

Review

Hydrodynamic Cavitation for the Sustainable Recovery of Bioactive and Functional Fractions from Agri-Food Residues and Plant-Derived Matrices: Process Functions, Quantitative Evidence, and Application Requirements

Lorenzo Albanese 

Institute of Bioeconomy, National Research Council of Italy, Via Madonna del Piano 10, 50019 Florence, Italy;
lorenzo.albanese@cnr.it

Abstract

Hydrodynamic cavitation is assessed as a conditional process-intensification platform for the sustainable recovery and transformation of bioactive and functional fractions from agri-food residues, food-processing by-products, and plant-derived matrices. The analysis focuses on fractions enriched in polyphenols, flavonoids, pectins, carotenoids, proteins, pigments, essential oils, and other value-added compounds with potential relevance for food, nutraceutical, formulation-oriented, and related high-value applications. Rather than being considered an inherently green or universally superior technology, hydrodynamic cavitation is evaluated according to the specific process functions it can provide, including matrix disruption, mass-transfer enhancement, solvent-use reduction, recovery of pectin-associated fractions, protein extraction, macromolecular restructuring, dispersion, and process integration. Quantitative and scale-relevant indicators are considered where available, including recovery yield, target-compound content, solvent use, operating conditions, treated volume, energy input, fraction quality, and reporting limits. Comparison with ultrasound-assisted extraction, microwave-assisted extraction, pulsed electric fields, subcritical water extraction, natural deep eutectic solvents, and enzyme-assisted extraction indicates that its advantage is most defensible when hydrodynamic effects address a clearly identified matrix or process limitation. The available evidence supports substantial potential for wet matrices, plant by-products, aqueous suspensions, and liquid food systems. However, critical gaps remain in energy reporting, selectivity, recovered-fraction stability, scale-up, downstream processing, and application-oriented validation. Recovered fractions should therefore be regarded as candidate ingredients or functional intermediates, rather than as direct evidence of efficacy in final products.

Keywords: hydrodynamic cavitation; agri-food residues; bioactive compounds; functional fractions; process intensification; sustainable processing



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1. Introduction

Agri-food residues, food-processing by-products, and plant-derived matrices represent important sources of bioactive and functional compounds that can be recovered within sustainable processing and circular-resource strategies. Citrus by-products are among the most extensively studied examples. Peels, albedo, flavedo, spent pulp, and juice-processing residues may contain flavonoids, pectins, essential oils, carotenoids, fibers, and other

functional components of interest for food, formulation-oriented, and broader high-value applications [1–3].

Pomegranate by-products provide another relevant case. These residues are rich in polyphenols, ellagitannins, and punicalagin, and have been investigated in several recovery and valorization strategies [4]. More broadly, the recovery of bioactive compounds from fruit-processing residues and other agri-food by-products requires technologies capable of overcoming structural barriers, mass-transfer limitations, stability constraints, and challenges associated with industrial implementation [5–8].

The value of these fractions does not depend only on the presence of bioactive molecules. It also depends on recovered-fraction quality, safety, stability, compatibility with the intended matrix, process sustainability, and the possibility of translating composition into reproducible functional performance. High extraction yield is therefore insufficient if the process compromises selectivity, functionality, or application-oriented transferability.

In this context, green extraction and process-intensification technologies have gained increasing attention. Ultrasound-assisted extraction, microwave-assisted extraction, pulsed electric fields, subcritical water extraction, natural deep eutectic solvents, enzyme-assisted extraction, and hydrodynamic cavitation have been proposed to improve the recovery of bioactive fractions while reducing processing time, solvent use, or the need for severe operating conditions [9–11].

None of these technologies, however, can be considered intrinsically superior in general terms. Their usefulness depends on the matrix treated, the target compound class, the dominant mechanism, energy requirements, downstream operations, and the quality of the final recovered fraction.

Hydrodynamic cavitation fits within this framework as a process-intensification technology based on the formation, growth, and collapse of vapor or gas–vapor cavities in a moving liquid. It can be generated using relatively simple devices, including Venturi tubes, orifice plates, vortex reactors, cavitating jets, and rotational devices [12–14].

Cavity collapse can generate microjets, pressure waves, shear gradients, local turbulence, micromixing, interfacial renewal, and enhanced mass transfer. These effects may promote the release of compounds retained within cellular or macromolecular structures, support matrix disruption, and enable the processing of aqueous suspensions, plant residues, and wet agri-food streams [12–15].

