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# Beyond Ultrasound Power: Acoustic Cavitation, Nucleation Kinetics and Polymorphic Control in Palm Oil Crystallization-A Critical Review

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**Abstract**

Ultrasound-assisted crystallization offers a route to manipulate the microstructure and functional properties of palm-based fats, yet acoustic, thermal, and hydrodynamic mechanisms are frequently conflated. This critical qualitative literature review synthesizes journal evidence published in 2020–2026 concerning acoustic cavitation, nucleation kinetics, polymorphic transitions, analytical characterization, and engineering translation. Direct palm-oil studies are differentiated from related work on cocoa butter, milk fat, coconut oil, and general sonocrystallization. The literature indicates that treatment position, subcooling, agitation, lipid composition, and emulsion architecture strongly moderate the observed response. Faster crystallization and smaller crystals do not necessarily predict higher hardness, greater solid fat content, or more stable emulsions. Nominal ultrasound power also provides an incomplete description of the actual acoustic field. A multiscale attribution framework is proposed that links acoustic forcing and energy dissipation to local temperature and flow, nucleation and growth, evolving polymorphs, crystal-network architecture, and application-specific performance. The review recommends thermal-history-matched controls, characterization of delivered acoustic energy, time-resolved scattering and NMR measurements, and transparent system-level energy balances. It concludes that ultrasound should be evaluated as a conditional, state-dependent processing tool rather than a universally beneficial crystallization intensifier.

**Keywords:** Palm Oil, Sonocrystallization, Acoustic Cavitation, Ultrasound, Nucleation Kinetics, Fat Polymorphism, Subcooling, Crystal Networks, Process Analytical Technology, Industrial Crystallization.

## Introduction

### Background and Industrial Context

Palm oil is not a single-component substance whose freezing temperature can be described by one equilibrium point. It is a chemically heterogeneous assembly of triacylglycerols (TAGs), minor constituents, and processing-dependent fractions that crystallize over temperature ranges and in competing structures. Dry fractionation converts these physical differences into commercially useful olein and stearin streams, while the texture and stability of shortenings, spreads, structured fats, and emulsions depend upon the solid network produced during cooling. A processing strategy that alters early nucleation can therefore change filtration, oil entrapment, and product functionality without meaningfully changing chemical composition. The consequences are not always monotonic: smaller crystals can increase connectivity, but may also influence slurry viscosity or separation differently according to composition and processing history. The industrial challenge is to obtain reproducible crystal populations, not merely to achieve the earliest possible solidification [1-4]. Palm oil crystallization often proceeds in equipment in which cooling, agitation, residence time, and feedstock composition are coupled. Operators can observe changes in solid fat content while remaining uncertain whether those changes reflect primary nucleation, growth of existing crystals, aggregation, or transformation between polymorphs. The literature on palm stearin and palm oil blends shows that even modest alterations in the TAG matrix can produce unexpected phase behavior, crystal-network characteristics, and apparent firmness. The practical implication is that a favorable operating setting for one batch should not be generalized to a different iodine value, palm fraction, or emulsified formulation. A genuinely physics-guided intervention must specify which structural stage it changes and how that change affects the intended outcome [5-8].

### Why Ultrasound Requires Critical Mechanistic Interpretation

High-intensity ultrasound introduces a disturbance that is qualitatively different from ordinary vessel agitation. Alternating pressure can cause pre-existing gas nuclei to oscillate, expand, collapse, or interact with neighboring bubbles, while acoustic streaming and localized flow redistribute thermal energy and suspended crystals. These processes may decrease an induction period, produce fragmentation or secondary nucleation, alter local temperature fields, and change the architecture of a crystal network. Yet a nominal generator power in watts is not

a measurement of the acoustic energy effectively deposited in the material. Vessel geometry, transducer immersion, amplitude, viscosity, gas content, temperature, and reflections determine the actual response. Studies of sono-processing repeatedly demonstrate that reporting electrical settings without field characterization creates serious barriers to comparison and scale-up [9-12].

Direct evidence specific to palm-based fats has become sufficiently substantial to support an interpretive review, but it does not support a universal ultrasound effect. Continuous palm-fat experiments demonstrated that treatment location and temperature interact with agitation; separate studies on palm-based emulsions showed that an intermediate treatment condition could enhance stability while stronger treatments favored different polymorphic organization. A more recent comparison with acoustic-wave-induced cavitation suggested that the way acoustic disturbances are generated matters for network development and sensory consequences, not simply the nominal power rating. These findings motivate a synthesis that distinguishes measured outcomes from inferred mechanisms and establishes the conditions needed to adjudicate alternative explanations [13-16].

Earlier controlled palm-specific experiments further demonstrate why acoustic settings cannot be considered independently of reactor configuration. Sonocrystallization in scraped-surface heat exchangers showed that the location of high-intensity ultrasound relative to subsequent agitation can change the resulting fat structure; a related low-saturation palm-based system linked treatment timing and position with oil-binding capacity and elastic response. The direct implication is that ultrasound may operate on different populations of nuclei and aggregates as the material travels through a continuous crystallizer, with post-treatment mixing potentially modifying the outcome [17,18].

**Urgency, Purpose and Contribution**

Interest in ultrasound-assisted crystallization has expanded in parallel with efforts to reduce process energy, control material structure, and develop continuous manufacture. However, a claim of improved sustainability requires a system boundary that accounts for electrical input, cooling duty, product quality, reject material, maintenance, and throughput. An apparent advantage calculated for a short sonication pulse cannot automatically be extended to an industrial production line. Reviews on sonocrystallization and industrial cavitation identify measurement, reproducibility, and reactor heterogeneity as persistent limitations. The purpose of this article is thus not to promote ultrasound as inherently superior, but to define a defensible physics-based framework for testing when it changes palm-fat crystallization beneficially [15,19-21].

