

COMPREHENSIVE REVIEW

Laser Cavitation Technology for Advanced Sustainable Liquid Food Processing: A Comprehensive Review on Equipment Design, Applications, and Challenges

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ABSTRACT

The global market for nonthermal processed foods is rapidly expanding due to their superior nutritional value and sensory qualities. Novel nonthermal technologies, which extend the shelf life of liquid foods, are gaining significant global attention for their safety and environmental friendliness, leading to widespread acceptance among manufacturers and consumers. Laser cavitation (LC) is an emerging, sustainable, and novel nonthermal technology for advanced liquid food processing. Cavitation bubbles are generated by laser irradiation, which focuses a high-intensity laser beam into a liquid, creating plasma and resulting in rapid bubble formation and collapse. This offers applications such as microbial reduction, bioactive compound extraction, emulsion improvement, and nutritional quality enhancement in liquid food. This review explores the mechanism of LC, its equipment design, configuration, and operation. In addition, it discusses the potential applications of laser-induced cavitation in the food processing sector, along with its challenges. Existing cavitation-based technologies, including acoustic and hydrodynamic cavitation, have several limitations. Acoustic cavitation can cause protein denaturation at high temperatures, high collapse intensity of bubbles, and reduced efficiency over time. Hydrodynamic cavitation faces challenges such as equipment deterioration, a lack of directional sensitivity, and complex setup requirements. To overcome these limitations, LC technology is preferred for its greater precision and controlled energy delivery. The noncontact, focused distribution of the laser beam makes it a more compact and energy-efficient option for processing liquid foods.

Abbreviations: ANN, artificial neural networks; CIP, clean-in-place; CP, cold plasma; DOEs, diffractive optical elements; Er³⁺-Er YAG, erbium-doped yttrium aluminum garnet.; EU, European Union; FDA, Food and Drug Administration; GA, genetic algorithms; GRIN, gradient index; HPP, high-pressure processing; LC, laser cavitation; MIR, mid-infrared; MPC, model predictive control; NIR, near-infrared; PCDIH, phase conjugate digital in-line holography; PDV, photonic Doppler velocity; PEF, pulsed electric fields; PID, proportional–integral–derivative; PLC, programmable logic controller; RTDs, resistance temperature detectors; SLMs, spatial light modulators; TRPP, time-resolved pump-probe; US, ultrasound; UV, ultraviolet; YAG, yttrium aluminum garnet.

1 | Introduction

Consumers' demand for minimally processed, nonthermal foods is steadily increasing as they recognize the benefits of maximum quality retention (Arya et al. 2023). To meet this demand, emerging nonthermal technologies such as cold plasma (CP), pulsed light, high-pressure processing (HPP), pulsed electric fields (PEFs), ultrasound (US) treatment, supercritical carbon dioxide processing, ultraviolet (UV) radiation, and ozone treatment are being widely adopted to enhance nutrient retention, improve food quality, and maintain safety standards (Jadhav and Choudhary 2024). These technologies are progressively being adopted across various food industries for their superior ability to preserve the quality of food products compared to traditional thermal methods (Safwa et al. 2024). The limitations of existing thermal processing methods include degradation of nutritional value, destruction of heat-sensitive bioactive components, lipid oxidation, and alteration of texture, rheology, and sensory attributes (Bonilla et al. 2024).

Existing nonthermal technologies, such as HPP, PEFs, US, CP, and UV irradiation present, distinct limitations. HPP and PEF are largely ineffective against bacterial spores. US and CP often result in uneven energy distribution and insufficient penetration in turbid or heterogeneous liquid foods. UV and PEF treatments can cause quality deterioration, including browning, cooked appearance, and off-flavors. CP in particular may accelerate lipid and protein oxidation. Furthermore, the overall energy efficiency and applicability of these techniques remain limited across diverse liquid food matrices (Ying et al. 2024). These limitations highlight the need for alternative approaches such as laser technology, an emerging nonthermal method that offers precise, contactless energy delivery with minimal thermal impact (Chavan et al. 2023; Kishore et al. 2024). Laser processing can enhance processing efficiency, preserve essential nutrients and sensory attributes, reduce environmental impact, and improve the safety and quality of liquid foods (Nguyen et al. 2024; Z. Zhang et al. 2024). It operates by the emission of coherent, monochromatic, and collimated light via light amplification by stimulated emission of radiation (LASER), with wavelengths ranging from 1 to 1800 nm (Teng et al. 2021). This unidirectional, high-energy light enables highly localized interactions with materials, allowing targeted treatment that maintains nutritional and organoleptic quality, which are critical for maintaining the quality of fluid foods.

Cavitation techniques are gaining importance in food processing due to their ability to enhance mass transfer, accelerate chemical reactions, and improve the efficiency of various food processing operations, such as extraction, homogenization, pasteurization, creaming, reducing the allergenicity of milk proteins, and reducing the viscosity (Bucur et al. 2023). Existing cavitation techniques include hydrodynamic cavitation and ultrasonic (acoustic) cavitation. These methods are widely used in various applications such as food processing, wastewater treatment, and biomedical applications (Movahed et al. 2023). Acoustic cavitation involves the formation of vapor or gas-filled microbubbles in liquids under intense ultrasonic excitation. These bubbles grow, oscillate, and collapse violently, creating high pressure and localized high temperatures necessary for processing liquid foods (Qin et al. 2024).

The drawbacks of this cavitation include denaturation of proteins at high temperatures, the release of free radicals, which can induce oxidation, the intense impact of probe Sono reactors due to close contact, high collapse intensity of cavitation bubbles, and a decline in efficiency with increased processing time (Kamal et al. 2023; Aldakheel et al. 2020). Conversely, hydrodynamic cavitation occurs when fluid flows through constricted components such as orifice plates, venturi tubes, or gates, causing a local pressure drop that leads to bubble formation and rapid collapse, generating high pressures (100–5000 bar) and temperatures (727°C–9727°C) for a few seconds (Arya et al. 2023; X. Sun et al. 2024). Some of the limitations of hydrodynamic cavitation techniques include the need for regular maintenance, equipment deterioration, lower intensity of cavitation collapse, lack of direction sensitivity, and complex setup requirements (Arya et al. 2023).

Recent literature highlighted the growing importance of cavitation-based technologies, particularly hydrodynamic cavitation and acoustic cavitation, in food processing. Arya et al. (2023) provided a detailed review of hydrodynamic cavitation, emphasizing its significant potential for process intensification, microbial inactivation, and the extraction of bioactive compounds from food systems. Stebeleva and Minakov (2021) examined various cavitation mechanisms, including acoustic and hydrodynamic cavitation, with a primary focus on their applications in oil processing. Laser cavitation (LC) is an emerging nonthermal food processing technology that involves the formation and collapse of bubbles within a liquid exposed to laser irradiation. This process generates localized high energy capable of enhancing bioactive compound extraction, improving emulsification, and reducing microbial contamination (Yu et al. 2023). LC is preferred over other cavitation methods due to its precision, controllability, and energy efficiency (Z. Zhang et al. 2024). Recent studies by Z. Zhang et al. (2023), C. Wang et al. (2024), and Gu et al. (2024) have demonstrated the generation of LC in liquid media. However, there is no comprehensive review focusing on the equipment design, configuration, and applications of LC in food processing.

Although laser technology has been previously reviewed by Teng et al. (2021) and Chavan et al. (2023), several key gaps remain unaddressed in the existing literature. Teng et al. (2021) provided a broad overview of laser applications in food processing, including cutting, drying, packaging, marking, extraction, and microbial inhibition. Chavan et al. (2023) explored the use of laser light in food processing, packaging, and testing, describing it as a sustainable and highly controllable method with potential for precise, minimal-impact applications. However, neither study specifically focused on LC applications in liquid food systems. In addition, there remains a lack of detailed analysis concerning laser equipment design and operational parameters, such as wavelength, pulse mode, spot size, and power intensity, and their direct implications for interactions with different food matrices. Moreover, previous works have not presented a systematic, application-specific classification or offered insights into emerging areas such as emulsion improvement and nutritional enhancement. Furthermore, recent advancements from 2021 to 2025 and real-world challenges, including running costs, scalability, and product-specific processing limitations, have not been critically examined. This review aims to bridge these gaps by

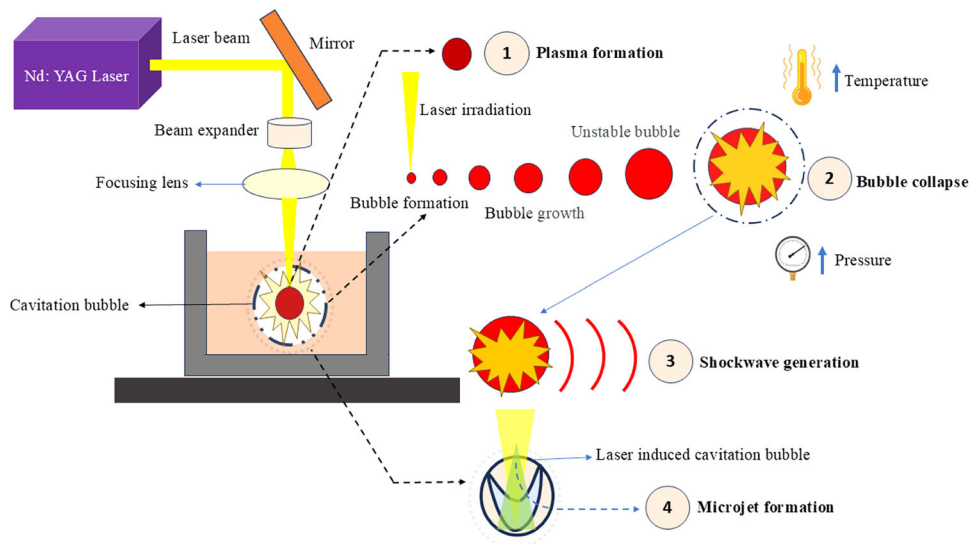


FIGURE 1 | Mechanism of laser cavitation generation.

providing an up-to-date, technically focused, and application-oriented synthesis of laser-induced cavitation technology for liquid food processing.

A thorough review of this emerging green technology is essential to address significant gaps in the literature, consolidate existing findings, and understand its benefits and limitations. Such a review will establish a foundation for future research, foster change, promote interdisciplinary collaboration, and support the development of regulatory guidelines and industry standards. It will also provide valuable insights into the current capabilities and future potential of LC. This review covers the mechanism of cavitation generation, the design and configuration of LC equipment, and its applications, including microbial reduction, bioactive compound extraction, food property and emulsion improvement, and nutritional quality enhancement. In addition, it will summarize the challenges and prospects of this technology.

2 | Cavitation Mechanism of Laser and Other Different Technologies

Cavitation generation mechanisms vary significantly depending on the technology employed, each leveraging unique physical phenomena to induce bubble formation, growth, and collapse. These differences profoundly influence the effectiveness, scalability, and applicability of cavitation in food processing and related fields. Laser-induced cavitation is a highly localized phenomenon where a focused laser beam, such as from an Nd:YAG laser operating at wavelengths of 532 or 1064 nm, deposits intense energy at a precise focal point within a liquid medium. The mechanism of LC generation in liquid food is illustrated in Figure 1. When the power density exceeds the breakdown threshold, plasma forms due to the ionization of the liquid, absorbing further laser energy and rapidly expanding to create a cavitation bubble (Chavan et al. 2023; Sreekala et al. 2025). The subsequent violent collapse of this bubble generates extreme temperatures, pressures, shock waves, and microjets that

act on the surrounding liquid matrix, inducing physical and chemical changes such as microbial inactivation and structural modification of food products (Kishore et al. 2024; Zheng et al. 2020). The key advantage of LC lies in its spatial precision and the ability to tightly control energy delivery, which minimizes collateral damage outside the target area (Raman et al. 2022; Teng et al. 2021). Figure 2 represents the schematic diagram of LC technology. However, this technology often requires complex and costly equipment, and its application is generally limited to relatively small treatment volumes (Lim et al. 2025). An overview of key findings relating to LC technology in food processing is shown in Table 1.

Ultrasonic cavitation relies on high-frequency sound waves propagating through a liquid medium, typically between 20 kHz and several MHz. The alternating compression and rarefaction cycles of the sound waves create microscopic vapor cavities that grow and collapse due to pressure fluctuations (Stebeleva and Minakov 2021). The collapse of these bubbles generates intense shear forces, localized heating, and shock waves, which enhance processes such as emulsification, extraction, and microbial inactivation in food systems (Arya et al. 2023). Ultrasonic cavitation is widely used due to its relatively simple implementation and ability to treat larger volumes, but it lacks the spatial precision of laser-induced cavitation and can lead to uneven energy distribution and potential overheating in bulk liquids (Arya et al. 2023).

Hydrodynamic cavitation arises from the abrupt acceleration and deceleration of fluid flow, often engineered via devices such as orifices or venturi tubes that cause local pressure drops below the vapor pressure of the liquid, leading to vapor bubble formation (Zoglopiti et al. 2025; Asaithambi et al. 2019). These bubbles subsequently collapse as the pressure recovers downstream, generating mechanical shear forces and turbulence that intensify mixing, enhance mass transfer, and inactivate microorganisms (Arya et al. 2023; Zoglopiti et al. 2025). Hydrodynamic cavitation is particularly valued for its energy efficiency and scalability, making it well-suited for industrial-scale food processing. How-

TABLE 1 | Recent key findings relating laser cavitation technology in food processing.

