread test as an endpoint cue	"When the sap is already heavy and can be pulled into a thread, it means it is thick enough." (V27)	Supersaturation, viscosity, and crystallizationreadiness in concentrated sugar matrices	Prepare syrups at different °Brix values, perform the thread test, and correlate sensory thread formation with refractometer readings and cooling behavior as the system approaches crystallisation.
Reading color and aroma as final heating signals	"The color turns golden brown and the aroma is like caramel, that is the sign it is just right." (V31)	Non enzymatic browning (caramelization), flavor development, and thermal history	Heat sugar solutions stepwise to increasing temperatures, document color with a simple photo scale and record aroma descriptors, then link these changes to time–temperature profiles and basic browning chemistry.
Maintaining clean tools and avoiding acidic materials near the stove	"We keep the tools clean and do not bring acidic ingredients close so the sugar is not damaged." (V34)	pH stabilisation, reduction of contamination risk, and control of sucrose inversion during heating	Add small amounts of mild acids to sugar solutions during heating, track pH and observe browning or crystallizationoutcomes, then discuss why traditional rules about cleanliness and avoiding acids matter for final product quality.

This phase also supports a clear practice → concept → activity pathway for chemistry learning. Laboratory models using sucrose solutions can allow students to vary heating time, burner intensity, stirring frequency, and acidity while monitoring °Brix, pH, mass loss, color change, and cooling behavior [34][35]. Through these activities, students can investigate how evaporation increases solute concentration, how acidity may affect sucrose inversion and browning, and how supersaturation becomes necessary for crystal formation. Sensory indicators used by producers can be formalized into analytical tasks by linking thread formation, color transition, aroma development, and syrup viscosity to measurable parameters such as refractometer readings, pH values, temperature profiles, and visual color scales. Safety considerations in handling hot, viscous sugar solutions also reinforce good laboratory practice, while traditional rules about clean tools and avoiding acidic materials can be interpreted through pH stabilization, contamination control, and product-quality maintenance. Empirical evidence confirms that sugar concentration, moisture reduction, and processing conditions influence aroma, taste, texture, stability, and consumer acceptance of palm sugar [36]. Table 2 summarizes these heating-related evidence maps by showing how local practices, informant quotations, reconstructed chemical concepts, and potential contextual learning activities are systematically connected.

8. Educational Recommendations

The heating, concentration, and early crystallization phase of granulated palm sugar production offers a compact pedagogical context for connecting traditional practice with core food chemistry concepts. In school or undergraduate laboratories, this phase can be modelled using sucrose solutions by varying heating time and intensity while monitoring Brix and pH to observe water loss, increasing solute concentration, boiling-point elevation, and the onset of supersaturation and crystallization [37]. Caramelization and color development can also be explored through simple non-enzymatic browning experiments that involve time–temperature profiles, visual color records, and basic aroma descriptors [38][39]. Traditional indicators such as thread tests and perceived syrup “heaviness” can be formalized by relating flow behavior to °Brix values, while brief guided sensory evaluations, where ethically permitted, may help students connect flavor perception with reaction pathways in concentrated sugar systems [40]. Emphasis on safe handling of hot, viscous solutions and controlled heating further reinforces good laboratory practice while preserving the contextual and pedagogical value of this critical production phase.

CONCLUSION

This study shows that traditional granulated palm sugar production is not merely a cultural food-processing practice, but a systematically regulated ethno-chemical system grounded in empirical control of physicochemical change. Through an AI-assisted applied ethnographic approach using public YouTube video data, the production workflow was reconstructed into four interrelated stages: sap collection and initial processing, heating–concentration–early crystallization, crystallization and granulation, and drying–stabilization–packaging. Among these stages, heating and concentration emerged as the central control window because this phase governs water removal, boiling-point elevation, viscosity increase, non-enzymatic browning, sucrose transformation, supersaturation, and the transition toward crystallization. The findings reveal that local producers employ tacit but highly structured control strategies, including fire regulation, foam and evaporation management, thread testing, color and aroma monitoring, moisture control, tool cleanliness, and avoidance of acidic materials. These practices function as an integrated ethno-chemical control system that can be scientifically mapped onto solution chemistry, thermochemistry, reaction kinetics, colligative properties, phase transitions, caramelization, and crystallization. Such mapping demonstrates that traditional knowledge contains chemically meaningful reasoning, even when expressed through sensory, empirical, and practice-based language rather than formal scientific terminology.

The study contributes to chemistry education by generating practice-to-concept evidence maps and preliminary contextual learning activities that translate indigenous food-processing practices into curriculum-relevant chemistry instruction. Granulated palm sugar production offers a culturally familiar context for teaching abstract concepts such as concentration, pH, heat transfer, evaporation, supersaturation, browning reactions, and physical versus chemical change. Although the study is limited by its reliance on mediated online data and the absence of direct experimental measurements such as pH, temperature, moisture content, and °Brix, it provides a transferable methodological framework for reconstructing local practices as scientifically grounded learning resources. Future research should combine direct field observation, laboratory validation, and classroom implementation to test the pedagogical effectiveness of this ethno-chemical reconstruction in secondary and undergraduate chemistry education.

ETHICAL STATEMENT

This study utilized publicly available YouTube videos as secondary data therefore, human subject approval was not required. The research followed digital ethnography ethical guidelines by ensuring that no personally identifiable information was extracted and that the content was treated strictly as observational data.

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