This critical qualitative literature review asks four connected questions: which acoustic pathways plausibly influence nucleation; which thermal and hydrodynamic pathways could produce the same observations; how TAG composition and phase history govern the polymorphs and networks that emerge; and which analytical and engineering practices are sufficient for trustworthy process design. The novel contribution is an attribution framework rather than a new empirical coefficient or a pooled effect size. It separates direct palm-fat experiments from evidence transferred from cocoa butter, milk fat, coconut oil, and general sonocrystallization. It also identifies negative evidence, measurement ambiguity, and contradictory outcomes as productive constraints on mechanistic inference. The review is intended for readers in applied physics, food materials science, thermodynamics, and process engineering [4,21-23].

**Literature Review**

**Composition, Phase Behavior and Polymorphic States**

TAG diversity gives palm oil a structured but nonideal phase landscape. Saturation pattern, acyl-chain length, symmetry, and the presence of diacylglycerols or other minor components modify packing preferences and competition among crystal structures. Palm olein generally behaves differently from harder stearin fractions, while palm kernel-derived materials have a different distribution of shorter-chain fatty acids. Contemporary studies of chemically modified and blended palm-based systems show that changes in composition can shift crystallization temperature, apparent induction behavior, crystal thickness, and mechanical response. These variations should be treated as essential moderators rather than experimental noise. A model fitted to a single reference fat cannot legitimately be assumed to describe all palm-derived fractions, nor can the behavior of a palm stearin-based emulsion be mapped unchanged onto a bulk-oil crystallizer [6,7,24,25].

Crystalline fats are typically discussed in terms of alpha, beta-prime, and beta polymorph families, each associated with distinct packing characteristics and transformation pathways. These labels are useful but insufficient unless accompanied by crystallographic evidence: the same apparent melting profile may reflect mixed TAG populations, coexistence of phases, or transformations during measurement. Stable versus metastable also depends on the chemical system and the experimental time scale. For industrial applications, beta-prime-rich networks may be useful in some plastic fats whereas beta structures can be desirable in others. It is consequently misleading to declare one polymorph universally preferable. Reviews of TAG crystal structures and alternative confectionery fats make clear that molecular packing, short-spacing diffraction, lamellar architecture, and microstructural organization must be interpreted together [22,26-28].

Molecular composition can produce non-additive outcomes. In mixtures, one TAG species may promote nucleation of another, form compounds, create eutectic behavior, or interfere with growth. A palm stearin and milk-fat blend is therefore not merely an interpolation between its two pure components. Research on palm-based and milk-fat mixtures, palmitic versus stearic substitutions, and fatty acid chain-length effects suggests that compositional interactions alter the free-energy landscape available to nuclei. A physically grounded review must distinguish a kinetic ultrasound response from a matrix whose phase relationships already favor rapid crystallization. Otherwise, an ultrasound-induced improvement can be overestimated because the underlying mixture was predisposed to crystallize under the selected cooling schedule [5,7,29,30].

**Nucleation Thermodynamics and Kinetic Models**

A simplified classical nucleation description represents the reversible work of forming a spherical crystallite as a favorable volume contribution opposed by an unfavorable interfacial contribution. For an idealized spherical nucleus, the free-energy barrier is given by Equation (1), where $\gamma$ denotes solid–liquid interfacial energy and $|\Delta g_v|$ denotes the magnitude of the bulk

free-energy change per unit volume. This relation is a conceptual guide, not a calibrated equation for multicomponent palm oil. It assumes homogeneous nucleation, a specific nucleus geometry, and well-defined interfacial properties, while industrial fats undergo heterogeneous nucleation, incomplete mixing, and polymorphic competition. Accordingly, changes in induction time under ultrasound cannot by themselves demonstrate that interfacial energy has decreased. Nucleation may also be favored by locally altered supersaturation, added surfaces, generated fragments, or temporal changes in temperature [4,12,21].

$$\Delta G^* = \frac{16\pi\gamma^3}{3(\Delta g_v)^2} \quad (1)$$

The widely used Avrami representation in Equation (2) summarizes the temporal development of a crystalline fraction X(t) under specified thermal conditions. Its fitted rate constant k and exponent n, however, do not uniquely determine a microscopic mechanism in a heterogeneous lipid system. Continuous nucleation, instantaneous nucleation, impingement, and growth dimensionality may all change over a run; measurement artifacts and mixing can also affect the curve. Physical interpretation therefore requires independent microstructural and polymorphic evidence. In palm-based materials, thermal analysis, NMR, microscopy, and X-ray measurements often observe different aspects of the evolving state, so any kinetic description must be tied to the observable used. Ultrasound-induced deviations from an Avrami fit should be investigated rather than automatically translated into a specified nucleation mode [3,23,31,32].

$$X(t) = 1 - exp(-k\, t^n) \quad (2)$$

**Bubble Dynamics and Energy Dissipation**

Cavitation begins with an acoustic pressure field acting on microscopic gas nuclei. A conceptual Rayleigh-Plesset balance relates bubble radius, inertia, liquid pressure, viscosity, surface tension, and forcing; in concentrated or viscous fats, the assumptions underlying a single isolated spherical bubble may be poor approximations. Collapse events can be highly localized and transient, but temperature descriptions borrowed from aqueous sonochemistry should not be generalized as measured temperatures in palm oil. Energy may be deposited into viscous dissipation, streaming, bubble oscillation, and heat transfer to the surrounding matrix. The scientific task is to establish the distribution of these effects under process-relevant conditions and to evaluate whether crystals encounter them during their nucleation and growth histories [10,12,33,34].