Objective	Methodology	Key findings	References
Investigating the effects of laser cavitation on food homogenization and emulsification.	<ul style="list-style-type: none"> • Pulsed laser system • Variations in laser power intensities and pulse durations 	<ul style="list-style-type: none"> • Laser cavitation significantly improved the emulsification of oil in water systems • The optimal power intensities lead to stable emulsions without over heating the food 	Delmas et al. (2023)
Examining the scalability of laser cavitation systems for large-scale food processing	<ul style="list-style-type: none"> • Comparative analysis of small-scale vs. large-scale cavitation chambers • Simulation of multilaser systems for continuous flow through processing 	<ul style="list-style-type: none"> • Multilaser arrays and flow-through cavitation chambers are effective for <ul style="list-style-type: none"> ◦ Scaling up ◦ Maintaining uniform cavitation, and ◦ Food quality at larger scales 	Khairani et al. (2023)
Evaluating energy efficiency in laser cavitation systems used in food processing	<ul style="list-style-type: none"> • Energy consumption measurements in laser system during cavitation of food samples • Analysis of energy-saving strategies like pulse modulation and closed-loop cooling 	<ul style="list-style-type: none"> • Optimized pulse control and closed-loop cooling systems reduced energy consumption by up to 30% in industrial applications without compromising cavitation intensity 	Harish et al. (2023)
Assessing safety protocols for laser cavitation systems in industrial food processing systems	<ul style="list-style-type: none"> • Safety assessments including laser safety protocols, pressure testing, and system shutdown responses <ul style="list-style-type: none"> • Real-time monitoring and automation were implemented 	<ul style="list-style-type: none"> • Laser shielding, automated shutdown systems, and real-time monitoring of pressure and temperature were critical to maintain safe operation of laser cavitation systems 	Babu and Amamcharla (2023)
Exploring the use of laser cavitation in food extraction processes (e.g., flavor, nutrients)	<ul style="list-style-type: none"> • Laser cavitation was used to extract bioactive compounds from fruits and vegetables • Variations in wavelengths, pulse durations, and laser intensities were compared for extraction efficiency 	<ul style="list-style-type: none"> • Laser cavitation enhanced extraction yields higher, particularly for polyphenols and antioxidants with minimal impact on food flavor or quality 	Xu et al. (2022)
Investigating cavitation dynamics in laser processing and its effect on particle size reduction in food systems	<ul style="list-style-type: none"> • Laser cavitation applied to various food matrices (liquids, purees) to analyze particle size distribution using dynamic light scattering 	<ul style="list-style-type: none"> • Laser cavitation reduced particle size effectively, particularly at higher intensities • This resulted in improved texture and sensory properties for emulsified and homogenized foods 	Mehta and Baruah (2022)
Examining the influence of the laser cavitation on microbial inactivation, and food safety in liquid food products	<ul style="list-style-type: none"> • Application of pulsed laser cavitation in liquid food samples (juices and dairy products) to assess microbial reduction and quality preservation through microbial assays 	<ul style="list-style-type: none"> • Laser cavitation significantly reduced microbial populations with optimal intensity achieving pathogen reduction while preserving sensory qualities of liquid foods 	Teng et al. (2021)
Evaluating the potential of laser cavitation for improving food shelf life and storage stability	<ul style="list-style-type: none"> • Long-term storage study with laser-treated food samples to evaluate shelf-life extension • Sensory attributes, microbial count, and chemical changes (e.g., pH, color) were monitored 	<ul style="list-style-type: none"> • Laser cavitation extended shelf-life by reducing microbial spoilage and slowing down oxidation, particularly for fruits and vegetables 	Arya et al. (2021)

(Continues)

TABLE 1 | (Continued)

Objective	Methodology	Key findings	References
Studying the effect of laser cavitation on food sterilization and pathogen reduction	<ul style="list-style-type: none"> Laboratory-based experiments using pulsed laser systems to treat food samples and monitor microbial load reduction at various laser parameters (pulse duration and intensity) 	<ul style="list-style-type: none"> Laser cavitation effectively reduced microbial load, with specific pulse durations and intensities being most effective for sterilization without degrading food quality 	Zheng et al. (2020)
Investigating the impact of laser cavitation on food texture and quality preservation during processing	<ul style="list-style-type: none"> Analysis of food texture changes and nutrient retention in fruits, vegetables, and meat after laser cavitation under different power levels and processing times 	<ul style="list-style-type: none"> Optimal cavitation conditions (moderate intensity and pulse durations) preserved food texture and nutrients, especially in heat-sensitive food products 	Illera et al. (2020)

ever, the mechanism offers less control over bubble size and collapse intensity compared to laser or ultrasonic methods, and the equipment can be prone to erosion due to cavitation-induced wear (Arya et al. 2023; Stebeleva and Minakov 2021).

Each cavitation technology brings a distinct balance of benefits and limitations. Laser-induced cavitation offers unmatched spatial precision and extremely high localized energy, ideal for targeted applications requiring minimal damage to surrounding material. However, its high cost, complexity, and limited treatment volume constrain its widespread adoption in food processing (Chavan et al. 2023; Kishore et al. 2024). Ultrasonic cavitation provides a versatile, moderately scalable option with relatively straightforward equipment and broad applicability in emulsification and microbial inactivation. Its main drawbacks include reduced spatial control and the potential for uneven energy distribution or localized overheating, which may affect product quality (Arya et al. 2023; Stebeleva and Minakov 2021). Hydrodynamic cavitation excels in energy efficiency and large-scale processing capability, offering a cost-effective route to intensify processes such as extraction and sterilization. Nevertheless, the inability to finely control cavitation dynamics and the risk of equipment erosion must be considered in its deployment (Arya et al. 2023; Zoglopiti et al. 2025). In summary, the choice of cavitation technology depends on specific application requirements such as treatment volume, precision, energy efficiency, and equipment cost. LC suits precision and small-scale applications, ultrasonic cavitation balances ease of use and scalability, while hydrodynamic cavitation provides an energy-efficient solution for large-scale processing.

3 | Equipment Design and Configuration of LC Technology

3.1 | Designing Chamber for LC

LC technology is a novel and highly effective technique for food processing that utilizes high-intensity laser pulses. LC technology induces cavitation by focusing laser energy into a liquid medium, generating microbubbles that collapse rapidly, producing intense confined heat, pressure, and shear forces. These forces can modify food structures, improving emulsification, homogenization, and even sterilization. Designing optimal cavitation chambers is

essential to ensure efficient energy transfer, controlled cavitation, and consistent product quality in food processing (Mancuso et al. 2020). The key design elements of cavitation chambers for LC include chamber geometry, shape, material selection, laser energy delivery, focusing mechanism, flow dynamics, residence time, pressure, temperature control, and real-time monitoring systems.

3.1.1 | Geometry and Shape

The geometry of the cavitation chamber plays a critical role in determining how laser energy is distributed throughout the liquid food medium and how efficiently cavitation bubbles are generated and collapse. An optimal chamber design ensures uniform laser energy propagation, minimizes energy losses, and promotes effective cavitation, which is vital for processes like microbial inactivation, emulsification, and bioactive extraction in liquid food matrices (Askarniya et al. 2023). Different chamber shapes are used depending on the processing mode and application requirements. Spherical chambers are commonly employed in batch systems because they naturally focus laser energy toward the center, enabling highly localized and intense cavitation. This geometry is particularly effective when precise targeting and maximum energy concentration are needed, such as in small-scale extraction or localized sterilization. Cylindrical chambers are better suited for continuous-flow processes, offering a more uniform energy distribution and consistent cavitation effects across the flow path, making them ideal for industrial applications requiring high throughput and uniformity (Albanese et al. 2017). Flat-surfaced chambers direct laser energy onto specific regions for surface-specific treatments, useful in surface sterilization of transparent liquids where clarity and minimal thermal degradation are priorities (Askarniya et al. 2023). Tapered or conical chambers influence flow dynamics, concentrating cavitation in particular zones to enhance shear forces, improve microbial disruption, or boost the extraction of sensitive compounds (Xu et al. 2022). Chamber geometry must be matched with laser parameters such as wavelength, pulse duration, and repetition rate. Short-pulse lasers that generate high peak powers may perform better in spherical or conical chambers, while longer pulse or continuous-wave lasers are better suited for cylindrical geometries with broader energy distribution (Albanese et al. 2017; Askarniya et al. 2023). Selecting the appropriate cham-

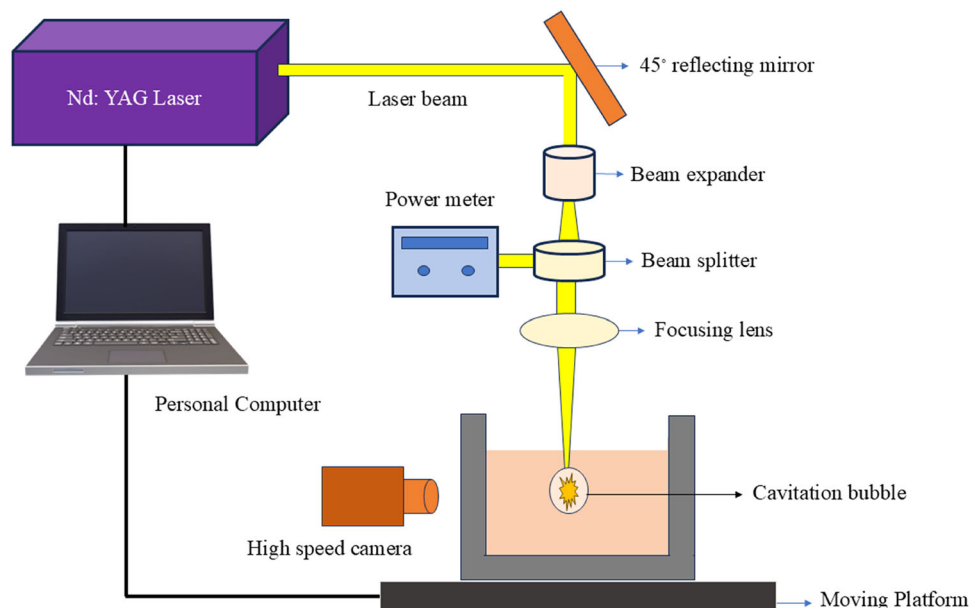


FIGURE 2 | Schematic diagram of laser cavitation technology.

ber geometry is essential for optimizing cavitation efficiency, uniform treatment, reducing energy waste, and supporting scalability.

3.1.2 | Material Selection

Material composition is a fundamental factor influencing the durability, efficiency, and safety of cavitation chambers. Collapsing bubbles generate intense local pressures and temperatures, causing mechanical stress and erosion on chamber walls. Materials must exhibit excellent mechanical strength, thermal stability, and resistance to cavitation-induced wear, especially in high-intensity laser applications (Arya et al. 2020; Chavan et al. 2023). Stainless steel (Grades 304 and 316) is widely used for food-grade chambers due to nonreactivity, ease of cleaning, corrosion resistance, and mechanical fatigue tolerance. Grade 316, with added molybdenum, offers superior corrosion resistance in acidic or saline environments, suitable for juices, dairy, and fermented liquids (Chavan et al. 2023; Xu et al. 2022). Titanium and engineered ceramics may be used in high-frequency or high-performance applications. Titanium provides a high strength-to-weight ratio and excellent cavitation erosion resistance, but is costly. Ceramic-lined chambers or hardened chrome coatings improve wear resistance, extend operational life, and reduce micro-pitting common in cavitation-intensive environments (Albanese and Meneguzzo 2019). Surface coatings enhance chamber lifespan and hygiene, minimizing contamination risks in food processing. Materials and coatings must comply with food-safety regulations such as the Food and Drug Administration (FDA) or European Union (EU) standards. Material selection should consider cavitation intensity, liquid matrix properties (pH, viscosity, particulate content), and hygiene requirements, with advanced coatings or alternative materials applied for aggressive cavitation or extended equipment life (Arya et al. 2020; Albanese and Meneguzzo 2019; Xu et al. 2022).

3.1.3 | Laser Energy Delivery and Focusing Mechanism

Laser energy delivery and focusing directly affect the efficiency, uniformity, and precision of cavitation, especially in liquids with varying viscosity, turbidity, and optical properties. The laser type, such as Nd:YAG, diode, or fiber, greatly influences energy distribution and system design. Short-pulse lasers from femtoseconds to nanoseconds deliver high peak power in extremely short durations, producing localized heating and rapid bubble formation without excessive bulk heating (Chavan et al. 2023; Sportelli et al. 2018). Energy is delivered via optical fibers, mirrors, or lenses. Single-mode fibers provide high precision, while multimode fibers deliver higher energy over larger volumes, useful for turbid or viscous liquids (Arya et al. 2023). Lenses and mirrors focus the beam to small liquid volumes to initiate cavitation. Shorter focal lengths produce concentrated spots, enhancing bubble formation in transparent, low-viscosity liquids like juices, whereas turbid liquids may require wider focal areas to maintain uniform energy distribution (Kentish 2017; Khairani et al. 2023). Beam focusing is one of the most influential parameters affecting cavitation efficiency, particularly in continuous-flow systems where uniform treatment is essential for microbial inactivation or emulsification (Arya et al. 2023; Chavan et al. 2023). Optimizing the optical delivery system and focusing setup based on the liquid's properties ensures efficient, targeted, and reproducible cavitation with minimal thermal degradation.

3.1.4 | Flow Dynamics and Residence Time

Flow dynamics and residence time management are central to optimizing LC performance. The internal flow path influences uniform energy delivery, bubble propagation, and overall treatment. Chamber flow design must accommodate liquids of varying viscosity and turbidity to avoid dead zones and promote

homogeneous exposure (Carpenter et al. 2017; Arya et al. 2023). Helical or spiral flow paths increase residence time, enhancing mixing, emulsification, microbial inactivation, or bioactive extraction (Carpenter et al. 2017; Mancuso et al. 2020). Longer residence times increase exposure to cavitation events, but excessive time may cause thermal degradation or undesired texture changes, especially in heat-sensitive beverages. In batch systems, residence time is controlled by pulse frequency, energy input, or treatment duration; in continuous-flow systems, flow rate and chamber length govern residence. Adjustable flow rates and real-time monitoring maintain optimal cavitation performance across product viscosities and processing conditions (Mancuso et al. 2020; Arya et al. 2023). Flow dynamics should align with laser parameters, ensuring each unit of liquid receives a uniform cavitation dose. Proper flow and residence time integration ensures efficient, uniform, and safe cavitation in diverse liquid food matrices.