The interest in hydrodynamic cavitation also derives from its potential integration into continuous or recirculated processes. This feature is particularly relevant for liquid matrices, plant suspensions, and wet by-products, which often require rapid and integrable treatments compatible with reduced use of organic solvents [12,13,15].

Hydrodynamic cavitation should not, however, be interpreted as an automatically green or universally effective technology. Its performance depends on reactor configuration, pressure, flow rate, temperature, number of passes, solid-to-liquid ratio, particle size, and matrix properties. Excessively intense treatment may also promote degradation, oxidation, loss of volatile compounds, or undesirable modifications of pigments, proteins, and pectin-associated systems [12,15].

The translation of recovered fractions into food, nutraceutical, formulation-oriented, or other high-value applications also requires caution. The presence of antioxidant, photoprotective, or anti-inflammatory compounds in a recovered fraction does not demonstrate the efficacy of a final product. Application relevance requires additional evidence on stability, dose, bioaccessibility, safety, compatibility with real matrices, formulation behavior, and claim substantiation.

In this work, hydrodynamic cavitation is examined as a conditional process-intensification platform for the sustainable recovery and transformation of bioactive and functional frac-

tions from agri-food residues, food-processing by-products, and plant-derived matrices. The aim is not to present the technology as a general solution, but to evaluate its role in relation to defined process functions. These include cell disruption, mass-transfer enhancement, solvent-use reduction, recovery of pectin-associated fractions, protein extraction, formation of macromolecular complexes, dispersion, emulsification, and process integration.

The analysis considers citrus by-products, pomegranate residues, apple residues, coffee grounds, conifer-derived materials, plant protein matrices, beverages, and liquid food systems. Where available, quantitative and scale-relevant indicators are considered, including recovery yield, target-compound content, solvent use, processing conditions, treated volume, throughput, specific energy input, recovered-fraction quality, stability, and downstream requirements. Comparison with ultrasound-assisted extraction, microwave-assisted extraction, pulsed electric fields, subcritical water extraction, natural deep eutectic solvents, and enzyme-assisted extraction is used to clarify when hydrodynamic cavitation may be preferable, equivalent, or less suitable for the recovery and transformation of bioactive and functional fractions.

1.1. Bioactive Compounds from Agri-Food Residues and Plant-Derived Matrices

Agri-food residues and plant-derived matrices are relevant sources of bioactive compounds and functional materials within sustainable processing and circular-resource strategies. Peels, seeds, spent pulps, juice-processing residues, and fibrous fractions may still contain valuable molecules, although their recovery is often limited by perishability, high water content, compositional variability, and stabilization costs [5–7].

Citrus fruits provide an emblematic case. Their by-products may contain flavanones, flavonoids, pectins, cellulose, essential oils, carotenoids, and volatile compounds [1–3]. This compositional complexity supports multiproduct recovery, but also requires evaluation criteria that go beyond the extraction of individual marker compounds.

Pomegranate residues represent a different but equally relevant case, characterized by high levels of polyphenols, ellagitannins, and punicalagins [4]. These by-products are often associated with antioxidant properties and potential high-value applications. However, composition, chemical activity, biological activity, and final application relevance should remain clearly distinct.

Other matrices, including apple residues, coffee grounds, conifer-derived materials, and woody plant-derived streams, further broaden the scope of sustainable recovery. These materials introduce additional challenges related to fibrous structure, lignification, compositional variability, and the possible recovery of multiple fractions [5,7,8]. Their circular use requires processes capable of treating wet or heterogeneous streams while limiting extensive drying and intensive solvent use.

Circular-resource valorization therefore does not simply mean converting a residual stream into an extract. It requires a process logic that accounts for the raw material, target fraction, co-products, residual streams, water, energy, and intended use. A process consistent with circular bioeconomy principles should maximize the overall value of the starting material while preserving sufficient quality for real applications [6,11].

1.2. Need for Green Extraction and Process Intensification

Conventional extraction technologies may require long processing times, high temperatures, organic solvents, and subsequent purification or concentration steps. These factors can reduce the sustainability of recovery processes and limit the compatibility of extracts with food, nutraceutical, formulation-oriented, or other high-value applications [9,11].