Cavitation is not equivalent to sonochemistry, and the purpose of sonocrystallization is not necessarily to induce chemical reactions. Nevertheless, high acoustic intensity can introduce risks such as oxidation, off-odor formation, and localized degradation if process conditions are poorly controlled. A mechanistic review must distinguish physical pathways such as crystal fragmentation or local mixing from possible chemical changes. Studies using acoustic-wave-induced cavitation and high-intensity ultrasound on palm oil and anhydrous milk fat suggest that different forcing configurations can yield different structural or energy outcomes. These comparisons are intriguing, but generator power alone cannot establish equal acoustic dose or identical cavitation fields [9,15,35,36].

**Ultrasound, Thermal Forcing and Shear**

Temperature is not a nuisance variable in lipid crystallization; it is part of the thermodynamic driving force. Sonication may heat the sample, reduce bulk subcooling, create gradients near the probe, or alter cooling demand through increased mixing. Simultaneously, acoustic streaming may affect boundary-layer transport and move existing crystals into new regions of temperature and shear. These pathways can point in opposite directions: a local fluctuation may trigger nuclei, whereas cumulative heating may delay crystallization or favor a different polymorph. Studies of palm-based emulsions and continuously crystallized palm fat provide strong reasons to consider thermal and hydrodynamic confounding as central explanatory variables. A causal experiment needs thermal-history controls that reproduce the non-acoustic heating path as closely as possible [13,14,37,38].

Shear modifies crystallization both directly, through transport and possible breakup of aggregates, and indirectly, through differences in heat transfer and residence-time distributions. When ultrasound is introduced into a stirred vessel, a reduction in crystal size can arise from primary nucleation, mechanical breakup, secondary nucleation, changed aggregation, or combinations of these effects. A product can become harder because its network is better connected even while total solid fat content remains similar. Conversely, very fine crystals can form a weak network if aggregation and connectivity are unfavorable. Research on cocoa butter, oleogels, and palm-based mixtures illustrates that mechanical stiffness, crystal population, and solid fraction should be measured independently [39-42].

**Characterization as a Mechanistic Triangulation Problem**

Differential scanning calorimetry estimates thermal transitions and enthalpy but convolves multiple events when polymorphs overlap. Pulsed NMR provides operationally valuable solid fat content but does not identify every crystal habit. X-ray scattering supports assignment of lamellar and short-spacing structures, while optical microscopy visualizes larger networks and rheology probes their emergent mechanics. Raman spectroscopy can supply chemical and conformational information, including opportunities for in-line monitoring. No individual technique can securely attribute all changes to ultrasound. A coherent program therefore combines measurement scales and relates each method to its observable, spatial resolution, temporal resolution, and assumptions. Recent methodological studies make this multimodal strategy substantially more practical, but measurement synchrony and sample disturbance remain important concerns [22,26,32,43].

Ultrasonic measurement has two distinct roles that should not be conflated. High-power ultrasound can be an active intervention that changes crystallization, whereas low-power acoustic spectroscopy can be a diagnostic method used to monitor changing compressibility or phase behavior. Acoustic velocity, attenuation, and phase-sensitive signals may track the developing lipid structure, and statistical methods may help estimate solid fat content from these data. Their calibration, however, depends on composition and temperature, and apparent predictive success is not identical to a validated physical explanation. The strongest studies combine ultrasound monitoring with reference DSC, scattering, or NMR measurements, permitting separation of diagnostic correlations from the causal effects of intentional high-intensity insonation [32,43-45].

## Method

### Qualitative Literature Review Design

The present study adopts a critical qualitative literature review rather than a systematic literature review, bibliometric review, or meta-analysis. The analytical unit is a published mechanistic claim, together with the experimental context that supports or limits it. Recent peer-reviewed research from 2020 through October 2026 was prioritized to capture contemporary laboratory results, physical characterization methods, and scale-up perspectives. Seminal theoretical concepts are discussed as disciplinary knowledge, but the cited journal bibliography is restricted to publications within the specified period. Relevant evidence was identified through iterative topic-based searches linking palm oil, lipid crystallization, ultrasound, sonocrystallization, cavitation, polymorphism, acoustic diagnostics, phase behavior, reactor design, and thermal analysis. The search process was purposive and iterative, not a protocol-driven census of all eligible publications. Consequently, no PRISMA flow diagram, pooled effect size, completeness claim, or quantitative risk-of-bias score is appropriate.

### Interpretive Selection and Evidence Boundaries

Sources were selected for their ability to illuminate at least one element of the proposed causal sequence: physical properties of palm lipids, applied acoustic conditions, cavitation pathways, crystallization kinetics, polymorphic organization, functional outcomes, characterization, or scale-up. A three-level evidence hierarchy was used. Tier A comprises direct experiments on bulk palm oil, palm fractions, and palm-based emulsions exposed to acoustic processing. Tier B contains closely related studies on other edible fats and structured lipid systems, where mechanisms may transfer only under stated compositional and thermal conditions. Tier C covers general acoustics, cavitation instrumentation, crystallization theory, and ultrasonic reactor engineering. These tiers denote directness of relevance, not a numerical ranking of experimental quality. Their separation prevents generic studies of aqueous cavitation or other fats from being mislabeled as direct proof about palm oil.

### Thematic Coding and Critical Appraisal

Each article was interpreted through an evidence matrix documenting material composition, experimental geometry, acoustic frequency and power description, treatment location and timing, thermal history, mixing conditions, structural measurements, and the strength of its proposed mechanism. Interpretive codes included primary or secondary nucleation, cavitation-driven versus thermal effects, hydrodynamic influence, polymorphic transformation, microstructural network formation, analytical observability, and industrial transferability. Where a study reported a change in hardness but did not resolve nucleation and growth separately, the observation was retained without asserting a unique mechanism. Where a study showed a correlation between applied power and a structural outcome, it was treated as a conditional association unless thermal and acoustic dose were adequately characterized. Attention was explicitly paid to negative or nonmonotonic findings and to differences among bulk fats, emulsions, and oleogels.