3.1.5 | Pressure and Temperature Control

Precise pressure and temperature regulation within the cavitation chamber is crucial for consistent and reproducible cavitation. Cavitation occurs when local pressure drops below vapor pressure, so controlling static and dynamic pressure ensures proper bubble formation and collapse (Babu and Amamcharla 2023). High-viscosity or turbid liquids require finer pressure control due to increased resistance to bubble formation. Sealed chambers with adjustable internal pressure or relief valves maintain optimal conditions, ensuring effective energy transfer and preventing premature collapse or insufficient cavitation (Arya et al. 2023). Temperature control prevents thermal degradation, particularly in juices, purees, and plant-based beverages. Localized heating near the laser focus can degrade nutrients or proteins; therefore, cooling systems such as jacketed chambers, circulating water baths, or heat exchangers stabilize temperature (Askarniya et al. 2023; Z. Zhang et al. 2024). Dynamic feedback systems further allow real-time adjustments, ensuring consistent processing across liquids with varying properties. Balancing cavitation intensity and thermal control preserves product quality and maximizes the benefits of nonthermal processing (Arya et al. 2023; Askarniya et al. 2023).

3.1.6 | Real-Time Monitoring Control Systems

Integration of real-time monitoring and control systems enhances precision, efficiency, and scalability. Sensors track pressure, temperature, flow rate, and laser intensity, allowing on-the-fly adjustments to maintain optimal cavitation (Freeland et al. 2021). Flow and pressure monitoring prevent energy loss in turbid or viscous liquids, while automated systems, including PLCs or MPC algorithms, adjust residence time, beam focus, and pulse energy for efficient treatment of each batch (Kyaw et al. 2024; Teng et al. 2021). Thermal monitoring preserves nutrients and sensory quality in heat-sensitive liquids. Automated feedback loops balance cavitation intensity with thermal load, critical at industrial scale. Hygienic design features, like stainless-steel surfaces, self-cleaning, and fouling alerts, minimize contamination risk and reduce downtime (W. Zhou et al. 2022; Albanese et al.

2017; Teng et al. 2021). Real-time monitoring ensures consistent energy delivery, adapts to varying liquid properties, and enables reproducible, effective, and safe cavitation, supporting large-scale food processing applications.

3.2 | Cooling and Integration of Sensors and Control Systems in LC

Cooling systems, integrated sensors, and control mechanisms play crucial roles in maintaining optimal thermal conditions, improving efficiency, and ensuring process stability in LC chambers. Cooling is essential in LC technology due to heat generation during cavitation, which occurs when vapor bubbles collapse and release energy in the form of heat, pressure, and shear forces (Albanese and Meneguzzo 2019). While localized heating can be beneficial for applications such as sterilization or extraction, excessive heat may degrade sensitive food components such as proteins, vitamins, and flavors. Incorporating effective cooling mechanisms ensures that cavitation occurs at the desired intensity without compromising food quality (Chavan et al. 2023; Xu et al. 2022).

3.2.1 | Cooling Systems

Effective thermal management in LC chambers is critical for maintaining process efficiency, product safety, and the nutritional and sensory quality of heat-sensitive liquid foods such as juices, dairy emulsions, and bioactive-enriched beverages. Although cavitation itself is primarily nonthermal, high-intensity laser pulses can lead to localized heating, particularly in high-viscosity or optically dense liquids, increasing the risk of thermal degradation (Arya et al. 2023; Chavan et al. 2023). Cooling jackets are widely used to circulate a cooling fluid such as water or glycol around the chamber, absorbing excess heat and maintaining optimal temperature to prevent bulk overheating. This is particularly important for turbid liquids, which tend to absorb more laser energy and may develop uneven temperature distribution (Singh et al. 2023). Heat exchangers provide indirect cooling, especially in continuous-flow systems, ensuring steady-state temperatures and consistent cavitation across large volumes (Ghorbani et al. 2017; Meroni et al. 2021). In batch-mode systems, direct cooling methods such as misting or jet sprays allow rapid dissipation of heat post-laser exposure, preventing localized overheating during high-power bursts. In addition, the use of high thermal conductivity materials, such as copper or aluminium, in chamber walls enhances passive heat dissipation, facilitating faster transfer of heat from laser-exposed regions to the chamber exterior (X. Yang et al. 2023). Industrial-scale LC systems often employ active cooling technologies, such as refrigeration coils or Peltier devices, providing precise temperature control essential for sensitive processes like liquid bioactive extraction or fruit juice pasteurization (Z.-H. Zhang et al. 2019). Maintaining the process temperature within 40°C–60°C is critical for preserving flavor, color, and nutritional value in fruit-based products (Illera et al. 2020). Overall, the choice of cooling system must be tailored to laser parameters, food matrix properties, and operational scale to ensure both effective cavitation and safe, high-quality food processing (Arya et al. 2023; Chavan et al. 2023).

3.2.2 | Integrated Sensors

The integration of advanced sensors in LC systems is essential for precise control of processing parameters, ensuring consistent cavitation effects tailored to the complex characteristics of liquid food matrices. Temperature sensors, including thermocouples, resistance temperature detectors (RTDs), and thermistors, monitor and regulate the thermal environment, preventing heat-sensitive foods from degradation due to localized laser heating, particularly at wavelengths such as 1064 nm, where water strongly absorbs radiation (Režek Jambrak et al. 2021; Arya et al. 2023). Pressure sensors maintain optimal cavitation conditions by monitoring local pressure to avoid fluctuations that could compromise cavitation efficiency or damage the chamber and food product (Xu et al. 2022; Arya et al. 2023). Flow sensors ensure uniform residence time in cavitation zones, which is critical for liquids with varying viscosity, preventing overprocessing or uneven treatment (Babu and Amamcharla 2023; Mancuso et al. 2020). Laser power sensors measure the intensity and stability of the laser beam, enabling adaptive modulation to maintain consistent cavitation in liquids with differing optical transparency or turbidity (Chavan et al. 2023; Xu et al. 2022). Modern LC systems combine these sensors into integrated networks with automated feedback control, allowing real-time adjustments of temperature, pressure, flow rate, and laser power. Some systems also monitor food quality parameters such as viscosity, pH, and turbidity, providing direct insight into emulsification, extraction, or sterilization processes (Patel et al. 2022). Sensor integration is particularly valuable for scaling LC technologies from pilot to industrial production while maintaining process consistency and product quality (Kyaw et al. 2024; L. Zhang et al. 2021). The integration of temperature sensors within cooling systems further prevents overheating, preserving the nutritional and sensory qualities of heat-sensitive foods while enhancing operational safety (Zadeike and Degutyte 2023).

3.2.3 | Control Systems

Control systems in LC technology automate process regulation, precisely controlling laser energy and cavitation intensity while enabling data-driven optimization. Closed-loop feedback systems and proportional–integral–derivative (PID) controllers are commonly employed, using real-time sensor inputs to dynamically adjust operational parameters (Askarniya et al. 2023; Zheng et al. 2020). Closed-loop systems automatically modulate laser power, cooling flow rates, and chamber pressure to maintain cavitation conditions within desired set points, while PID controllers minimize deviations from target values to ensure stable temperature, pressure, and cavitation intensity. Precise control of laser energy input, including pulse frequency, duration, and power, is particularly critical for heat-sensitive liquids to prevent thermal degradation. Flow rate control ensures uniform exposure to cavitation effects in continuous-flow systems, avoiding under- or over-processing (Chavan et al. 2023). Advanced systems incorporate data logging for post-process analysis and adaptive algorithms that automatically adjust to variations in food matrix properties such as viscosity, maintaining consistent cavitation intensity and processing efficacy (Arya et al. 2020; Askarniya et al. 2023; Zheng et al. 2020). The synergistic integration of cooling systems, sensors, and control mechanisms enhances

the efficiency, scalability, and reliability of LC systems while maintaining high food quality standards. Future advancements in sensor precision, cooling strategies, and control algorithms are expected to further optimize LC technology, enabling wider industrial adoption in food processing applications (Arya et al. 2023; Askarniya et al. 2023).

3.3 | Laser Source Selection and Specifications

The optimization of laser parameters in liquid food processing critically depends on the distinct physical and optical properties of liquid matrices, which differ substantially from those of solid foods. A primary consideration is the energy absorption characteristic of the liquid, dictated mainly by water content and dissolved components. Water, the major constituent in most liquid foods, strongly absorbs laser energy in the near-infrared (NIR) range (700–1000 nm), which has guided the widespread use of infrared lasers in cavitation-based processing systems (Arya et al. 2023; Chavan et al. 2023). This absorption produces rapid localized heating and bubble formation, initiating cavitation. However, absorption varies with the type of liquid: clear liquids like filtered juices absorb less and allow deeper penetration, while pigmented or turbid beverages absorb more energy near the surface, potentially limiting cavitation depth (Zoglopiti et al. 2025). These interactions permit tuning of laser wavelength and pulse energy to maximize cavitation without causing undesirable thermal damage.

Viscosity significantly affects cavitation efficiency. Higher viscosities impede bubble nucleation and growth by damping fluid motion, reducing cavitation intensity (Stebeleva and Minakov 2021; Arya et al. 2023). Stebeleva and Minakov (2021) observed a 40% reduction in cavitation bubble size when viscosity increased from 1 to 50 cP in a model sucrose solution. Low-viscosity fluids such as milk or clear juices (~1 cP) allow vigorous cavitation, whereas viscous syrups or purees (>100cP) require increased pulse energy or longer pulse durations to generate sufficient pressure for effective cavitation. Repetition rates and exposure times may also be optimized to sustain cavitation over the processing period (Kishore et al. 2024). Turbidity influences laser energy delivery through scattering and diffusion. Suspended particles in highly turbid liquids reduce the effective intensity reaching the target region, limiting cavitation efficiency and penetration depth (Zheng et al. 2020; Zoglopiti et al. 2025). Mitigation strategies include longer wavelength lasers, filtration, or homogenization, enhancing penetration and bubble formation (Sreekala et al. 2025). Optical transparency and refractive index further affect performance: transparent liquids permit deeper penetration and precise focusing, while opaque or colored liquids necessitate surface-focused laser application. Refractive index mismatches can cause beam divergence and reduced energy density at the focal point, impairing cavitation efficiency (Lim et al. 2025; Sreekala et al. 2025). In summary, turbidity, viscosity, optical clarity, and refractive index collectively determine the effectiveness of laser energy absorption and cavitation in liquid food matrices. Turbidity scatters light, reducing penetration depth; viscosity dampens bubble dynamics; optical clarity promotes volumetric energy delivery; and refractive index affects beam focus and energy concentration (Raman et al. 2022; Kishore et al. 2024). Tailoring laser source characteristics such as wavelength,

pulse duration, and power based on these parameters enables nonthermal, energy-efficient treatments while preserving food quality and safety (Arya et al. 2023; Chavan et al. 2023; Zoglopiti et al. 2025).

3.3.1 | Pulse Duration

Pulse duration determines the laser's ability to deposit energy efficiently and initiate cavitation. Shorter pulses, typically nanoseconds to picoseconds, generate high peak power essential for localized bubble formation and rapid collapse (Y. Zhou and Wang 2018). Nanosecond lasers (e.g., Nd:YAG) are widely used due to their capability to deliver sufficient energy quickly, enabling effective cavitation with minimal thermal damage (Arya et al. 2023; Kishore et al. 2024). Picosecond and femtosecond pulses allow precise energy confinement but are less common due to higher cost and operational complexity (Agrež et al. 2023; Sreekala et al. 2025). Pulse effectiveness is influenced by the liquid's properties. High viscosity dampens bubble dynamics, often requiring longer or more energetic pulses to sustain cavitation (Stebeleva and Minakov 2021). Turbidity reduces penetration, making short pulses advantageous for confining energy before scattering attenuates the beam (Zoglopiti et al. 2025). Optical transparency and refractive index also affect focusing and energy distribution, with transparent liquids promoting uniform cavitation (Lim et al. 2025; Teng et al. 2021). Typical pulse energies range from 10 to 500 mJ, with higher energy needed for larger or more viscous volumes (Geng et al. 2021; Kishore et al. 2024). Optimization balances cavitation efficiency and thermal safety, preserving food quality (Chavan et al. 2023; Arya et al. 2023).

3.3.2 | Repetition Rate

Repetition rate, or pulse frequency, defines how often laser pulses are emitted and affects cavitation dynamics. Higher rates produce continuous cavitation, enhancing processes such as emulsification, bioactive extraction, and microbial inactivation (Sinibaldi et al. 2019). Repetition rates typically range from 1 Hz to several kHz, depending on the food matrix and desired throughput. Increased rates improve process efficiency but raise thermal loads, requiring cooling to prevent nutrient degradation (Arya et al. 2023; Chavan et al. 2023). Beam quality (M^2 value) is closely linked to repetition rate efficacy, as high-quality beams ($M^2 \approx 1$) focus energy precisely, enhancing cavitation uniformity, especially in turbid or viscous liquids (W. Yang and Zhou 2017; Zoglopiti et al. 2025). Average power output, correlated with repetition rate and pulse energy, is crucial for balancing cavitation intensity and energy consumption, with industrial lasers ranging from 1 W to over 100 W based on chamber size and liquid volume (Letzel et al. 2019; Soyama 2020). Matching repetition rate and power to liquid properties ensures effective cavitation while preserving product quality (Arya et al. 2023; Zoglopiti et al. 2025).