The term “green” therefore requires careful use. A technology is not sustainable simply because it uses less solvent or is described as innovative. Energy use, water consump-

tion, reagents, processing time, temperature, effective recovery yield, compound stability, downstream operations, and final fraction quality must all be considered [11].

Process intensification aims to reduce physical or physicochemical limitations that hinder the release of the target fraction. These limitations may include cellular barriers, slow diffusion, poor wettability, low solubility, macromolecular aggregation, or insufficient contact between solvent and matrix. Intensification is meaningful only when it provides a net advantage over appropriate controls and comparators [9–11].

Comparison among green technologies is therefore essential. Ultrasound-assisted extraction, microwave-assisted extraction, pulsed electric fields, subcritical water extraction, natural deep eutectic solvents, and enzyme-assisted extraction do not act through the same mechanisms. Hydrodynamic cavitation should be positioned within this framework as a technology with specific strengths and limitations, not as a universally preferable alternative [10–12].

1.3. Hydrodynamic Cavitation as a Conditional Process-Intensification Platform

Hydrodynamic cavitation has attracted increasing interest because it can generate intense local effects in relatively simple devices. In the recovery of bioactive and functional fractions, these effects may help overcome structural and diffusional barriers, improve contact between the matrix and the solvent, and enhance mass transfer [12–14].

Its relevance is particularly clear when the treated system is wet, fibrous, heterogeneous, or difficult to process using conventional methods. In such cases, a hydrodynamic technology can be integrated into aqueous suspensions, liquid matrices, or recirculated process streams. It may also contribute not only to recovery, but also to dispersion, macromolecular modification, and the production of fractions with application-relevant functional properties [12–15].

Hydrodynamic cavitation is strongly dependent on reactor design and operating conditions. Different devices can generate different cavitation regimes, and even the same device may produce different effects as pressure, flow rate, temperature, number of passes, solids content, or solvent properties vary. Reproducibility and comparability across studies therefore require accurate reporting of the system configuration and operating parameters [12–15].

For bioactive compounds, the key issue is to balance release and preservation of the target fraction. Treatment intensity should increase accessibility and mass transfer without promoting degradation, oxidation, loss of volatile compounds, or undesirable changes in proteins, pigments, and pectin-associated systems. The most useful condition is not necessarily the most intense cavitation regime, but the one that improves a defined process function while preserving the quality of the recovered fraction [12,15].

2. Scope, Literature Basis, and Critical Assessment Criteria

Assessing hydrodynamic cavitation for the sustainable recovery and transformation of bioactive and functional fractions requires an explicit methodological and interpretive framework. The available studies differ in the matrices treated, process configurations, operating scales, technological objectives, and performance criteria. For this reason, any comparison based only on extraction yield would be too narrow.

Hydrodynamic cavitation is not considered here as an intrinsically superior technology. It is instead treated as an intensification platform whose value depends on the function performed in a given system. This function may involve the recovery of a bioactive fraction, solvent-use reduction, enhanced mass transfer, matrix disruption, macromolecular modification, dispersion, or integration into a broader sustainable processing chain [16,17].

This approach is necessary because the term “hydrodynamic cavitation” encompasses different devices, hydraulic regimes, and operating conditions. The occurrence of cavitation does not automatically imply the same effect on the matrix, the same quality of the recovered fraction, or the same overall process sustainability. A distinction is therefore made among observed effect, process function, and application relevance.

2.1. Scope of the Analysis

Hydrodynamic cavitation is assessed as an intensification technology for the recovery and transformation of bioactive and functional fractions from agri-food residues, food-processing by-products, and plant-derived matrices. The target fractions include polyphenols, flavonoids, carotenoids, pectins, proteins, peptides, pigments, essential oils, volatile compounds, and macromolecular complexes. The scope also includes process functions beyond extraction, including cell disruption, mass-transfer enhancement, solvent-use reduction, aqueous-extract production, macromolecular modification, formation of protein–polyphenol complexes, dispersion, emulsification, and integration into continuous or semi-continuous processing [17,18].

Application relevance is treated cautiously. Hydrodynamic cavitation is not considered an established route to finished functional products, but an upstream platform for generating candidate fractions, functional extracts, ingredients, or intermediates. Comparison with ultrasound-assisted extraction, microwave-assisted extraction, pulsed electric fields, subcritical water extraction, natural deep eutectic solvents, and enzyme-assisted extraction is included to avoid isolated technology assessment and to clarify when hydrodynamic cavitation may be preferable, equivalent, or less suitable [18,19].