### Synthesis Logic and Limitations

The synthesis proceeded by comparing convergent and conflicting observations across evidence tiers, identifying alternative physical explanations, and deriving experimental tests capable of discriminating among them. The review is intentionally analytical rather than exhaustive: it does not claim complete database coverage and does not produce pooled estimates of ultrasound efficacy. The principal limitations are uneven direct palm-specific evidence, inconsistent descriptions of acoustic energy, differing process temperatures, and variable use of polymorphic and rheological characterization. These limits are not concealed; they frame the interpretation and motivate the proposed research agenda. The results section presents thematic findings, whereas the discussion integrates the findings into a mechanistic framework and translates them into recommended measurements, controls, and engineering criteria.

## Results: Thematic Findings

### Direct Evidence from Bulk Palm Fats and Continuous Processing

One of the most consequential findings is that ultrasound response depends on when and where acoustic energy enters the crystallization process. In a continuous palm-based fat system, da Silva and colleagues found that treatment position, operating temperature, and agitation jointly affected physical performance. This observation undermines the idea that an optimal sonication condition can be expressed through amplitude or applied power alone. A pulse delivered before substantial nuclei form can interact with a different material state from a pulse delivered after aggregation begins. At the process scale, thermal history, residence time, and local crystal concentration determine which pathway is plausible. The evidence therefore favors a state-dependent treatment strategy in which ultrasound is synchronized to the actual progression of crystallization rather than applied as a detached preprocessing step [1,3,13].

A 2025 study compared acoustic-wave-induced cavitation generation and high-intensity ultrasound in palm oil. It reported acceleration of early crystallization under both treatments, but found differences in the organization of final crystal networks and in off-odor observations. Importantly, neither treatment yielded a universal increase in hardness. This makes the study valuable as a counterexample to simplistic claims that accelerated nucleation necessarily produces a stronger material. The experiments also illustrate that different forcing configurations may produce different bubble fields, fluid motion, and thermal loads. Cross-comparison remains conditional because power ratings, vibration geometry, acoustic frequencies, and local energy distribution differ. The appropriate conclusion is that acoustic processing mode deserves independent study, not that a low-frequency configuration is always superior [15,21,35].

### Emulsions and the Problem of Interfacial Crystallization

Palm-based emulsions introduce a second mechanism: droplets and their interfaces constrain where crystals form and how they influence material stability. A 2024 oil-in-water study using a palm olein-stearin lipid phase found that greater applied ultrasound power promoted beta-type crystalline organization, while an intermediate condition improved storage stability and reduced partial-coalescence kinetics. The investigators emphasized changes in subcooling associated with ultrasound treatment. This indicates that a favorable emulsion result cannot be attributed solely to stronger nucleation. The interfaces, emulsifier layers, droplet populations, and evolving fat crystal morphology jointly determine whether crystals stabilize the dispersion or promote partial coalescence. Transfer of this result to bulk palm oil is therefore limited because the emulsion boundary conditions and failure mechanisms differ [14,28,46].

A separate study of water-in-oil emulsions based on palm oil, palm stearin, and soybean oil observed changes in crystal distribution and texture after high-intensity ultrasound treatment. In some conditions, the resulting emulsions exhibited finer structures while hardness and elastic modulus decreased. This finding is particularly important because it makes clear that the direction of a desirable effect depends on the intended product: lower stiffness may be beneficial for spreadability even if it would be undesirable in a firm shortening. Network organization, droplet structure, solid fat fraction, and phase compatibility should be interpreted as separate outcomes. Measurements of microstructure need to be linked to an explicitly defined application metric rather than used as proxies for generic product improvement [14,16,28].

**Transferable Results from Other Fat Systems**

Cocoa butter experiments provide informative, but nonidentical, evidence concerning secondary nucleation and crystal-network development. A 2026 study varying ultrasound probe diameter, amplitude, and treatment time reported a dense elastic network under a particular combination of conditions and found that greater mechanical strength was not a straightforward function of applied power. The result supports a plausible mechanism in which ultrasound alters the number and organization of growing crystallites while leaving overall solid fat content comparatively unchanged. Yet cocoa butter differs from palm oil in its dominant TAG distribution and polymorphic behavior. The relevant transferable insight is the potential decoupling between solid fraction and network mechanics, not a prediction that a specific cocoa-butter amplitude should be used for palm oil [27,39,42].

Recent work on coconut oil and monoglyceride-containing oleogels adds evidence that simultaneous shear, ultrasound, and formulation chemistry influence crystal organization. Ultrasound combined with stirring in coconut oil accelerated crystallization and modified beta-prime structure, while sonicated monoglyceride systems showed altered network order and rheological response. In vegetable wax oleogels, high-intensity ultrasound improved structuring for some waxes but worsened it for others. The collective result is a picture of strongly formulation-dependent behavior, including sign reversals in a material property. These comparative studies help explain why a review should resist treating ultrasound as a single independent treatment with a universal mechanistic result [37,38,40,47].

**Compositional Moderators of Reported Ultrasound Effects**

Independent palm crystallization studies consistently show that composition can alter the baseline against which ultrasound is assessed. Modifying diacylglycerol and polyunsaturated fatty acid content changes crystal ordering and domains; blending palm olein with other oils changes melting and rheology; and designed combinations involving palm stearin can create unusual eutectic or compound-forming behaviors. These observations imply that any reported ultrasound enhancement may be amplified, diminished, or redirected by the initial TAG distribution. A mechanistic interpretation must therefore report relevant compositional descriptors rather than relying on a generic category such as palm fat. Even a nominally identical commodity oil can vary with fractionation conditions, feedstock origin, and refining history [5,6,7,25].