3.3.3 | Types of Laser Sources

Laser source choice determines cavitation efficiency by governing energy interaction with the food matrix. Nd:YAG lasers (1064 nm; frequency-doubled 532 nm) are preferred for water-rich liquids

due to strong absorption, high pulse energy, and nanosecond-to-picosecond pulse durations, overcoming viscous damping and ensuring efficient cavitation (Chavan et al. 2023; Arya et al. 2023). Diode lasers (800–1000 nm) are compact, cost-effective, and suitable for low-viscosity liquids, though their lower power limits penetration in turbid matrices (Zheng et al. 2020). Fiber lasers (~1060 nm) offer high beam quality and precision, advantageous in turbid or viscous liquids, with superior heat management for sustained high-power operation (Petkovšek et al. 2020). CO₂ lasers (10.6 μm) have poor absorption in water-rich liquids, restricting cavitation but remaining suitable for nonliquid or thicker food matrices (Anton y Otero et al. 2023; Arya et al. 2023).

3.3.4 | Laser Source Selection

Selecting an appropriate laser requires careful consideration of matrix properties, processing objectives, cost, safety, and scalability. Liquid food matrices require specific wavelengths and laser powers to achieve effective cavitation (Sreekala et al. 2025). For example, water-rich liquids such as fruit juices, milk, or broths favor Nd:YAG lasers at 1064 nm for effective cavitation due to strong water absorption, while diode lasers are better suited for clearer beverages (Sreekala et al. 2025; Arya et al. 2023). Turbid or viscous liquids may require higher power or tailored pulse durations to achieve uniform cavitation (Zoglopiti et al. 2025; Teng et al. 2021). Short-pulse lasers enable precise energy delivery for delicate bioactive extraction, whereas high-energy pulsed lasers with higher repetition rates are ideal for surface sterilization or emulsification (Chavan et al. 2023; Kishore et al. 2024; Askarniya et al. 2023). To prevent adverse effects, laser parameters should be maintained within recommended limits based on the maximum permissible exposure (MPE) for the specific wavelength and exposure duration. For Class IV lasers commonly used in liquid food processing (e.g., 1064 nm), continuous-wave power above 500 mW or pulsed energy density exceeding 10 J/cm² can be hazardous (Occupational Safety and Health Administration 2023). Laser systems must include safety enclosures, warning systems, and protective eyewear, and Class IV laser safety standards must be strictly followed. In addition, the system should allow scalability for different production scales, from small-batch to industrial applications (Teng et al. 2021; Xu et al. 2022). Selected lasers must support scalability and integration from pilot to industrial production (Arya et al. 2023). In conclusion, effective laser source selection involves aligning wavelength, pulse duration, energy, repetition rate, and beam quality with liquid properties and processing goals. Nd:YAG lasers remain the standard, while fiber and diode lasers are gaining traction for specific applications. A holistic approach considering matrix characteristics, processing objectives, safety, and scalability ensures reliable, energy-efficient, and sustainable laser-based food processing systems (Chavan et al. 2023; Kishore et al. 2024; Sreekala et al. 2025).

3.4 | Optical Delivery Systems for LC

LC relies on the precise delivery of focused laser energy to generate high temperatures, pressure, and mechanical forces necessary for cavitation. Optimal processing effects in food applications are achieved by efficiently transferring laser energy

from the source to the liquid medium, concentrating on the target area. The optical delivery system ensures that the laser is precisely controlled, directed, and concentrated for effective cavitation (Arya et al. 2020). Key components of optical delivery systems include beam shaping, collimation, focusing optics, beam steering, scanning, and fiber optic delivery systems.

3.4.1 | Beam Shaping and Collimation

Collimation is a critical step in LC systems, ensuring that the laser beam remains focused and intense over extended distances. This minimizes energy loss and maximizes cavitation efficiency in liquid food matrices. Collimators convert naturally divergent laser light into a parallel beam, which is essential when the beam travels through optical fibers or long optical paths commonly used in food processing setups (Zheng et al. 2020). Maintaining beam coherence and intensity is particularly important for liquid foods with higher turbidity or viscosity, as these properties can scatter and absorb laser energy (Sreekala et al. 2025; Zoglopiti et al. 2025). Lens collimators use convex lenses to focus and collimate light and are simple and cost-effective, though they may introduce chromatic aberrations with broadband or pulsed lasers (Zheng et al. 2020). Mirror collimators employ curved mirrors to collimate beams without chromatic distortion, suitable for high-power lasers where lens heating or damage is a concern (Rao et al. 2022). Fiber collimators, designed for laser light coupled in and out of optical fibers, provide compact and flexible delivery, useful for precise beam placement in processing lines (Chavan et al. 2023). Gradient index (GRIN) lens collimators offer high-quality, compact collimation by varying the refractive index within the lens, advantageous in integrated or miniaturized systems (Sreekala et al. 2025).

After collimation, beam shaping modifies the spatial intensity profile of the laser beam to optimize cavitation. Most lasers emit a Gaussian profile where intensity peaks at the center and decreases outward, potentially causing localized overheating and uneven cavitation. Beam shaping transforms Gaussian beams into flat-top or uniform profiles to evenly distribute energy across the treatment area (Chavan et al. 2023; Rao et al. 2022). Beam expanders further increase the beam diameter, lowering peak intensities and improving uniform energy delivery over larger volumes (Zheng et al. 2020). Advanced techniques such as diffractive optical elements (DOEs) and spatial light modulators (SLMs) allow precise control over beam shape and customizable intensity profiles (Chavan et al. 2023). Uniform energy distribution promotes consistent cavitation bubble formation, reduces hotspots, and enhances emulsification, bioactive extraction, and microbial inactivation, directly impacting product quality and safety (Arya et al. 2023; Teng et al. 2021; Zoglopiti et al. 2025). Selecting the appropriate collimator and beam shaping method based on laser wavelength, power, and optical characteristics of the food matrix is essential for effective and scalable LC systems (Chavan et al. 2023; Zheng et al. 2020; Sreekala et al. 2025).

3.4.2 | Optical Focusing

Focusing the laser beam to a precise spot is critical for inducing efficient cavitation effects. Lenses or mirrors concentrate laser energy at the target, influencing the intensity and effectiveness of

cavitation (Teng et al. 2021). The focal spot size and energy density govern bubble formation, collapse dynamics, and overall cavitation efficiency. Short focal lengths produce smaller spots with higher energy density, generating intense localized cavitation, ideal for precision treatments such as microbial inactivation or targeted bioactive extraction (Arya et al. 2020; Chavan et al. 2023). Longer focal lengths create broader spots that distribute energy over a larger area, suitable for larger volumes in continuous-flow systems like emulsification or homogenization (Z. Zhang et al. 2024). Spot size directly affects cavitation intensity: smaller spots produce confined bubbles with higher collapse pressures, enhancing microbial disruption or emulsification efficiency. Excessively small spots or high energy density can, however, cause thermal damage to heat-sensitive food components (Arya et al. 2020; Chavan et al. 2023). Beam shape also plays a role; Gaussian, Bessel, and annular beams have been studied to optimize cavitation uniformity. Bessel beams, with non-diffracting and self-reconstructing properties, generate cavitation along an extended focal line, improving uniformity in emulsions (Chavan et al. 2023; Zheng et al. 2020). Tailoring beam shape to the application enables controlled cavitation, improving efficiency while minimizing unwanted thermal effects.

3.4.3 | Beam Steering and Scanning

LC in liquid foods requires precise control of the beam's position and movement to ensure uniform treatment. Beam steering technologies, such as galvanometer-driven mirrors and motorized stages, allow dynamic adjustment of the laser path, enabling scanning over large or irregular liquid volumes. This is critical for emulsification, extraction, and microbial sterilization, where uniform cavitation affects product quality (Poelma 2017; Heindel 2018). High-speed scanning mirrors rapidly deflect the beam, distributing energy evenly and reducing localized overheating, which is especially important in large-scale or continuous-flow systems (Stoian et al. 2019). Motorized stages further enhance precision, allowing customized scanning patterns adapted to properties such as viscosity, turbidity, and volume (Heindel 2018). Fiber optic delivery complements beam steering, providing flexible, low-loss transmission to confined or hard-to-reach areas, allowing precise targeting in small volumes or intricate flow channels without significant intensity loss (Ding et al. 2019). Combined, beam steering and fiber optics enable scalable, adaptable, and efficient LC setups, promoting uniform cavitation distribution, enhanced energy efficiency, and integration with existing food processing equipment (Poelma 2017; Chavan et al. 2023).

3.4.4 | Fiber Optic Delivery Systems

Fiber optics is essential for guiding laser energy from the source to the treatment site, allowing precise and controlled cavitation in complex or confined environments. Fibers are classified as single-mode or multimode. Single-mode fibers transmit highly focused beams with minimal divergence, ideal for localized cavitation, bioactive extraction, or microbial inactivation (Arya et al. 2020, 2023). Multimode fibers allow multiple light modes to propagate, transmitting higher energy over broader areas, suitable for

large-scale applications like emulsification or continuous-flow treatments (Arya et al. 2023). Fiber optics enables integration into various processing systems, particularly when access to the laser-target interaction zone is limited or high spatial precision is required. High-energy pulses generate thermal loads, necessitating efficient thermal management with water jackets, heat sinks, or thermoelectric coolers to prevent component degradation and maintain system stability (Sim 2020). Safety systems are equally important, protecting operators from eye or skin injury and ensuring compliance with food industry standards. Protective measures include beam shutters, optical windows, interlocked enclosures, and beam path shielding (Teng et al. 2021; Arya et al. 2020, 2023). The effectiveness of fiber optic delivery in LC depends on proper fiber selection, thermal management, and safety integration. Advances in optical materials, fiber technologies, and integrated cooling continue to improve adaptability and scalability for applications ranging from small-batch treatments to high-throughput industrial processes.

3.5 | Factors Influencing LC Design

The LC equipment is influenced by characteristics such as distance between the cavitation zone and the sample surface, operation mode (pulsed or continuous), power intensity and impact times, spot size, running costs, product type, and product depth.

3.5.1 | Distance Between Cavitation and Sample Surface

The distance between the laser-induced cavitation zone and the surface of the food sample is a critical factor affecting efficacy and quality in LC processing of liquid food matrices. This distance influences how the energy released by collapsing cavitation bubbles is transferred to the food medium, impacting homogenization, emulsification, and sterilization outcomes. If the cavitation zone is positioned too far from the sample surface, substantial energy is dissipated due to absorption and scattering within the liquid matrix, especially in foods with high viscosity or limited optical transparency. This attenuation diminishes cavitation intensity and leads to inefficient processing (Petkovšek et al. 2020). Conversely, placing the cavitation zone too close increases the risk of localized overheating and confined thermal effects, which can degrade heat-sensitive nutrients, alter texture, and negatively affect sensory attributes (Chavan et al. 2023; Patel et al. 2022; Teng et al. 2021).

Optimal performance depends on balancing mechanical energy transfer and minimizing thermal damage. Research suggests maintaining a distance of approximately 1–2 cm between the cavitation zone and the food surface achieves this balance across a range of liquid foods (Petkovšek et al. 2020). However, this distance must be adjusted based on the specific characteristics of the food matrix, including viscosity, optical transparency, and thermal sensitivity. High viscosity or opaque liquids require closer cavitation focus to counteract energy losses, while thermally labile products need greater distance and precise temperature control. The intended application also guides distance optimization. Processes requiring gentle mixing or emulsification may tolerate larger cavitation-to-sample distances to avoid excessive

heating. Sterilization demands more intense cavitation effects achievable through closer positioning, often complemented by integrated cooling systems (Chavan et al. 2023; Teng et al. 2021). Careful control of this distance, combined with real-time monitoring of temperature, pressure, and flow, ensures uniform cavitation energy distribution and maximizes the efficacy and safety of LC in food processing.

3.5.2 | Operation Mode

LC systems in liquid food processing typically operate in two primary modes: pulsed and continuous, distinguished by the temporal pattern of laser energy delivery. Pulsed operation delivers the laser in short, high-intensity bursts ranging from microseconds to milliseconds. This produces localized, transient cavitation with confined heating, ideal for applications requiring intense but controlled cavitation, such as sterilization and selective extraction (Nagalingam, Toh, et al. 2023). High peak power generates stronger cavitation bubbles capable of disrupting microbial cells or releasing intracellular compounds while minimizing excessive thermal damage. Pulsed LC is especially suited for matrices with moderate to high optical transparency, where precise energy deposition maximizes cavitation efficiency without overheating. Continuous mode delivers a constant laser beam to the cavitation zone. This facilitates uniform, sustained cavitation, making it suitable for emulsification and pasteurization, where consistent mechanical disruption or pathogen reduction over larger volumes is required (Burfoot et al. 2017). Continuous lasers provide lower peak power but longer energy exposure, benefiting viscous or optically dense liquids by enabling gradual energy penetration and uniform bubble generation. However, continuous operation requires robust cooling and real-time control to prevent thermal degradation (Albanese and Meneguzzo 2019; Arya et al. 2023; Teng et al. 2021). Studies suggest pulsed lasers excel in high-intensity, localized cavitation applications, while continuous mode ensures even treatment in large-scale or continuous flow processes. Selecting the appropriate operating mode depends on food matrix properties, balancing cavitation intensity, and thermal management to optimize quality and efficiency (Arya et al. 2023; Teng et al. 2021).