2.2. Literature Base

The available studies differ in matrix type, physical state of the material, water-to-solid or solvent-to-solid ratio, reactor configuration, operating pressure, temperature, treatment time, experimental scale, and analytical parameters.

In some cases, hydrodynamic cavitation is assessed as an extraction method. In others, it acts as a pretreatment, a mass-transfer intensifier, a cell-disruption tool, a technology for beverage processing, a method for modifying proteins or polysaccharides, or a component of a broader sustainable processing strategy [16–19].

This heterogeneity prevents interpretation based on a single efficacy criterion. Extraction yield alone does not establish whether a process provides an overall advantage. Higher recovery may be obtained at the expense of greater energy consumption, higher process severity, partial degradation of sensitive compounds, lower selectivity, or more demanding downstream operations.

For these reasons, a uniform meta-analytical ranking was not applied. The available studies are heterogeneous in terms of feedstock, reactor configuration, operating conditions, solvent system, target fraction, analytical endpoints, and scale. However, quantitative information was extracted whenever available. The indicators considered include recovery yield, total phenolic content, flavonoid or target-compound concentration, pectin or protein yield, solvent composition, liquid-to-solid ratio, treatment time, temperature, pressure or flow conditions, treated volume, throughput, specific energy input, and stability-related outcomes.

This approach allows quantitative evidence to be reported without imposing an artificial ranking on non-homogeneous studies. The aim is therefore to identify the conditions under which hydrodynamic cavitation shows a measurable technological advantage, the cases in which the evidence remains preliminary, and the minimum requirements needed for a more robust application-oriented assessment.

The approach adopted is therefore comparative and evidence-weighted. A positive result is not considered sufficient on its own. It must be interpreted in relation to appropriate controls, comparison with alternative technologies, operating parameters, quality of the recovered fraction, and consistency with the proposed application.

The central criterion is that hydrodynamic cavitation is relevant when it improves a defined process function. Producing a measurable effect is not enough. The function may involve recovery, solvent-use reduction, mass-transfer enhancement, matrix disruption, extract stabilization, favorable modification of colloidal properties, or integration into a sustainable processing chain [16–19].

2.3. Criteria for Critical Assessment

The assessment of the studies is organized according to recurring criteria. The first criterion concerns the starting matrix. Citrus by-products, pomegranate peels, apple residues, coffee grounds, bark, conifer needles, seeds, protein fractions, and liquid matrices differ in structure, composition, water content, and accessibility of bioactive compounds.

The second criterion concerns the target compound class. Polyphenols, flavonoids, carotenoids, pectins, lignans, proteins, peptides, pigments, essential oils, and volatile compounds differ in solubility, localization, thermal sensitivity, susceptibility to oxidation, and interactions with polysaccharides or proteins. The same cavitation condition may favor one compound class while being less suitable for another.

The third criterion concerns process configuration. Venturi devices, orifice plates, rotational devices, vortex reactors, and hybrid systems do not generate the same pressure field, distribution of active zones, or energy consumption. The operating mode, whether single-pass or recirculated, also changes the meaning of treatment time and process severity [17–19].

The fourth criterion concerns comparison with alternative methods. The comparison should not be limited to absolute recovery yield. Solvent type, process duration, selectivity, recovered-fraction quality, energy demand, compatibility with the intended use, and complexity of downstream operations should also be considered.

The fifth criterion concerns stability and preservation of functionality. In the recovery of bioactive and functional fractions, documenting the release of a molecule or compound class is not sufficient. It is also necessary to evaluate whether the process preserves, transforms, or degrades the recovered fraction.

The sixth criterion concerns application relevance. For food, nutraceutical, formulation-oriented, and other high-value applications, relevant aspects include fraction composition, stability, compatibility with real matrices, possible bioaccessibility, functional performance, and incorporation into products. The presence of antioxidant, antimicrobial, photoprotective, or other biologically relevant compounds should not be interpreted as direct evidence of final product efficacy.

The seventh criterion concerns scalability, process integration, and sustainability. A green recovery technology should also be assessed in terms of treatable volumes, real matrices, continuous or semi-continuous operation, water and energy consumption, management of residual streams, and compatibility with downstream processes [17–19].