Additional evidence from enzymatically modified palm stearin blends, palm kernel stearin mixtures exposed to pressure, and particle-containing palm oil suspensions confirms that physical context is decisive. Chemical interesterification alters the distribution of TAG molecular species and therefore crystal architecture; pressure changes nucleation and structural features without necessarily changing all polymorphic assignments; and suspended carbohydrate particles affect crystallization and crystal-network geometry. These interventions are not ultrasound experiments, but they serve as valuable controls on overinterpretation. If relatively modest changes in composition, pressure, or suspended solids can reproduce an observed reduction in crystal size, that observation alone is not diagnostic of cavitation. A convincing cavitation claim requires measurements that identify the acoustic pathway or experiments that exclude alternative explanations [24,29,48,49].

**Polymorphic Evolution is not a Single Endpoint**

A recurring weakness in the evidence is the presentation of a final alpha, beta-prime, or beta assignment as if it described the entire crystallization pathway. Lipid transformations occur over time and may coexist with nucleation, melting, recrystallization, and changes in molecular packing. Recent work on palm-rich blends demonstrates beta-prime to beta transitions associated with molecular compound formation, while studies of palm kernel stearin show that cooling rate can influence less stable forms. The available evidence therefore supports a path-dependent view: ultrasound may influence which nuclei emerge, how rapidly they grow, and whether subsequent thermal exposure enables polymorphic conversion. Final diffraction alone cannot identify which step was affected by the acoustic pulse [7,22,28,31].

X-ray scattering studies emphasize that polymorphic order and microstructural geometry must be examined at different length scales. Synchrotron measurements can help distinguish changes in crystalline fraction from changes in specific surface area and structural arrangement, while smaller-scale scattering informs lamellar stacking and crystal nanoplatelet geometry. A single peak shift is insufficient to infer a complete network mechanism. Moreover, crystals may reorganize after ultrasound ends, especially during storage or repeated cooling cycles. Future studies should report when each measurement was made relative to the pulse, cooling schedule, tempering period, and storage interval. Without that temporal context, apparent disagreement between studies may arise from comparing different stages rather than contradictory physical laws [22,26,32,49].

**Network Mechanics and Product Functionality**

Solid fat content is a vital process variable, but not a mechanical constitutive law. Two fats with similar crystalline fraction may differ in elastic modulus, hardness, oil-binding capacity, yield stress, or microstructural anisotropy. Factors include the number and size of crystal aggregates, interparticle junctions, connectivity, and spatial arrangement. Rheological methods have therefore been used to monitor palm fraction crystallization, while nonlinear viscoelastic measurements can reveal behavior not visible in small-amplitude modulus alone. Acoustic treatment may increase stiffness when it creates load-bearing connections, or decrease stiffness when it disrupts fragile aggregates. Explaining the result requires a structural description of the network, not only a final NMR solid-fat reading [3,39,41,42].

The same network can also affect oil retention, separation

yield, and emulsion performance in different ways. Smaller crystals may lower entrainment during fractionation if the size distribution and filtration conditions are favorable, but dense crystal suspensions can complicate flow and separation. Emulsion stability additionally depends on whether the crystals reside inside droplets, near interfaces, or in a continuous phase where they promote droplet bridges. Reviews of crystallized food lipids and experimental studies of emulsions caution that product performance must be treated as application-specific. A physics-guided processing objective might seek an optimal network for oil release in one process and an optimal network for retention in another. Their preferred acoustically induced structures need not coincide [2,14,28,46].

Direct oil-retention experiments reinforce the distinction between crystalline fraction and mechanical functionality. In a palm-kernel fat, high-intensity ultrasound reduced oil migration and crystal size without significantly changing measured solid fat content; subsequent work on interesterified palm-based fats also linked oil-binding capacity to hardness, enthalpy, and crystal characteristics under differing cooling and ultrasound histories. These findings support the interpretation of ultrasound as a network-structuring intervention rather than simply an instrument for increasing the quantity of solid lipid [50,51].

**Observability and Acoustic Measurement Gaps**

The intervention itself is often incompletely characterized. Generator-rated power does not specify transmitted acoustic power; the latter is not necessarily the same as calorimetric dissipation, and neither fully describes spatial cavitation activity. Cavitation noise, hydrophone measurements, temperature evolution, and other diagnostic approaches each capture different parts of the acoustic field. At higher viscosity, bubble motion may differ strongly from familiar low-viscosity aqueous cases. Techniques suitable for one reactor may be unsuitable for another because of probe geometry, attenuation, scattering, or measurement interference. This uncertainty is not a peripheral reporting issue: it directly limits claims about the causal mechanism responsible for crystallization acceleration [10,11,34,52].

Process analytical technology provides a complementary opportunity. Acoustic phase-velocity measurements, supervised learning combined with ultrasound sensing, and in-line Raman methods can report the changing state of a crystallizing fat. Their strongest role may be to locate the process stage at which an active high-intensity pulse would have the desired effect. Nevertheless, a sensor model calibrated in one composition or temperature range may fail when shifted to another palm fraction, and a good prediction of solid fat content does not prove knowledge of polymorphism. Sensor development should therefore combine physics-based calibration with independent thermal and scattering methods, and should express uncertainty rather than presenting one deterministic estimate as a universal property [22,43-45].

**Energy Consumption and Scale-Up Findings**

The energy argument for ultrasound is plausible but not settled. A comparison of cavitation-generation modes in milk fat reported lower energy consumption under one experimental configuration, yet system-level energy efficiency requires more than dividing nominal electric power by sonication time. Cooling loads, heat extraction, acoustic transmission, throughput, off-specification yield, and maintenance must all be included. Industrial sonocrystallization reviews show that cavitation intensity can be uneven and the active volume may occupy only part of a reactor. Reproducing a laboratory field at greater scale can demand multiple transducers or alternative geometries, with consequences for capital cost and power consumption. The current evidence supports targeted development and verified pilot tests rather than claims of general industrial superiority [9,15,20,21].