3.5.3 | Power Intensity and Impact Times

Laser power intensity, typically expressed in W/cm^2 , fundamentally influences cavitation intensity and effectiveness in food processing. Higher intensities generate stronger cavitation forces by producing vigorous bubble formation and collapse, enhancing mechanical effects such as homogenization and emulsification (Biryukov et al. 2022). Excessive power risks thermal degradation in heat-sensitive foods, altering nutrient profiles, flavor, and texture. Very high power can also cause rapid bubble collapse, diminish cavitation efficiency and lead to inconsistent outcomes. The temporal aspect (pulsed or continuous) impacts cavitation dynamics: pulsed lasers produce intense, transient events ideal for rapid microbial inactivation without prolonged heating (Chavan et al. 2022). Continuous operation at lower intensities offers sustained cavitation suitable for gentle mixing in emulsification (Rostamabadi et al. 2023). The duration of laser exposure must be carefully balanced. Extended irradiation enhances cavitation

but raises thermal damage risk, particularly in thermally sensitive or low-optical-transparency foods. Empirical studies suggest an effective range of 10–50 W/cm² for various food applications, depending on viscosity and absorption characteristics (Chavan et al. 2022). Controlling both power intensity and exposure duration is essential to maximize cavitation efficiency while preserving quality, requiring advanced cooling and real-time monitoring (Biryukov et al. 2022; Rostamabadi et al. 2023).

3.5.4 | Spot Size

Spot size, defined as the laser beam diameter at the focal point, determines the spatial distribution and intensity of energy in the cavitation chamber. Smaller spot sizes concentrate energy into a localized area, producing intense cavitation forces. This promotes microscale mechanical disruption, beneficial for high-precision applications such as emulsification or targeted microbial inactivation in thermally sensitive liquids (Udepurkar et al. 2023). Spot sizes below 1 mm produce pronounced cavitation due to dense energy focus. Larger spot sizes (2–5 mm) distribute energy over a broader area, resulting in more uniform cavitation suitable for large volumes or continuous flow systems. Uniformity prevents localized overheating, ensuring consistent product quality in viscous or less transparent liquids (Arya et al. 2023; Chavan et al. 2023; Sutariya et al. 2018). Spot size selection should consider thermal sensitivity, optical transparency, and rheology of the food matrix. Smaller spots risk localized heating, while larger spots mitigate this. Optimal spot size balances cavitation intensity with uniform energy distribution, preserving food integrity. Advances in laser optics and fiber delivery systems continue to refine spot size control, enhancing versatility and scalability (Udepurkar et al. 2023; Arya et al. 2023).

3.5.5 | Running Costs

Laser power and exposure duration influence both effectiveness and operational costs. High-intensity lasers improve homogenization, emulsification, and microbial inactivation, but prolonged or excessive exposure may cause thermal damage in sensitive foods (Biryukov et al. 2022; Chavan et al. 2022). Pulsed lasers deliver energy in short bursts, producing intense cavitation with minimal thermal diffusion, making them ideal for quality-critical treatments (Nagalingam, Raghunathan, et al. 2023). Continuous wave (CW) lasers provide steady input for large volumes but increase cumulative thermal load (Arya et al. 2023). Operational costs include energy, maintenance, consumables, and labor. Pulsed systems consume 1–3 kWh/h depending on power and duty cycle, whereas continuous systems (500–1000 W) consume 5–10 kWh/h (Carpenter et al. 2017; Fujisawa 2022). Cooling systems, essential for preventing thermal buildup during both pulsed and continuous operation, also contribute to energy consumption, typically requiring 1–2 kWh per hour depending on system size and design. Annual maintenance for small-to-medium systems ranges from \$1000 to \$3000, with additional costs for cooling, consumables, and labor. Total annual running costs for small-scale pulsed systems fall between \$2500 and \$5000, while larger continuous systems may reach \$10,000–\$25,000. Despite high initial investment (\$50,000–\$200,000), LC systems

become competitive with optimized energy usage and cooling (Tiang et al. 2024).

3.5.6 | Product Type

The effectiveness of LC strongly depends on the type of product being treated, as different food matrices respond differently to laser energy. Physical properties such as opacity and viscosity, along with chemical composition including sugars, lipids, proteins, and salts, can significantly influence the efficiency of LC. Liquid foods such as juices, milk, and soups usually allow better laser penetration and more uniform energy distribution, especially when they have lower viscosity and greater optical transparency. These conditions enable more effective cavitation and energy absorption even at lower laser intensities and smaller spot sizes (Albanese and Meneguzzo 2019). This helps improve emulsification, microbial inactivation, and stability without compromising nutritional quality (Askarniya et al. 2023; Xu et al. 2022). For example, laser treatment of raisin and pomegranate juices preserved sugar content and improved clarity or membrane filtration efficiency (Alaboudi et al. 2022; Salehinia et al. 2021). In goat milk, UV laser exposure achieved microbial inactivation with minimal effects on protein and fat content (Kasahara et al. 2015). Similarly, bovine milk maintained its sugar and lipid profiles even though it has higher opacity (Smith et al. 2002). Opacity plays an important role in how much energy reaches inside the sample. More turbid liquids like cow milk require higher energy due to increased light scattering. In one study, Nd:YAG laser exposure reduced pathogens in milk while keeping salt and sugar levels largely unchanged, though slight changes in viscosity were observed due to protein modifications (Yasmin et al. 2017). Another study using diode lasers on natural milk showed that high turbidity and protein concentration demand more energy for effective treatment compared to clearer and lower-viscosity liquids such as wastewater (Gonca et al. 2023). Viscosity also affects how cavitation forms and spreads. High-viscosity foods may resist uniform cavitation and require different treatment conditions. For instance, in konjac glucomannan solution, laser exposure significantly reduced molecular weight and viscosity, showing that viscous polysaccharides are highly sensitive to laser energy (Lin et al. 2019). In contrast, beer with moderate turbidity and sugar content responded well to pulsed UV laser treatment without major changes in its main components (Hosseini et al. 2011). The chemical makeup of the food, including sugars, fats, proteins, and salts, also influences how it reacts to laser energy. These components affect not only how energy is absorbed but also how the quality of the food is preserved. For example, chlorophyll-rich extracts like papaya leaf, which have both pigmentation and low viscosity, served effectively in microbial inactivation through laser exposure (Astuty et al. 2019). In more complex matrices like milk, LC treatment was able to achieve sterilization with minimal changes to viscosity, protein, or fat content, although higher opacity increased the energy needed for effective processing (Zheng et al. 2020). In conclusion, the success of LC treatment is highly dependent on the product type. Properties such as transparency, viscosity, and chemical composition directly influence how the laser interacts with the food. Therefore, laser parameters must be carefully optimized based on the unique characteristics of each food matrix to ensure both microbial safety and the preservation of quality.

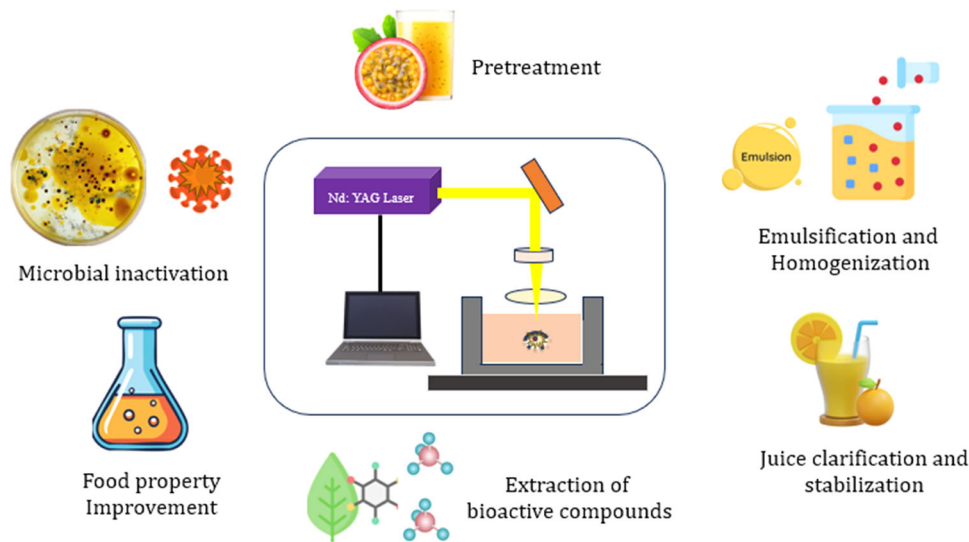


FIGURE 3 | Laser cavitation applications in liquid food processing.

3.5.7 | Product Depth

Product depth, or sample thickness, critically determines how effectively LC treats liquid or semiliquid matrices. Shallow products (juices, thin suspensions) allow cavitation zones close to the surface, requiring lower power and shorter pulses without inducing excessive thermal damage. Lower viscosity further facilitates energy transfer and bubble dynamics for effective homogenization or microbial inactivation. Deeper or bulk samples (thick sauces, purees) present challenges: optical transparency limits laser penetration, and energy absorption per unit volume decreases. High viscosity dampens bubble expansion and collapse, while thermal sensitivity requires balancing cavitation intensity with heat management. Strategies include increasing laser power or pulse energy, using multiple passes, adjusting pulse duration, selecting suitable wavelengths, and integrating cooling or thermal control. Residence time or slowed flow can ensure deeper regions receive sufficient cavitation without overheating near the surface. Empirical studies by Chavan et al. (2023) and Arya et al. (2023) emphasize that product depth interacts with other parameters such as spot size, distance, mode, and intensity, and no universal setting exists. Proper tailoring of laser parameters according to energy absorption, viscosity, optical transparency, and thermal sensitivity ensures uniform treatment and preserves quality.

4 | Applications of LC Technology in Food Processing

This section focuses exclusively on liquid and semiliquid food systems, including milk, juices, beverages, and emulsions. References to solid-food examples are included only where scientifically adaptable to liquid matrices. Table 4 illustrates the optimal LC parameters for liquid food processing. The utility of cavitation in liquid food processing is well established in hydrodynamic systems (Arya et al. 2023; Zoglopiti et al. 2025), and laser-induced cavitation offers a more tunable approach. Figure 3 represents the LC applications in liquid food processing. For example, Zheng et al. (2020) demonstrated effective microbial inactivation in

liquid media, supporting its use in sterilizing juices, milk, and other beverages. Laser parameters such as wavelength, pulse duration, spot size, and energy intensity must be optimized for liquid matrices. High-absorption wavelengths in water-rich media, particularly in the NIR and UV ranges, are effective for initiating cavitation and energy transfer (Kishore et al. 2024). Fluid properties such as refractive index and viscosity influence bubble dynamics, which are critical for uniform treatment in emulsified beverages and soups. Raman et al. (2022) explored the use of single cavitation bubbles to generate microemulsions, highlighting applications in homogenizing milk or formulating stable functional beverages with nano-dispersed bioactives. While earlier reviews have broadly covered laser applications in food (Teng et al. 2021; Chavan et al. 2023), none have specifically focused on LC. Emerging applications include nutrient extraction from plant-based juices, microbial inactivation in dairy products, and emulsion improvement. Laser systems can be designed for both batch and continuous flow setups, offering scalability for industrial processing. Stebeleva and Minakov (2021) discuss cavitation reactor designs in oil systems, insights from which can be adapted for high-viscosity fluids such as broths and emulsions. Transitioning from laboratory-scale studies to industrial applications requires addressing fluid-specific challenges such as flow turbulence, bubble coalescence, and energy dispersion in high-throughput environments. Hybrid systems involving liquid–solid interfaces, such as laser treatment of surface-contaminated packaging fluids or soups with particulates, can further enhance microbial inactivation or enable targeted nutrient extraction, providing a multidimensional processing strategy.

4.1 | Pretreatment

Laser-induced cavitation pretreatment is an emerging, precise, noncontact, and sustainable approach for improving processing efficiency and quality of liquid and semiliquid foods, including milk, juices, broths, soups, and beverages. Laser systems deliver localized energy, unlike conventional thermal pretreatments, enabling targeted disruption of microstructures at or near the liquid–solid interface. This precision is critical in systems where

TABLE 4 | Optimal laser cavitation parameters for liquid food processing.

S. no.	Product	Laser type	Operating conditions	Key findings	References
1	Wastewater and natural milk	Diode laser (visible)	<ul style="list-style-type: none"> Laser power: 1 W Treatment time: 60–180 s 	<ul style="list-style-type: none"> Effective microbial inactivation achieved. Milk (higher turbidity) showed reduced penetration compared to clearer wastewater Low transparency and strong scattering limit laser penetration depths Demonstrates the trade-off: laser systems may function for both high- and low-turbidity liquids, but scattering and absorption dominate in opaque fluids 	Gonca et al. (2023)
2	Chlorophyll extract (papaya leaf)	Diode laser (visible) + photosensitizer	<ul style="list-style-type: none"> $\lambda = 650$ nm Energy density = 20–40 J/cm² 	<ul style="list-style-type: none"> Chlorophyll (or photosensitizer) strongly absorbs visible light. The opaque and turbid suspension benefits from enhanced energy coupling via photosensitizer Promising for photodynamic-like action in complex matrices 	Astuty et al. (2019)
3	Konjac glucomannan solution	Laser + H ₂ O ₂ -assisted degradation	<ul style="list-style-type: none"> Laser power: 10 W Treatment durations: 0–6 min 	<ul style="list-style-type: none"> Viscosity decreases with exposure, indicating breakdown of the polymer network At low solute concentrations, the solution becomes more transparent. Improving light penetration, but at higher viscosity, scattering reduces efficiency Optical properties can be tuned, and optimal conditions can yield significant degradation 	Lin et al. (2019)
4	Cow milk	Nd:YAG laser (1064 nm)	<ul style="list-style-type: none"> Power: 0.5–2 W Irradiation time: 5–20 s 	<ul style="list-style-type: none"> Pathogen inactivation was successful using near-IR (1064 nm) Near-IR light penetrates turbid media better than UV. However, fat and protein scattering still pose challenges Nd:YAG (1064 nm) is a favorable for nonthermal sterilization in turbid liquids 	Yasmin et al. (2017)
5	Goat milk	Pulsed UV light (laser source)	<ul style="list-style-type: none"> Beam area: ~3 cm² <ul style="list-style-type: none"> Dose: 10,000 mJ/cm² (60 pulses) $\lambda = 248$ nm; pulse frequency = 20 Hz 	<ul style="list-style-type: none"> Achieved ~6 log reduction of <i>Escherichia coli</i> Goat milk is less turbid than cow milk, which aids UV penetration Sensory and nutritional quality largely preserved, indicating UV laser pulsed treatment is viable nonthermal method for lower-turbidity dairy systems 	Kasahara et al. (2015)