Regulatory caution is also required when a recovered fraction is proposed as a new ingredient, extract, or functional component. In such cases, the assessment should include safety, traceability, conditions of use, and consistency with the applicable regulatory framework [20].

Within this framework, hydrodynamic cavitation is interpreted as a conditional intensification platform. Its value does not depend on the mere occurrence of cavitation, but on its ability to provide a measurable, reproducible, and application-relevant advantage

in relation to a defined objective and an appropriate comparator. In the absence of adequate controls, comparable metrics, or data on the quality and stability of the recovered fraction, the process should be considered promising but not yet fully demonstrated for the specific application.

Evidence strength was assigned qualitatively according to the completeness of the available information. Evidence was considered moderate when studies reported a defined matrix and target fraction, appropriate controls or comparator technologies, quantitative recovery indicators, operating conditions, and at least partial information on fraction quality, stability, scale, or downstream processing. Evidence was considered limited when recovery data and process conditions were available, but information on energy, scale, stability, comparator technologies, or downstream requirements remained incomplete. Evidence was considered preliminary when the available information was limited to proof-of-concept recovery, composition, biological activity, or functional response without adequate process comparison, stability assessment, or scale-relevant data.

The evidence categories and interpretive criteria are summarized in Table 1, with particular attention to the relationship among matrix type, target fraction, reported or assessed hydrodynamic cavitation effect, process purpose, evidence support, and interpretation boundary. This separation is intended to distinguish what hydrodynamic cavitation is reported or expected to do in a given matrix from the technological objective assigned to the process.

Table 1. Critical assessment matrix for hydrodynamic cavitation in the recovery and transformation of bioactive and functional fractions from agri-food residues and plant-derived matrices.

Matrix or System	Target Fractions	Main Reported or Assessed HC Effect	Process Purpose	Evidence Support and Interpretation Boundary
Citrus by-products	Flavonoids, pectins, essential oils, volatile compounds	Matrix disruption and mass-transfer enhancement	Low-solvent recovery of citrus-derived fractions	Moderate; requires stability, selectivity, temperature control, downstream separation, and comparison with green alternatives
Citrus pectin-associated systems	Flavanones, phenolics, pectin-associated fractions	Release and partial restructuring of pectin-rich fractions	Recovery of complex pectin-containing fractions	Moderate; requires structural characterization, reproducibility, molecular-property assessment, and stability beyond total phenolic yield
Pomegranate by-products	Punicalagin, ellagitannins, polyphenols	Tissue disruption and enhanced polyphenol release	Recovery of polyphenol-rich fractions	Limited; requires distinction among antioxidant activity, bioaccessibility, functional relevance, and final-product efficacy
Fruit residues and wet processing by-products	Polyphenols, phenolic acids, fibers	Enhanced solid–liquid contact and wet-stream processing	Recovery from variable wet matrices with reduced preprocessing	Limited; requires matrix variability, water use, process severity, mass balance, and scale relevance

Table 1. *Cont.*

Matrix or System	Target Fractions	Main Reported or Assessed HC Effect	Process Purpose	Evidence Support and Interpretation Boundary
Coffee grounds and lignocellulosic plant-derived streams	Phenolics, lignans, cellulose, microfibrils	Mechanical disruption and multiphase fraction release	Integrated recovery of soluble and solid fractions	Limited; requires energy demand, separation requirements, co-product quality, and multiproduct feasibility
Beverages and liquid food systems	Hop compounds, proteins, peptides, aroma compounds	Mixing, dispersion, precursor transformation, and process integration	Direct processing of liquid matrices or food intermediates	Moderate; requires sensory quality, colloidal stability, system specificity, temperature effects, and energy use
Plant protein matrices	Plant proteins and peptides	Protein release and structural modification	Recovery of protein fractions and improvement of techno-functional properties	Moderate; requires solubility, digestibility, structural integrity, nutritional quality, and antinutritional-factor assessment
Protein–polyphenol systems	Complexes, conjugates, colloids, emulsions	Macromolecular restructuring and interaction modulation	Generation of functional complexes or structured intermediates	Limited; requires distinction among functionalization, aggregation, denaturation, and non-specific structural effects
Application-oriented candidate fractions	Polyphenols, flavonoids, antioxidants, formulation-relevant fractions	Upstream recovery, dispersion, or structuring	Production of candidate ingredients or functional intermediates	Preliminary; composition alone does not support efficacy claims without safety, stability, bioaccessibility, formulation, and regulatory evidence

Note: HC, hydrodynamic cavitation. Evidence support is classified qualitatively as preliminary, limited, or moderate according to the completeness of the available information, including matrix definition, comparator quality, quantitative recovery indicators, operating conditions, fraction characterization, stability data, energy or scale information, downstream requirements, and intended use. The classification is not intended as a numerical ranking, maturity scale, proof of sustainability, demonstration of technological superiority, or regulatory validation.