## Discussion and Analysis

### A Multi-Pathway Interpretation of Ultrasound Response

The central synthesis is that ultrasound affects palm fat crystallization through several pathways that may operate concurrently. First, oscillating and collapsing bubbles can generate local disturbances capable of interacting with incipient crystals or pre-existing solid fragments. Second, acoustic streaming and induced flow alter the transport of heat, solutes, and dispersed material. Third, dissipated energy modifies temperature and therefore the driving force for nucleation and subsequent growth. Fourth, applied mechanical stresses may reorganize or fragment crystal aggregates after the initial solid phase has formed. The observable result is the combined outcome of these pathways acting on a composition-dependent phase landscape. None can be isolated from an ordinary comparison between a sonicated and an untreated sample unless controls or diagnostics constrain the others [12-14,33].

The potential sequence from acoustic forcing to crystalline outcome can therefore be viewed as a mediated causal network, not a direct line from power to hardness. Electrical power and waveform influence acoustic pressure and bubble dynamics; those variables influence dissipation, temperature gradients, and flow; and these fields interact with current lipid state to determine nucleation, growth, and transformation. Network structure subsequently influences mechanics, filtration, and storage stability. In practice, feedbacks make the sequence even more complex: crystallization changes viscosity and acoustic attenuation, which in turn can change local energy delivery. Figure 1 presents this deliberately testable framework. It should not be mistaken for an experimentally estimated path model; rather, it makes explicit the competing causal mechanisms that future studies must separate [9,12,34,44].

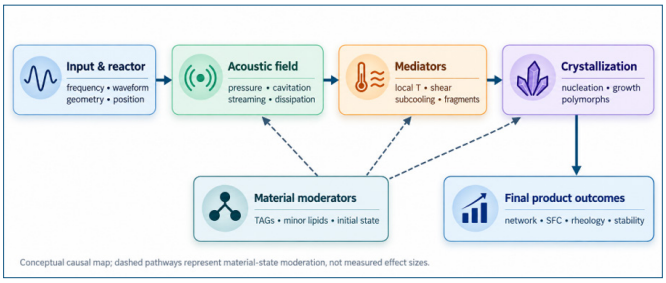



**Figure 1:** Proposed Multiscale Causal-Attribution Framework for Palm Oil Sonocrystallization (Original Conceptual Synthesis).

Figure 1 maps measurable inputs and intervening mechanisms that a rigorous experiment should distinguish. An observed change in crystal size cannot be assigned to cavitation merely because it follows sonication; thermal, hydrodynamic, and compositional variables must also be observed. In this conceptual map, dashed arrows indicate how initial TAG composition

and material state may moderate the acoustic field, mediating conditions, and crystallization response; they are not estimated effects or measured feedback coefficients [10,21,44].

**Alternative Explanations for Accelerated Nucleation**

A shorter measured induction period admits several explanations. Acoustic events may increase the number of active nucleation sites, create fragments that function as secondary nuclei, or enhance transport near existing crystalline surfaces. Equally, measured induction time can shift because sonication changes the spatial temperature distribution, the detection threshold of an analytical instrument, or the availability of pre-existing seeds. The appropriate test is not simply whether the ultrasound-treated curve rises sooner. It is whether the experiment measures local temperature, acoustic activity, crystal number or size distribution, and polymorphic identity with adequate temporal resolution. Isothermal controls, intentionally seeded and unseeded trials, and an independently reproduced thermal history can help separate competing explanations [19-21,39].

One particularly informative comparison is between conditions producing similar bulk temperature profiles with and without high-intensity ultrasound. If crystallization still differs, an acoustic or hydrodynamic mechanism becomes more plausible, although local gradients may remain unresolved. A second comparison uses a mechanically stirred condition matched as closely as possible for average mixing and cooling, recognizing that microstreaming cannot be perfectly replicated by bulk agitation. A third comparison delivers sonication before and after the onset of visible crystals. Stronger effects after solids appear would support a role for secondary nucleation or aggregate breakup, while changes before solids appear could arise through primary nucleation and early thermal pathways. These controls are scientifically more discriminating than an extensive sweep of nominal generator percentages alone [9,13,37,38].

**Polymorph Selection as a Time-Dependent Competition**

Polymorphism should be modeled as a competition between nucleation and transformation pathways under nonstationary conditions. A metastable form may appear rapidly and later transform as cooling, warming, shear, or storage proceeds. Ultrasound might alter the number of early nuclei without determining the final stable structure; alternatively, localized thermal excursions may accelerate an existing transformation. Therefore, the statement that ultrasound 'produced beta crystals' is mechanistically incomplete unless the investigators establish the initial state, the time of the pulse, the post-treatment thermal path, and the evolution of diffraction evidence. The palm emulsion literature is particularly useful here because it explicitly links power-related changes in polymorphic structure with subcooling and stability [7,14,22,31].

To operationalize this reasoning, Figure 2 distinguishes nucleation and subsequent polymorphic development from the macroscopic mechanics of the final network. It includes no fabricated numerical energy barriers or phase-transition rates. Instead, it illustrates that a population of smaller crystals with higher connectivity can sometimes carry more load than a more crystalline but poorly connected material. Experimental support for any specific arrow would require a controlled time sequence using scattering, microscopy, NMR, and rheology. The main scientific advantage of the diagram is to prevent a common interpretive shortcut: treating one final hardness or DSC peak as proof that ultrasound directly selected a thermodynamically preferred crystal form [5,26,32,39].