(Continues)

TABLE 4 | (Continued)

S. no.	Product	Laser type	Operating conditions	Key findings	References
6	Fruit juice (raisin)	Visible laser + thermal pasteurization	<ul style="list-style-type: none"> • $\lambda = 650$ nm • 50–70 mW + heat at 85°C for 30 s 	<ul style="list-style-type: none"> • Posttreatment, pH and Brix changed due to thermal and photochemical interactions • More transparent juices showed better laser penetration. Turbid juices absorbed more laser energy near the surface, limiting depth effect • Combining visible laser with mild heat can synergistically enhance pasteurization, better suited to relatively clear juices 	Alaboudi et al. (2022)
7	Orange juice (water extract)	Laser-induced breakdown spectroscopy (LIBS)	<ul style="list-style-type: none"> • Pulsed laser to generate plasma 	<ul style="list-style-type: none"> • Presence of pulp and turbidity increases light absorption and scattering, reducing the consistency and intensity of plasma signals • LIBS remains effective for real-time compositional analysis in complex juice matrices 	Boussaidi (2012)
8	Bovine milk	Pulsed UV laser (excimer)	<ul style="list-style-type: none"> • ~ 25 J/cm² • $\lambda = 248$ nm 	<ul style="list-style-type: none"> • Achieved cold pasteurization (pathogen inactivation) in thin films • UV absorption and scattering limit penetration depth, so thin sample thickness is essential • Demonstrates the feasibility of nonthermal sterilization under controlled conditions 	Smith et al. (2002)
9	Nonalcoholic beer	Pulsed UV laser	<ul style="list-style-type: none"> • $\lambda = 355$ nm at 100 J/cm² (1-log kill) • $\lambda = 266$ nm at 40–60 J/cm² (6-log kill) 	<ul style="list-style-type: none"> • 266 nm UV was significantly more effective per dose than 355 nm in inactivating <i>E. coli</i> and yeasts • Moderate transparency of beer allows deeper penetration • Shorter-wavelength UV is more potent even in semi-transparent beverage systems 	Hosseini et al. (2011)
10	Acidic beverages (immersion study)	Nd:YAG laser (post-irradiation)	<ul style="list-style-type: none"> • Indirect/immersion mode 	<ul style="list-style-type: none"> • In acidic, low-viscosity liquids, light-material interactions are more favorable • Physical properties (viscosity, absorption) influence the laser's effect on surface/material interactions 	Naylor et al. (2006)

(Continues)

TABLE 4 | (Continued)

S. no.	Product	Laser type	Operating conditions	Key findings	References
11	Pomegranate juice (membrane clarification)	Continuous laser irradiation	<ul style="list-style-type: none"> Laser: 1 W, $\lambda = 532$ nm MF membrane PVDF, pore size = 0.22 μm Best conditions: 0.5 bar Flow rate = 10 mL/s Vertical alignment, large exposure surface 	<ul style="list-style-type: none"> Laser improved permeate flux by reducing total resistance Reversible fouling resistance dropped from ~ 56.6 % (without laser) to ~ 4.6 % (with laser) Share of irreversible fouling and cake resistance increased (67.6 % and 21.9 %, respectively) but total resistance was lower Laser altered the blocking index over time and led to transitions to standard or intermediate blocking in late stages Physicochemical parameters (turbidity, phenolics, anthocyanins, acidity, EC₅₀, pH) were only marginally affected: e.g., percentage rejection of TSS was 12.94 % (with laser) vs. 17.00 % (without); turbidity removal ~ 99.8 % (with laser) vs. 99.1 % (without) 	Salehinia et al. (2021)

heat-sensitive nutrients and volatile flavor compounds must be preserved, commonly in fresh juices, dairy-based drinks, and functional beverages (Chavan et al. 2023; Teng et al. 2021). In liquid–solid matrices (such as pulp-enriched juices or soups with particulate matter), LC pretreatment can selectively perforate or weaken cell walls and cuticles of suspended solids (e.g., berry skins or vegetable fibers), enhancing mass transfer and bioactive compound extraction without affecting the bulk liquid (Teng et al. 2021; Arya et al. 2023). Qu et al. (2022) and Munzenmayer et al. (2020) applied CO₂ lasers to create micro-perforations in whole fruits before drying. The mechanism enhanced moisture diffusion through selective perforation, which can be adapted to liquid systems such as juice slurries or emulsified beverages, where laser pretreatment may improve yield and reduce drying or concentration time. The same principle applies to soups or emulsified sauces containing skin-on ingredients or encapsulated nutrients. In juice clarification, Salehinia et al. (2021) demonstrated that laser pretreatment can significantly improve the efficiency of membrane filtration processes, as shown in their work with pomegranate juice. Laser exposure helped reduce membrane fouling and increased permeate flux, ultimately enhancing the clarification performance without compromising juice quality. This highlights the potential of laser technologies in reducing filtration bottlenecks in viscous or particulate-rich juices.

The noncontact nature of laser pretreatment also enhances hygienic control, a key concern in liquid food processing. Laser beams can be delivered remotely through transparent windows or fiber optics, where there is no direct interaction with the food, eliminating physical contamination risks (Velooso et al. 2021; Chavan et al. 2023). The recent studies have explored the

generation of microbubbles and cavitation phenomena in liquids through laser pulses, further expanding the relevance of laser pretreatment in fluid systems. Alaboudi et al. (2022) reported that visible laser treatment can alter key quality parameters in raisin juice, while Boussaidi (2012) used laser-induced plasma to potentially sterilize orange juice extracts. In nonalcoholic beer, pulsed UV lasers effectively inactivated *Escherichia coli* and *Saccharomyces cerevisiae*, showing clear relevance in beverage sterilization (Hosseini et al. 2011). Nd:YAG laser treatment has been shown to alter substrate surfaces such as dentin, even in the context of acidic beverages, providing a basis for understanding laser-liquid interactions in acidic matrices (Naylor et al. 2006). Moreover, laser systems offer energy-efficient processing, particularly when integrated with fluid dynamics. Hydrodynamic cavitation has been widely studied for liquid food treatment (Arya et al. 2023; Zoglopiti et al. 2025), and laser-induced cavitation offers similar benefits but with finer spatial and temporal control. This level of control allows process intensification for sensitive fluids where traditional cavitation or thermal methods may be too aggressive. Stebeleva and Minakov (2021) noted that cavitation efficiency depends on fluid viscosity and interface characteristics, insights that directly apply to soups, sauces, and pulpy beverages. In addition, LC processing in liquids has implications for the integration of nanotechnology in food systems.

Sreekala et al. (2025) explored the generation of nano-colloids in liquid environments using laser ablation as a mechanism that could be adapted for creating nutrient-loaded colloidal suspensions in functional beverages or nutritional broths. In bioactive systems, diode lasers paired with chlorophyll extract (e.g., papaya leaf) have shown strong antimicrobial photodynamic effects

against biofilms such as *Candida albicans* (Astuty et al. 2019), offering potential in minimally processed functional foods. Similarly, laser-assisted degradation of konjac glucomannan using H₂O₂ has been shown to modify the physicochemical properties of this soluble fiber, suggesting further applications in thickened beverages or gut-health formulations (Lin et al. 2019). Laser pretreatment also supports inline sensing and quality monitoring. Technologies like laser-induced breakdown spectroscopy (LIBS) allow real-time composition analysis of liquid or semiliquid food products without sample destruction (Lim et al. 2025). This opens avenues for continuous monitoring of juice sugar levels, milk fat content, or broth salinity during processing, enhancing both quality control and traceability. In summary, while many prior applications of laser pretreatment have been demonstrated on solid foods, the underlying principles, such as selective energy delivery, cavitation, and noncontact precision, are fully translatable and arguably even more advantageous in liquid and interface-rich food systems. Laser pretreatment offers a novel, scalable, and sustainable strategy for improving the efficiency, safety, and quality of fluid foods, with promise in clean-label and minimally processed beverage development.

4.2 | Microbial Reduction

LC is gaining attention as a nonthermal, noninvasive method for microbial inactivation in liquid and semiliquid foods such as milk and fruit juices. This technique involves exposing microorganisms directly to high-intensity, coherent laser light, with key parameters such as wavelength, pulse duration, beam diameter, and power density governing the mode and efficiency of microbial reduction (Teng et al. 2021; Chavan et al. 2023). Table 3 represents the effect of laser irradiation on microorganisms. In fluid foods, where uniform thermal distribution is often challenging, laser treatment offers rapid, localized photothermal effects that target microbial contaminants while minimizing damage to heat-sensitive nutrients. Lasers operating in the visible and NIR spectra (400–800 nm) can disrupt bacterial cell structures and viral capsids through mechanical vibrations and local energy absorption. Pulsed lasers in this range can induce transient, nonequilibrium photothermal effects that break down microbial membranes without continuous heating. Kohmura et al. (2020) reported a 3-log reduction in *E. coli* using nanosecond-pulsed 532 nm lasers within 10 min at only 50 kJ/cm², demonstrating high antimicrobial efficiency without bulk heating.

This technology has been applied with promising results across different types of milk. In cow milk, Yasmin et al. (2017) utilized an Nd:YAG laser to inactivate foodborne pathogens, including *E. coli* and *S. aureus*, achieving microbial reduction while preserving nutritional and sensory properties. Similarly, Smith et al. (2002) used pulsed UV laser light for bovine milk pasteurization, showing that cold laser treatment could achieve microbial control without affecting product quality. For goat milk, Kasahara et al. (2015) demonstrated that pulsed UV laser light was effective against *E. coli*, showing the method's applicability beyond conventional cow-based dairy. Gonca et al. (2023) examined the effect of a 450 nm blue diode laser on both natural milk and wastewater, achieving microbial inhibition rates of 65.9% for *Staphylococcus aureus*, 34.5% for *E. coli*, and 43.6% for *C. albicans* in natural milk. The blue wavelength outperformed red and green lasers,

likely due to stronger absorption in microbial chromophores and intracellular components.

Beyond milk, laser microbial inactivation has shown effectiveness in fruit juices, nonalcoholic beer, and specialty functional beverages. Alaboudi et al. (2022) observed that visible laser irradiation effectively reduced microbial load in raisin juice while preserving organoleptic and nutritional quality. Boussaidi (2012) also demonstrated laser-induced plasma characterization of orange juice, providing insights into in situ monitoring during laser treatment. In beer, Hosseini et al. (2011) achieved microbial reduction in nonalcoholic formulations using pulsed UV lasers while maintaining sensory attributes. Astuty et al. (2019) explored diode lasers combined with papaya leaf chlorophyll for photodynamic inactivation of *C. albicans* biofilms. Lin et al. (2019) demonstrated that konjac glucomannan solutions treated with laser plus hydrogen peroxide underwent physicochemical changes that also contributed to microbial safety. Laser-induced cavitation has emerged as a potent nonthermal antimicrobial mechanism, creating shockwaves that mechanically rupture microbial membranes (Zheng et al. 2020; Kishore et al. 2024). The noncontact nature of laser treatment further minimizes recontamination risk, making it suitable for clean-in-place (CIP) systems in liquid food processing.

4.3 | Improvement of Food Properties

Laser-induced cavitation technology has shown significant potential for improving food properties through precise, localized, and controllable energy delivery, especially in fluid and semifluid food systems such as soups, sauces, dairy emulsions, and protein beverages. Unlike conventional bulk heating, laser-based processing enables fine spatial and temporal control of heat application, allowing targeted modulation of viscosity, texture, protein conformation, and flavor development (Blutinger, Meijers, and Lipson 2019). Laser parameters (such as wavelength, power, scan speed, and spot size) can be precisely tailored to control heat penetration depth, a factor critical in layered or viscous liquid products. Depth-specific thermal gradients induced by lasers may regulate phase separation, particle dispersion, or protein gelation, ultimately enhancing the homogeneity and mouthfeel of dairy-based smoothies, gravies, or fortified soups. NIR and mid-infrared (MIR) lasers have been shown to induce surface and subsurface browning, which can be exploited in packaged liquid meals to enhance flavor and aroma without damaging heat-sensitive bioactives (Blutinger, Meijers, Chen, et al. 2019).

Laser treatment has also been reported to enhance membrane filtration efficiency in fruit juice processing. Salehinia et al. (2021) investigated the application of laser treatment on pomegranate juice before membrane clarification, finding improved juice clarity and filtration efficiency by altering suspended particle properties, reducing membrane fouling, and enhancing permeate flux. In dairy systems, laser processing shows notable promise. Smith et al. (2002) demonstrated pulsed UV laser light for cold pasteurization of bovine milk, maintaining safety and nutritional quality. Kasahara et al. (2015) achieved effective *E. coli* inactivation in goat milk using pulsed UV lasers, while Yasmin et al. (2017) applied Nd:YAG lasers to cow milk, improving microbial safety

without compromising nutritional or sensory attributes. Laser-induced cavitation and microjet formation mechanisms are vital in improving homogenization and stability of emulsified systems, stabilizing globule size, and enhancing interfacial mixing in milk-based drinks, plant-protein beverages, and oil-containing broths (Raman et al. 2022; Kishore et al. 2024). Advancements in software-controlled laser systems and image-guided pattern recognition (Fukuchi et al. 2012) may also enhance spatial targeting during cavitation-based processing, enabling controlled structuring of gel-like or layered liquid products.