The technological meaning of hydrodynamic cavitation changes according to the matrix treated, the target fraction, and the function assigned to the process, as summarized in Table 1. In some cases, cavitation acts primarily as an extraction intensifier. In others, its role concerns matrix disruption, mass-transfer enhancement, macromolecular restructuring, emulsification, or process integration. For this reason, the available evidence cannot be assessed only through extraction yield, but must also consider fraction quality, stability, comparator technologies, energy demand, downstream requirements, and scale relevance. The main process routes and operating principles considered in the comparative assessment are summarized in Figure 1. The scheme does not rank the technologies, but identifies the main physical or chemical route through which each process may promote recovery or transformation of bioactive and functional fractions. This distinction is relevant because similar recovery outcomes may derive from different mechanisms and may therefore require different interpretation criteria.

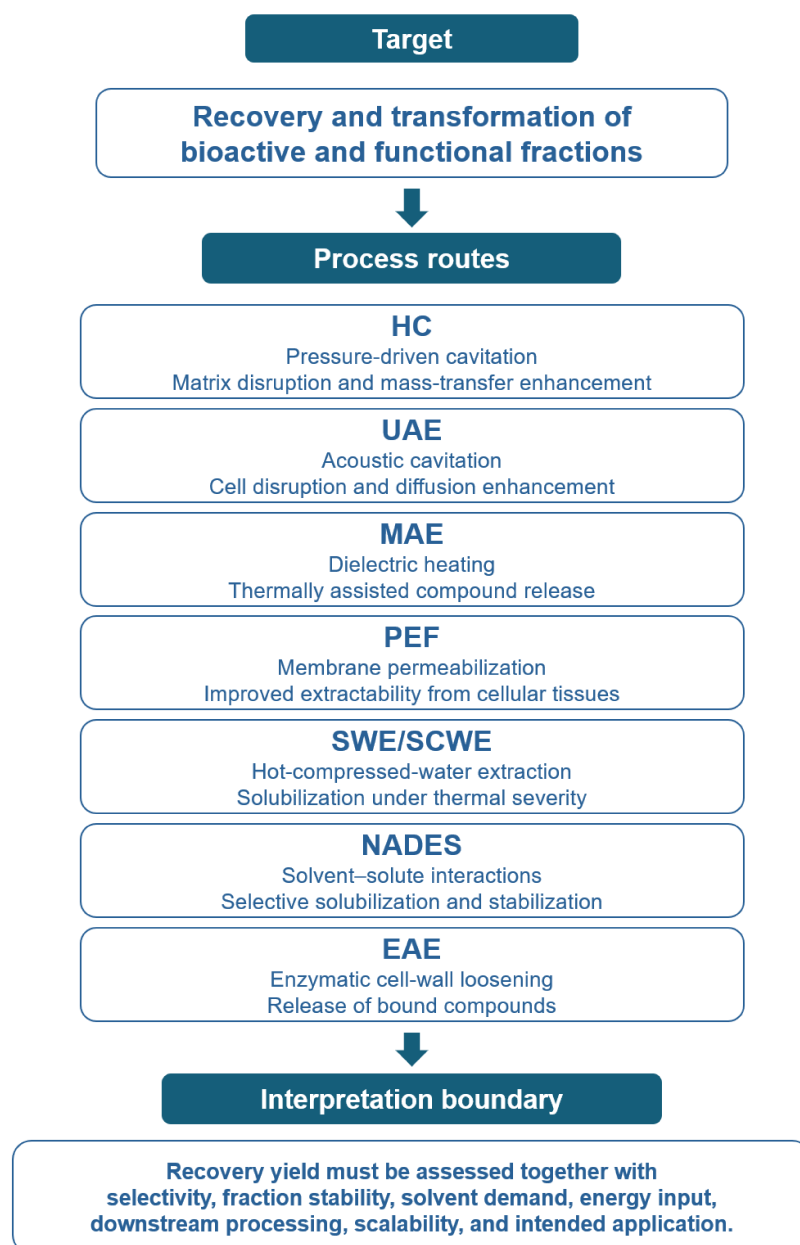


Figure 1. Operating principles of hydrodynamic cavitation and selected comparator technologies for the recovery and transformation of bioactive and functional fractions from agri-food residues and plant-derived matrices.