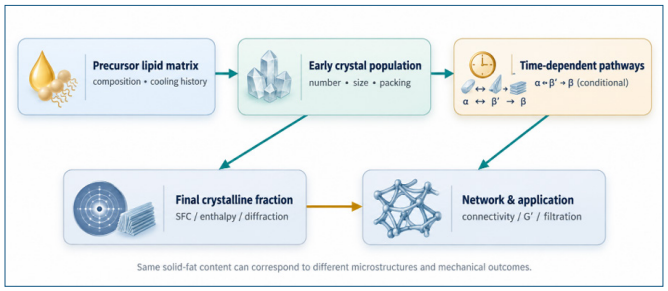



**Figure 2:** Time-Dependent Polymorphic and Crystal-Network Pathways; Relationships are Conceptual and not Quantitative (Original Diagram).

When interpreted together, palm stearin blends, palm olein fractions, emulsions, and other edible fats reveal that composition sets the possible polymorphic pathways while processing changes their rates and relative populations. The impact of a sonication pulse can thus be expected to differ according to the proportions of high-melting TAGs, unsaturation, emulsifier identity, and the presence of foreign surfaces. Such moderators can make two well-conducted experiments report contrasting effects without either being incorrect. A useful future review tradition would report experimental conditions in sufficient detail to distinguish actual contradiction from different material states [6,23,29,49].

**What Can Legitimately be Transferred Between Fat Systems?**

Studies on cocoa butter, coconut oil, and anhydrous milk fat are mechanistically informative because they share broad physical processes such as supercooling, nucleation, growth, and network formation. However, their TAG distributions and polymorphic preferences differ, as do melting intervals and storage behavior. A principle such as the need to control temperature during sonication transfers well; a claim that a particular amplitude yields a beta-prime-rich palm network does not. Similar caution applies to studies of crystallization in aqueous solutions or metallic melts, where density, surface tension, acoustic impedance, and interfacial chemistry may differ sharply from edible fats. Physical analogy should be explicit about what transfers and what requires new experiments [27,37,39,52].

A further limitation is that bulk oils, oil-in-water emulsions, water-in-oil emulsions, and wax-based oleogels are not interchangeable mechanical systems. Droplet interfaces constrain crystal location, partial coalescence introduces failure pathways not present in bulk oil, and the architecture of oleogelators can dominate network properties. This helps explain why some ultrasound treatments increase stiffness while others decrease it. The reasonable synthesis is therefore conditional: acoustic processing is a route for modifying crystallization pathways, but the direction of a functional benefit depends on phase geometry, composition, and the chosen product target. General claims about improved texture or stability without specifying these conditions are too broad [14,16,38,47].

**A Physics-Informed Reporting and Experimental Standard**

A minimum reporting standard for new research should specify the oil or fat fraction, TAG composition or appropriate proxies, initial crystal state, thermal pretreatment, cooling and agitation

profiles, total residence time, ultrasound waveform and frequency, device geometry, generator settings, directly estimated delivered power, and temperature history. Where feasible, acoustic field characterization and cavitation diagnostics should complement calorimetry. At the outcome level, investigators should report at least one measure of crystalline fraction, one polymorphic descriptor, one microstructural descriptor, and a product-relevant functional variable. These multiple observables need not be acquired on every sample, but their logic should be represented in the design. Such reporting would make mechanistic reanalysis and replication more realistic [10-12,22].

Figure 3 translates this recommendation into a staged experimental sequence. It begins with composition and thermal-history control, compares nonsonicated and thermal-mimic conditions, then adds acoustic diagnostics and time-resolved structural measurements. The final stage links structure to functional performance and whole-process energy use. This order matters: without validated baselines, multivariate optimization could identify a profitable operating recipe while leaving researchers unable to explain why it works or when it will fail [8,13,20,44].

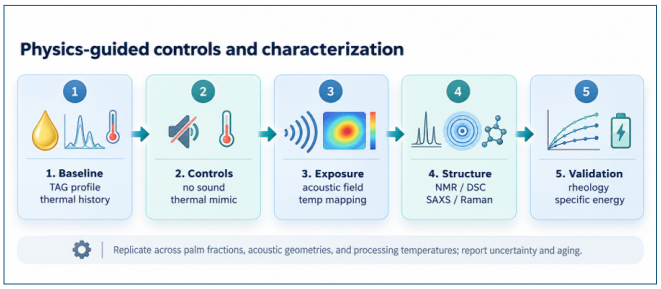



**Figure 3:** Physics-Guided Experimental and Pilot-Validation Sequence for Ultrasonic Fat Crystallization (Original Diagram).

Within this sequence, statistical design and mechanistic modeling can complement rather than compete with one another. Data-driven models of palm fractionation show that feedstock differences alter optimal conditions, but optimization should respect mass and energy balances and acknowledge changes in material state. A physics-informed surrogate need not solve a complete multiphase cavitation problem; it may combine a reduced thermal model, a crystallization-state estimator, and experimentally measured acoustic activity. Such a system would be more auditable than a black-box predictor of final hardness from electrical power and exposure duration alone. The recommended use of artificial intelligence is therefore bounded by physical interpretability and external validation [8,12,21,44].

**Reactor Design and Energy Tradeoffs**

Scale-up is a field-distribution problem before it is a power problem. Large vessels can develop regions of intense and weak acoustic activity because of attenuation, standing waves, reflection, and evolving viscosity. Probe placement that works in a bench reactor may become ineffective when fluid depth, flow pattern, or transducer array changes. Flow-through and continuous designs create additional opportunities to locate the treatment pulse near a targeted crystallization state, but also generate residence-time distributions and fouling risks. Industrial ultrasound reviews stress that successful scale-up requires simultaneous engineering of reactor geometry, energy delivery, process control, and product consistency. A nominally larger transducer is not a scale-up strategy by itself [9,11,20,21].