4.4 | Enhancement of Nutritional Quality

Laser-based technologies are gaining prominence as nondestructive tools for enhancing the nutritional quality in liquid and semiliquid foods. These techniques also enable real-time evaluation of chemical and physical properties such as sugar content, viscosity, bioactive compound concentration, and antioxidant levels (Lim et al. 2025; Chavan et al. 2023). LC treatment can induce selective extraction of bioactive compounds from suspended particles in juices or soups by weakening cell walls of plant tissue, thereby improving the overall nutrient density without compromising flavor (Arya et al. 2023). Pulsed laser treatment can also stabilize heat-sensitive vitamins and polyphenols, unlike conventional thermal methods, which often lead to degradation (Zoglopiti et al. 2025). LC can further improve the functional properties of proteins and polysaccharides in beverages and soups, enhancing the digestibility and bioavailability of nutrients. Laser-assisted photodynamic treatment using natural photosensitizers (e.g., chlorophyll extract) has been demonstrated to selectively inactivate microbes while preserving bioactive compounds, an approach suitable for functional beverages and nutraceuticals (Astuty et al. 2019).

4.5 | Extraction of Bioactive Compounds

LC has proven effective for the extraction of bioactive compounds from plant-based liquid systems. The mechanism involves laser-induced micro-perforations and cavitation, facilitating enhanced mass transfer and release of phytochemicals, pigments, and antioxidants (Teng et al. 2021; Qu et al. 2022). For example, in pulp-rich fruit juices, laser exposure increases the release of polyphenols, flavonoids, and carotenoids without the need for high temperatures, maintaining nutritional and sensory quality (Munzenmayer et al. 2020). Laser-assisted extraction has also been applied to emulsified systems where bioactive compounds are embedded in oil droplets or fiber matrices. By optimizing wavelength, pulse duration, and energy density, selective release of bioactives can be achieved while minimizing degradation (Sreekala et al. 2025). This approach is particularly valuable in functional beverage production, where targeted nutrient enrichment and preservation of organoleptic properties are critical.

4.6 | Emulsion and Rheology Modification

Laser-induced cavitation is increasingly explored for the stabilization and modification of emulsions in food systems. Microbubble formation and controlled shockwaves improve mixing and

droplet size distribution, enhancing emulsion stability in dairy, plant-based, and protein-fortified beverages (Raman et al. 2022; Kishore et al. 2024). Laser treatments can also alter rheological properties of semi-solid and viscous liquids, modulating viscosity and gel strength in soups, sauces, and yogurt-like products. NIR and pulsed UV lasers have been used to induce targeted structural modifications at the microlevel without compromising macro-level texture (Blutinger, Meijers, Chen, et al. 2019). Such precise control over droplet interface and fluid mechanics enables enhanced mouthfeel, uniformity, and functional delivery of nutrients and bioactive compounds in complex liquid matrices. Laser-induced cavitation, characterized by rapid bubble expansion and collapse, can be employed to enhance homogenization or assist in emulsification processes (Zheng et al. 2020; Kishore et al. 2024). This is particularly important in the production of nano-emulsions for functional drinks. Raman et al. (2022) demonstrated that single laser-induced cavitation bubbles can drive micro-emulsification, a technique directly applicable to stabilizing fat-water interfaces in dairy drinks or enriched fruit beverages.

5 | Comparative Analysis of LC, Ultrasonication, and Hydrodynamic Cavitation in Liquid Food Processing

This section provides a quantitative comparison of LC, ultrasonication, and hydrodynamic cavitation based on microbial log reduction, nutrient retention rates, and physicochemical changes reported in various studies. Laser-induced cavitation, as reported by Zheng et al. (2020), achieved approximately 1.0-log reduction of foodborne bacteria in milk using a microfluidic chip setup. Gonca et al. (2023) applied a diode laser to natural milk and obtained up to 3 log reductions for *E. coli* and *S. aureus*, with even higher reductions reaching 4.5 logs in wastewater due to better light penetration. Kasahara et al. (2015) demonstrated a more intense pulsed UV light treatment achieving a 6-log reduction of *E. coli* in goat milk, which is higher than typical LC treatments while still nonthermal. Smith et al. (2002) reported microbial reductions ranging from 2.5 to 5 logs in bovine milk using pulsed UV lasers. Yasmin et al. (2017) also showed significant microbial inactivation with Nd:YAG lasers, although exact log reductions were not specified. In comparison, ultrasonication exhibited higher microbial efficacy, with Khan et al. (2022) achieving 3- to 5-log reductions in pathogens across milk, juices, and emulsions depending on amplitude and exposure time. Hydrodynamic cavitation, notable for its scalability, demonstrated up to 5-log microbial inactivation in liquid foods as reported by Jadhav (2025).

LC excels in nutrient preservation due to its localized and brief cavitation events. Zheng et al. (2020) found proteins, fats, and vitamins remained stable after treatment. Alaboudi et al. (2022) reported that laser-treated raisin juice retained 92% of total phenolics, compared to only 78% retention in thermally pasteurized samples, with minimal changes in color and pH. Ultrasonication improves functional properties such as emulsification and bioactive retention but carries the risk of degrading sensitive nutrients if exposure is excessive (Khan et al. 2022). Trishitman (2025) combined US with forward osmosis in pomegranate juice, achieving significant viscosity reduction, increased concentration

rate, improved bioactive retention, enhanced sensory attributes, and shelf-life extension by up to 14 days. Hydrodynamic cavitation induces more pronounced physicochemical changes. Datla et al. (2025) reported a 38% reduction in turbidity, a 15% increase in total phenolics, and an 18%–22% rise in antioxidant activity, alongside a pH decrease from 5.5 to 4.8. These effects are attributed to enhanced cell wall rupture and release of bound compounds. Pandey et al. (2025) further demonstrated its effectiveness in droplet breakup and emulsification, highlighting potential for homogenization applications.

LC is notably gentle on physicochemical properties, causing negligible changes to pH, viscosity, or protein structure (Zheng et al. 2020). Ultrasonication can reduce viscosity and particle size while enhancing homogenization and solubility, but may slightly increase acidity with long exposure (Khan et al. 2022). Hydrodynamic cavitation has stronger effects, including pH reduction and increased antioxidant activity (Datla et al. 2025). For example, Lin et al. (2019) used LC with hydrogen peroxide to reduce the molecular weight and viscosity of konjac glucomannan by over 40%, demonstrating how photonic cavitation can be tailored for functional structuring rather than sterilization. In beverages, laser and ultrasonic cavitation both preserve antioxidants better than thermal treatments. Hosseini et al. (2011) reported over 4 log reductions of *E. coli* and *S. cerevisiae* in beer using a pulsed UV laser, indicating effectiveness in clear beverages. Naylor et al. (2006) noted that laser irradiation altered micromorphological features in acidic beverages without significantly changing chemical composition.

While all three cavitation methods share nonthermal principles, their performance varies quantitatively across key metrics. LC offers highly precise and gentle treatment with microbial reductions around 1–3 logs and near-complete nutrient preservation, making it ideal for delicate liquids like milk. However, its scalability and cost may limit broader application. Ultrasonication provides a balance between microbial inactivation (3–5 logs) and functional benefits such as emulsification and concentration, but requires careful energy control to avoid nutrient damage. Hydrodynamic cavitation excels in microbial efficacy and scalability, delivering up to 5-log reductions alongside improvements in clarity, antioxidant content, and product stability, making it well-suited for large-scale juice and emulsion processing. Ultimately, LC leads in precision and nutrient retention, making it the preferred choice when product quality and sensitivity are paramount.

6 | Challenges in LC Technology

6.1 | Challenges in Scaling Up

Scaling up LC systems from laboratory-scale experiments to industrial production environments presents several critical challenges. In small-scale systems, a single laser source can effectively generate cavitation within a limited sample size (H. Sun et al. 2023; Kishore et al. 2024). However, for industrial applications, it is necessary to distribute laser energy uniformly across larger volumes of food to ensure consistent cavitation effects (Teng et al. 2021; Chavan et al. 2023). This requires precise adjustment of laser power, beam delivery methods, and pulse parameters to

avoid uneven treatment, which can affect product quality. In addition, industrial-scale processing demands significantly higher throughput. The system must be capable of handling larger batches or continuous flows of food, which necessitates redesigning cavitation chambers and optimizing operational speed to maintain efficiency without causing excessive downtime (Sarraf et al. 2022; Arya et al. 2023). Table 2 summarizes a few factors to be considered during the scaling up of the LC system with potential solutions. Another major challenge lies in integrating LC systems with existing industrial food processing lines. This integration involves adapting the laser system to work seamlessly alongside equipment such as mixers, conveyors, and packaging units (Chavan et al. 2023; Zoglopiti et al. 2025). Ensuring compatibility and synchronization is essential to maintain smooth operation and prevent bottlenecks. Furthermore, industrial environments impose stringent requirements on the durability and longevity of LC systems. Laser components and optical assemblies must be robust enough to withstand continuous use, mechanical vibrations, and exposure to food residues. Minimal maintenance frequency and ensuring ease of repairs are crucial to sustaining high throughput and reducing operational costs (Chavan et al. 2023; Sreekala et al. 2025).

The translation of LC technology from the lab to commercial food processing settings involves addressing both technical and operational factors. One important consideration is the customization of LC parameters based on the specific food product being processed. Different products have varying textures, compositions, and sensitivities, which influence how cavitation impacts quality and safety (Zheng et al. 2020; Raman et al. 2022). Therefore, laser settings and chamber designs need to be tailored to preserve product integrity while achieving effective treatment (Lim et al. 2025). Process validation and regulatory compliance are also key aspects of industrial translation. The demonstration of consistent microbial inactivation, nutrient retention, and sensory quality at scale is essential to meet food safety standards and gain regulatory approval (Zoglopiti et al. 2025; Kishore et al. 2024). Moreover, the high capital cost associated with industrial laser systems necessitates a clear demonstration of return on investment, such as improved processing efficiency, product quality, or energy savings (Arya et al. 2023; Teng et al. 2021). The decisions on whether to retrofit existing production lines or invest in new equipment will affect adoption feasibility. The introduction of laser technology to industrial settings also requires comprehensive operator training and the implementation of strict safety protocols to manage potential laser hazards and maintain operational reliability (Chavan et al. 2023). Finally, successful industrial deployment depends on establishing robust support infrastructure, including spare parts supply chains, maintenance services, and technical assistance. These support systems are vital for minimizing downtime and ensuring the long-term sustainability of LC processes in food manufacturing (Sreekala et al. 2025).

6.2 | Industrial-Scale Designs

Scaling laser-induced cavitation systems to industrial levels presents several critical challenges that must be addressed to ensure consistent, efficient, and safe food processing. One major issue is achieving uniform cavitation across large processing volumes. While small-scale systems can precisely control cavitation

TABLE 2 | Factors to be considered during scaling up of laser cavitation system with potential solutions.

Factor	Key considerations	Potential solutions	References
Scalability and industrial adaptations	<ul style="list-style-type: none"> Scaling from lab to industrial scale requires managing higher throughput and larger food volumes Uniform energy distribution across larger surfaces Integration with existing industrial systems 	<ul style="list-style-type: none"> Multilaser arrays for even energy distribution Flow-through cavitation chambers for continuous processing Modular system designs for flexibility 	Askarniya et al. (2023)
Energy efficiency	<ul style="list-style-type: none"> Laser systems can be energy-intensive Need for energy optimization in large-scale operations Balancing high power with processing speed 	<ul style="list-style-type: none"> Pulse control to modulate laser intensity Efficient cooling systems (closed loop, heat exchangers) <ul style="list-style-type: none"> Waste heat recovery systems 	Harish et al. (2023)
Safety features	<ul style="list-style-type: none"> Risks from high-power lasers (eye injury, skin burns) Pressure and temperature management due to cavitation forces Food safety during processing. 	<ul style="list-style-type: none"> Laser enclosures, optical shielding, and safety interlocks. Pressure relief valves and automated shutdown systems. <ul style="list-style-type: none"> PPE for operators. 	Babu and Amamcharla (2023)
Food quality preservation	<ul style="list-style-type: none"> Overheating can lead to food degradation (loss of nutrients, flavor, texture) Need to maintain consistent cavitation parameters for food quality 	<ul style="list-style-type: none"> Temperature and pressure sensors for real-time monitoring Automated feedback control systems to adjust parameters based on food characteristics 	Zadeike and Degutyte (2023)
Laser power and distribution	<ul style="list-style-type: none"> Laser power must be distributed evenly across large food volumes High-intensity lasers can cause overheating 	<ul style="list-style-type: none"> Multilaser systems to cover larger areas Variable power modulation based on food type and required cavitation intensity 	Sarraf et al. (2022)
Cooling system efficiency	<ul style="list-style-type: none"> Cooling systems account for a significant portion of the system's energy consumption Cooling needs to manage excess heat generated by cavitation 	<ul style="list-style-type: none"> Closed-loop cooling systems and heat exchangers. Active-cooling methods like refrigeration or Peltier devices for precise temperature control 	Teng et al. (2021)
Processing time and throughput	<ul style="list-style-type: none"> Industrial-scale systems must achieve high throughput Need to optimize processing times without compromising food quality 	<ul style="list-style-type: none"> Faster laser pulses or continuous processing modes Modular system designs that can scale as needed to increase throughput 	Xu et al. (2022)

zones, industrial applications require multiple lasers arranged in parallel or arrays to cover wider areas, which can lead to uneven energy distribution and inconsistent treatment if not carefully managed. The design of flow-through cavitation chambers must ensure homogeneous cavitation exposure even at higher flow rates, which is complicated by the complex fluid dynamics within the chamber (Arya et al. 2023; Zoglopiti et al. 2025). Ensuring

consistent cavitation intensity throughout a large volume demands precise synchronization of laser sources and optimized chamber geometry to avoid dead zones or hotspots. Another significant challenge lies in the increased complexity and cost associated with multilaser systems. Incorporating multiple high-power lasers necessitates advanced optical alignment, heat management, and control systems, all of which contribute to higher

TABLE 3 | Effect of laser irradiation on microorganisms.