The scheme in Figure 1 provides a process-level comparison and does not imply technological superiority. Similar recovery outcomes may result from different mechanisms, including pressure-driven cavitation, acoustic cavitation, dielectric heating, electroporation, hot-compressed-water extraction, solvent-solute interactions, or enzymatic cell-wall loosening. HC, hydrodynamic cavitation; UAE, ultrasound-assisted extraction; MAE, microwave-assisted extraction; PEF, pulsed electric fields; SWE, subcritical water extraction; SCWE, supercritical water extraction; NADES, natural deep eutectic solvents; EAE, enzyme-assisted extraction.

3. Bioactive and Functional Fractions from Agri-Food Residues and Plant-Derived Matrices

The sustainable recovery of bioactive and functional fractions requires a preliminary distinction between starting matrices and target compound classes. Food-processing

residues and plant-derived matrices do not constitute a homogeneous group. They differ in water content, cellular structure, polysaccharide composition, presence of essential oils, protein content, degree of lignification, and distribution of phenolic compounds.

These differences strongly affect the response to extraction and intensification technologies. Matrix composition is therefore treated as an assessment variable, not as background information. Relevant descriptors include the dominant bioactive class, target-fraction localization, co-extractable compounds, water and fiber content, and possible associations of phenolics with pectins, proteins, cellulose, or other structural components.

3.1. Citrus By-Products

Citrus by-products are among the most relevant matrices for the recovery of bioactive and functional compounds from food-processing residues. Peels, albedo, flavedo, spent pulp, and juice-processing residues may contain flavanones, glycosylated flavonoids, phenolic acids, pectins, cellulose, essential oils, carotenoids, and volatile compounds [21,22].

Their interest is not limited to individual well-known molecules, such as hesperidin, narirutin, or naringin. In many cases, their technological value lies in complex fractions in which flavonoids, pectins, and other cell-wall constituents may occur as associated systems or phytocomplexes. For this reason, extraction should not be assessed only on the basis of the total amount of a marker compound.

From a process perspective, citrus matrices present specific challenges. The distribution of bioactive compounds varies among flavedo, albedo, and pulp residues. Essential oils and volatile compounds require processing conditions that differ from those suitable for hydrophilic flavonoids or pectins. Some fractions may also be sensitive to temperature, oxidation, pH, and treatment duration.

Different extraction techniques have been applied to citrus residues, including conventional methods, ultrasound-assisted extraction, and aqueous or low-solvent protocols [23,24]. Hydrodynamic cavitation is relevant for this class of matrices because it can combine physical disruption, mass-transfer enhancement, and aqueous-phase processing. However, the critical issue is not only to increase recovery. The recovered fraction should also be stable, adequately characterized, functionally meaningful, and compatible with the intended application.

3.2. Pomegranate By-Products

Pomegranate by-products are of particular interest for the recovery of polyphenolic fractions. Peels, internal membranes, and processing residues may be rich in ellagitannins, punicalagins, ellagic acid, and other antioxidant compounds [25].

Pomegranate-derived fractions are often associated with nutraceutical and health-related interest. However, the transfer of these properties to an ingredient, extract, or formulated product requires caution. The presence of compounds with documented chemical or biological activity does not automatically demonstrate functional efficacy, bioavailability, stability, or suitability for a specific application [25–27].

For hydrodynamic cavitation, pomegranate residues represent a relevant matrix because the target compounds are largely associated with plant tissues rich in cell-wall material and phenolic components. Mechanical and hydrodynamic effects may promote the release of polyphenols and phytocomplexes. The value of the process, however, depends on the chemical profile of the recovered fraction, the preservation of sensitive compounds, and the reproducibility of the result.