Energy accounting must include both ultrasound and the cooling system. Since acoustic energy dissipates into heat, it may increase the cooling duty even while accelerating early crystal formation. Moreover, an increase in nucleation rate may not improve economics if the resulting slurry is difficult to filter or produces a less suitable final network. A rigorous comparison should specify energy per unit acceptable product at equivalent product specifications and comparable throughput. Sensitivity analyses should test variations in feedstock, temperature, and equipment efficiency. Claims about low-carbon, sustainable, or cost-efficient ultrasonic processing should remain provisional until a defensible energy and material balance is available at a relevant operating scale [1,15,35,53].

**Safety, Chemical Integrity and Unintended Consequences**

Physical intensification can introduce chemical or sensory side effects, especially when lipid matrices are exposed to localized reactive environments and heat. Evidence of off-odor differences between cavitation modes in palm-related experiments indicates that product integrity must be monitored alongside crystallization rate. The underlying chemistry requires direct analytical testing: a sensory difference alone does not identify a radical mechanism or prove oxidation. Assessments can include peroxide value, secondary oxidation products, volatile profiles, and relevant sensory testing, with proper controls for storage and oxygen exposure. Processing claims should distinguish documented product quality from hypothetical molecular mechanisms [15,33,36].

Oil quality is also dynamic during post-processing. A network that appears favorable immediately after ultrasound may coarsen, transform, or redistribute during refrigerated storage or transportation. Formulation studies in structured lipids and emulsions show that storage-related crystal evolution can change stability and functionality. Consequently, industrial qualification should measure the time-dependent trajectory of texture, melting behavior, and polymorphism rather than only the initial response. An operational optimum that creates a desirable structure for several minutes but accelerates undesirable transitions over days is not necessarily a successful processing condition [25,28,40,54].

Storage and formulation must also be included when comparing treatment performance. A 2025 investigation of fully hydrogenated palm-kernel lipid matrices varied ultrasound, cooling rate, concentration, and storage temperature, finding that oil-binding capacity depended on multiple correlated physical variables and that fast cooling coupled with ultrasound was particularly effective under the tested conditions. This evidence supports a processing-window perspective, while its specific performance relationships should not be generalized unchanged to nonhydrogenated palm oil or every palm fraction [55].

**A prioritized Interdisciplinary Research Agenda**

The highest priority is a controlled experiment in a well-characterized palm oil fraction comparing high-intensity ultrasound, thermal-history-matched controls, stirring-only controls, and combined treatments. Actual acoustic power should be estimated and temperature recorded at several positions, while initial crystal state and TAG composition should be documented. Time-resolved pulsed NMR, DSC, scattering,

and imaging should separate crystalline fraction from network geometry. The design should predefine mechanistic predictions: for example, if increased early crystal number is the favored explanation, microscopy or scattering should demonstrate it independently of changes in bulk temperature. A small factorial design focused on discriminating pathways may be more scientifically valuable than a large optimization grid lacking causal controls [13,14,22,32].

A second priority is the development of models that combine bubble-field measurements, process-scale heat transfer, and crystallization-state equations. Full multiphase simulation may be computationally impractical across industrial geometries, so a hierarchy of models is preferable: simple calorimetric and residence-time balances; reduced-order acoustic and hydrodynamic mappings; and detailed submodels for strategically selected regimes. Model validation should use measurements collected outside the fitting conditions, especially across different palm feedstocks and reactor geometries. Uncertainty estimates must distinguish measurement variability from structural model error, because a seemingly precise prediction may merely encode the assumptions of an unverified bubble model [10-12,34].

A third priority is transparent pilot-scale evaluation against industrial targets. The target should not be vague 'better crystallization' but a measurable combination of solid fat profile, crystal-size distribution, filtration behavior, oil-binding requirement, acceptable sensory profile, and energy per kilogram of saleable product. A field trial should document equipment wear, fouling, acoustic homogeneity, throughput variation, and reproducibility across batches. It should also distinguish energy savings that result from faster crystallization from savings that result from altered cooling conditions or separation yield. Only this integrated performance evidence can establish whether ultrasound moves beyond an intriguing physical intervention toward a technically justified manufacturing strategy [9,20,21,53].

**Conclusion**

Palm oil sonocrystallization is best understood as a coupled physical process rather than a simple relationship between ultrasound power and crystal quality. Acoustic cavitation, streaming, localized thermal dissipation, secondary nucleation, crystal growth, and polymorphic transformations can overlap, and their relative influence changes with lipid composition and the evolving state of the sample. Direct palm-based studies show meaningful opportunities for manipulating crystallization kinetics and network structure, but they also document nonmonotonic effects and dependence on temperature, agitation, emulsion architecture, and treatment timing. The most defensible conclusion is therefore conditional: ultrasound can be useful when the desired material response and the relevant physical pathways are identified and experimentally controlled.

The central theoretical contribution of this review is a multiscale attribution framework linking acoustic forcing to thermal and hydrodynamic mediators, nucleation and polymorphic pathways, microstructural network development, and application-specific outcomes. The framework also explains why an apparently favorable result such as shorter induction time, smaller crystals, or increased elastic modulus is not sufficient to prove a unique cavitation mechanism. Better interpretation requires matched thermal and mechanical controls, independent structural measurements, and attention to acoustic field heterogeneity. Evidence from other edible fats and sonochemical systems should be used to generate hypotheses, not to replace direct verification in palm oil.

Future research should prioritize physically characterized ultrasonic conditions, time-resolved multiphase measurements, causal experimental designs, validated reduced-order models, and robust pilot-scale comparisons against established processing. Practical evaluation must include product stability, sensory and chemical integrity, equipment reliability, and system-level energy consumption. The broader recommendation is to move from recipes based on nominal device settings toward reproducible processing windows defined by acoustic dose, material state, thermal conditions, and target function. This transition would make ultrasound-assisted palm oil crystallization more scientifically interpretable and more credible as an industrial processing option.

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