SI. no.	Type of laser	Working condition	Food microorganism	Inference	References
1	Nd:YAG laser	Wavelength: 355 and 266 nm and energy: 185 mJ	<ul style="list-style-type: none"> <i>Pseudomonas aeruginosa</i> <i>Escherichia coli</i> <i>Staphylococcus aureus</i> <i>Salmonella typhimurium</i> <i>Listeria monocytogenes</i> 	<ul style="list-style-type: none"> <i>P. aeruginosa</i> showed maximum inhibition, followed by <i>E. coli</i>, <i>S. aureus</i>, <i>S. typhimurium</i>, and <i>L. monocytogenes</i> grown on agar surface Laser was able to reduce the population of 1.65×10^5 by 4.7 logs, of <i>P. aeruginosa</i> The reduction patterns of <i>E. coli</i>, <i>Salmonella</i> sp. yeasts, and <i>Lactobacillus</i> sp. were 30%, 25%, 47%, and 30%, respectively, with laser technology 	Yasmin et al. (2017)
2	Nd:YAG laser	Wavelength: 1064 nm, power: 10–50 W, and time: 2 min	<ul style="list-style-type: none"> <i>E. coli</i> and <i>Listeria monocytogenes</i> 	<ul style="list-style-type: none"> Complete sterilization of bacteria and fungi at laser power 50 W for 2 min pH of milk was reduced from 6.18 for the control sample in the first day down to 4.50 for the highest laser-treated sample after 5 days pH of milk was reduced when increasing laser output power 	Marouf and Sara (2018)
3	Diode laser	Wavelength: 445 and 650 nm laser activated the chlorophyll extract of the papaya leaf (0.5 mg/L)	<i>Candida albicans</i>	<ul style="list-style-type: none"> The absorbance percentage of chlorophyll extracts on wavelengths of 650 and 445 nm, respectively, were 22.26% and 60.29% The inactivation was about 32% for 650 nm ($p = 0.001$), while the 445 nm lasers only 25% ($p = 0.061$) The maximum malondialdehyde levels by treatment of the laser 650 nm were (0.046 ± 0.004) nmol/mg 	Astuty et al. (2019)
4	Mid-IR femtosecond laser radiation	Wavelength: 5.8 and 3.4 μm , pulse energies of 10 μJ (6 μm) and 30 μJ (3 μm), and repetition rate of 1 kHz	<i>P. aeruginosa</i> bacteria	The bacterial inactivation done by the 6 μm ultra short laser pulses is attributed to dissociative denaturation of lipids and proteins in the cell membranes and intra-cell nucleic acids	Kompanets et al. (2021)

Abbreviations: Er, erbium-doped yttrium aluminum garnet; Nd:YAG, neodymium-doped yttrium aluminum garnet.

capital and operational expenditures. The technical difficulty of maintaining beam quality and avoiding interference effects among lasers further complicates system design (Askarniya et al. 2023; Kishore et al. 2024). Moreover, managing the thermal load generated by these lasers requires robust cooling solutions to prevent damage to equipment and degradation of food quality. Operator safety also becomes a heightened concern with larger laser arrays necessitating stringent protective measures and compliance with laser safety standards (Chavan et al. 2023; Teng et al. 2021). Industrial-scale processing must also address variability in food products. Different types of foods vary widely in texture, composition, and flow characteristics, all of which

influence cavitation generation and efficacy. The design flexibility and modular systems that can be adapted to various products are essential but increase the complexity of both hardware and control strategies (Xu et al. 2022; Arya et al. 2023). Flow dynamics within cavitation chambers must be optimized to accommodate higher throughput without sacrificing treatment efficacy, a balance that requires careful engineering to avoid turbulent flows or blockages that can reduce cavitation efficiency (Stebeleva and Minakov 2021; Zoglopiti et al. 2025). Automation and real-time process control play crucial roles in maintaining stability during large-scale operations. Effective LC processing requires continuous monitoring and feedback mechanisms that adjust

laser power, flow rates, and chamber conditions dynamically to maintain optimal cavitation intensity (Askarniya et al. 2023; Lim et al. 2025). The development of reliable sensors that are capable of capturing cavitation dynamics and integrating them into automated control systems is technically demanding, especially when scaled across multiple laser modules. Finally, energy efficiency and regulatory compliance are significant hurdles. High-powered lasers consume substantial energy, making system optimization for energy use critical to economic feasibility and environmental sustainability. Furthermore, scaling up LC technology for food processing requires comprehensive validation to meet food safety regulations, which involves extensive testing to prove consistent quality and safety outcomes under industrial conditions (Arya et al. 2023; Zheng et al. 2020). Addressing these challenges through interdisciplinary collaboration will be vital for advancing the industrial adoption of laser-induced cavitation technologies.

6.3 | Energy Demands in LC Systems

Laser-induced cavitation technology, particularly when operated at high intensities and over extended durations, is inherently energy-intensive. The power demands for laser operation rise substantially, making energy management a critical challenge, especially in large-scale food processing, where continuous, high-throughput operation is common as the processing scale increases (Teng et al. 2021). This increase in energy demand not only drives up operational costs but also raises environmental sustainability concerns, highlighting the need for effective energy efficiency strategies. The optimization of laser pulse control is fundamental to manage energy use. Pulsed lasers with adjustable pulse duration and repetition rates allow tailoring of the energy input to the precise needs of the food processing task, thus avoiding unnecessary power expenditure (Teng et al. 2021). However, determining the optimal pulse parameters is complex, requiring extensive experimentation and advanced control systems to accommodate varying food matrices and processing objectives (Arya et al. 2023). This complexity is compounded by the diverse physical and chemical properties of food products, which influence cavitation dynamics and energy requirements (Zoglopiti et al. 2025). Cooling systems represent another significant energy consumer in LC setups. High-power lasers generate substantial heat, necessitating continuous cooling to maintain system stability and prevent equipment damage. The integration of closed-loop cooling systems and sophisticated heat exchangers employing combinations of air, water, or refrigerants can help to recycle heat and minimize external cooling demands (Chavan et al. 2023). However, designing such systems to balance thermal management, cost, and operational reliability remains a formidable engineering challenge (Stebeleva and Minakov 2021).

Power modulation techniques further contribute to energy savings by adjusting laser intensity based on real-time processing needs. Higher intensities are necessary for demanding applications like sterilization or intense emulsification, while lower power settings are adequate for mild treatments (Arya et al. 2023; Kishore et al. 2024). The challenge lies in implementing fast, reliable modulation at industrial scales without compromising process consistency or treatment efficacy. In addition, capturing and repurposing waste heat from lasers and cooling systems holds

potential for reducing overall energy consumption. The recovered heat can be redirected for ancillary processes such as heating water or maintaining facility temperatures by enhancing overall energy efficiency (Anton y Otero et al. 2023; Arya et al. 2023). However, designing efficient and cost-effective heat recovery systems that integrate with food processing operations is complex and requires careful thermal and process engineering (Sreekala et al. 2025). In summary, energy demands in laser-induced cavitation systems encompass multifaceted challenges involving laser operation optimization, thermal management, adaptive process control, and integration of auxiliary energy recovery systems. Overcoming these challenges is essential to ensure the economic feasibility and environmental sustainability of large-scale food processing applications using LC technologies.

6.4 | Safety Features in LC Equipment System

The safety hazards considered in LC systems are laser safety, pressure and temperature management, and food safety. High-powered lasers used for cavitation can pose significant risks to human operators, especially in terms of eye injury or skin burns. These hazards necessitate the installation of safety features such as protective enclosures, laser shielding, and safety interlocks to prevent accidental exposure to the laser beam (Albanese et al. 2017). Cavitation generates intense heat and concise pressure variations within the system. Pressure vessels and cavitation chambers must be designed to handle these fluctuations to avoid rupture or thermal damage. The laser safety requires incorporating pressure relief valves and temperature control systems that can adjust or shutdown the process (Chavan et al. 2023). The cavitation process is often used to sterilize or pasteurize food, ensuring that the temperature and pressure conditions are optimal for microbial inactivation. Monitoring systems and redundant safety features, such as pressure and temperature sensors, are necessary to maintain food safety standards (Arya et al. 2020). The key safety features in LC systems are laser enclosures and shielding, automated shutdown systems, pressure relief and ventilation, operator training, and personal protective equipment. High-powered laser systems must be housed in protective enclosures that prevent direct exposure to the laser beam. Laser enclosures often include optical glass or coatings that block the laser wavelengths to ensure that operators and nearby personnel are shielded from the laser (Zheng et al. 2020).

Automated safety shutdown systems are critical in cavitation setups and can deviate the laser or adjust processing parameters (such as reducing intensity or stopping laser pulses) if unsafe conditions are detected. Proper training for operators on safety protocols is essential, along with personal protective equipment (such as laser safety goggles, gloves, and protective clothing), to reduce the risk of exposure to laser radiation (Teng et al. 2021). Babu and Amamcharla (2023) highlighted that cavitation equipment must also undergo rigorous safety testing and compliance with international standards such as ANSI Z136.1 for laser safety. Incorporating these standards ensures that industrial systems operate safely while protecting operators from hazards associated with high-powered lasers. The successful scaling up of LC technology for large-scale food processing also depends on considering safety in tandem with energy efficiency and system design. Multilaser arrays, modular cavitation chambers,

and optimized cooling systems can improve throughput and energy management while maintaining safe operating conditions (Chavan et al. 2023). Integrating these considerations will be key to ensuring that the technology remains effective, feasible, and safe for large-scale industrial applications.

7 | Future Prospects

The future prospects for laser-induced cavitation technology in food processing are promising, particularly as they address the key challenges identified in current systems. One major challenge is achieving precise chemical-free processing while preserving the nutritional and sensory qualities of food products. LC technology offers significant potential here by enabling highly controlled cavitation effects that improve microbial inactivation and nutritional enhancement without chemical additives, thus ensuring food safety and quality (Zheng et al. 2020; Arya et al. 2023). Scalability and industrial translation have been persistent challenges. Advances in laser systems and process optimization, such as the development of multilaser arrays and modular cavitation chambers, are expected to improve throughput, uniform energy distribution, and system scalability, making industrial-scale applications more viable (Chavan et al. 2023; Zoglopiti et al. 2025). Multifocal laser systems, adaptive optics, and phase control techniques such as SLMs and phase conjugate digital inline holography (PCDIH) further enhance uniform energy delivery, precise focus, and cavitation efficiency across large processing volumes (Mazumdar et al. 2020; Pushkin et al. 2022; L. Wang et al. 2022). High energy demands of LC systems remain a critical hurdle. Integrating energy-efficient laser technologies, including pulse modulation, optimized cooling systems, and AI-based predictive modelling, addresses this challenge by reducing operational costs, minimizing carbon emissions, and tailoring power usage to precise processing needs (Chavan et al. 2023; Arya et al. 2023; Kishore et al. 2024; Z. Zhang et al. 2024). In addition, the incorporation of smart and nanostructured materials with high absorption coefficients at targeted wavelengths enhances energy conversion efficiency, further improving cavitation process effectiveness while reducing wasted energy (Lei et al. 2021; Sreekala et al. 2025). The complexity of cavitation dynamics can limit process precision and industrial applicability. Hybrid computational approaches combining artificial neural networks (ANNs) with genetic algorithms (GA) and simulation tools show promise for accurately predicting cavitation behaviour, enabling more precise and consistent applications (H. Yang 2024). Advanced diagnostic tools like photonic Doppler velocity (PDV) and time-resolved pump-probe (TRPP) systems provide detailed insights into laser-induced effects, allowing fine-tuning of processing parameters to ensure product safety, quality, and uniform treatment (Liu et al. 2024; Tahan et al. 2020). Finally, operator safety, pressure management, and food safety remain essential considerations in industrial applications. Improved process control through real-time monitoring, adaptive optics, and automated feedback can minimize hazards associated with high-powered lasers and intense cavitation, complementing existing safety protocols such as protective enclosures, interlocks, and operator training (Chavan et al. 2023). Collectively, these advancements are expected to overcome current technical, operational, and energy-related challenges, paving the way for safe, scalable, and energy-efficient LC systems in food processing.

8 | Conclusion

LC has developed as an effective, eco-friendly, cutting-edge technology in food processing. The application of this technology can significantly enhance food safety, quality, process efficiency, and contribute to achieving sustainability. It holds the promise to transform the food sector, and its advancement and implementation will remain vital in improving the extraction of high-value ingredients. LC is currently being applied in the food industry for various purposes, including microbial inactivation, microbial reduction, bioactive compound extraction, emulsion improvement, and the enhancement of nutritional quality in liquid foods. However, future research should aim to improve the efficiency of laser systems while reducing their ecological footprint and energy usage. Additional research is required to investigate the possibilities of applications of LC in new areas like food waste pretreatment, wastewater treatment, and the conversion of food waste into value-added products such as volatile fatty acids, lactic acid, biogas, biodiesel, and biohydrogen. Further development in this field can overcome existing challenges in this technology, such as equipment cost and optimization of process parameters. LC holds the potential to advance liquid food processing by facilitating the production of safer, nutrient-dense nonthermal liquid foods, effectively meeting global consumer demands for high-quality food products.

Author Contributions

Ganga Kishore S.: methodology, conceptualization, investigation, writing – original draft. **Madhuresh Dwivedi:** conceptualization, validation, project administration, writing – review and editing, writing – original draft. **R. Rahul:** methodology, writing – review and editing. **Seema Ramniwas:** formal analysis, software, investigation. **C. S. Neethu:** investigation, formal analysis, writing – review and editing. **J. Deepa:** writing – review and editing, formal analysis. **G. Jeevarathinam:** writing – review and editing, supervision, investigation.

Conflicts of Interest

The authors declare no conflicts of interest.

Data Availability Statement

No data was used for the research described in the article.

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