Pomegranate residues are therefore useful for assessing hydrodynamic cavitation as a recovery strategy for high-value polyphenolic fractions from agri-food residues. At the same time, a polyphenol-rich extract should be considered a candidate fraction for further

development, not direct evidence of efficacy in a final food, nutraceutical, formulation-oriented, or other functional product.

3.3. *Apple, Coffee, Conifer-Derived Materials, and Other Plant Matrices*

Beyond citrus and pomegranate residues, several plant and food-processing matrices offer opportunities for the recovery of bioactive and functional compounds. Apple residues, spent coffee grounds, conifer needles, bark, softwood-derived materials, and other plant-derived residues may contain polyphenols, phenolic acids, lignans, flavonoids, antioxidant compounds, antimicrobial fractions, free amino acids, cellulose, and other components of interest.

Conifer-derived materials and softwood residues are of specific interest because they may contain lignans, phenolic compounds, and fractions with reported antioxidant, antimicrobial, and other biological activities [28–32]. These matrices, however, are generally more complex than soft fruit residues. Their lignocellulosic structure can limit the accessibility of target compounds and may require more intensive processing conditions.

Spent coffee grounds represent a different case. In this matrix, the recovery of soluble compounds can be associated with the valorization of the residual solid fraction. For example, the simultaneous recovery of caffeic acid and production of cellulose microfibrils by hydrodynamic cavitation has been proposed [33]. This approach shifts the focus from the production of a single extract to a multiproduct fractionation strategy.

Apple by-products provide a further example of a wet and variable agri-food matrix. Their processing by hydrodynamic cavitation is relevant because it involves real processing streams and pilot-scale evidence [34]. In this case, the interest does not depend only on extract composition, but also on operating scale, water consumption, fraction stability, and possible integration with downstream operations.

These matrices show that sustainable recovery cannot be assessed through a single interpretive logic. In relatively soft and water-rich materials, cavitation may act mainly through mass-transfer enhancement. In more fibrous or lignocellulosic matrices, a stronger mechanical contribution may be required. In multiproduct systems, process value also depends on the quality of residual fractions and on the feasibility of the overall recovery pathway.

3.4. *Proteins, Peptides, Pectins, and Bioactive Macromolecules*

The recovery of bioactive and functional fractions is not limited to small phenolic molecules, pigments, or volatile compounds. Increasing attention is being directed toward macromolecules and supramolecular systems, including plant proteins, peptides, pectins, polysaccharides, protein–polyphenol complexes, conjugates, and colloidal systems.

Plant proteins are relevant for both nutritional value and technological functionality. Mixed systems containing whey proteins and plant proteins, or proteins combined with other functional components, may display synergistic properties of interest for food and formulation-oriented applications [35]. In this area, hydrodynamic cavitation may contribute to protein release or structural modification, but assessment should include solubility, digestibility, techno-functional properties, and preservation of the protein fraction.

Pectins represent another important class of plant-derived functional compounds. In citrus by-products and other residues, they may act both as structural components and as association partners for flavonoids and other bioactive molecules. Innovative techniques, including ultrasound-assisted extraction, microwave-assisted extraction, and enzyme-assisted extraction, have been widely investigated for pectin recovery from plant waste streams [36,37].

Pectin recovery should not be assessed only in terms of yield. Degree of esterification, molecular weight distribution, solubility, viscosity, gelling capacity, associated compounds, and formulation compatibility are also important. Excessive process severity may increase release while altering properties that are decisive for the intended application.

Protein–polyphenol systems and macromolecular conjugates introduce an additional level of complexity. Interactions between proteins and phenolic compounds may modify solubility, antioxidant activity, oxidative stability, emulsifying capacity, and behavior during digestion or storage. However, non-covalent complexation, covalent conjugation, aggregation, and denaturation should be clearly distinguished.

The matrices and compound classes considered in this section show that the sustainable recovery of bioactive and functional fractions is a multidimensional problem. The same technology may have different meanings depending on whether the objective is to extract flavonoids from citrus residues, recover polyphenols from pomegranate residues, process fibrous plant-derived materials, obtain plant proteins, or produce functional complexes. Hydrodynamic cavitation should therefore be evaluated as a potentially useful tool only when its action addresses a specific limitation of the matrix or process.

4. Hydrodynamic Cavitation as a Process-Intensification Platform for Bioactive and Functional Fraction Recovery

Hydrodynamic cavitation is generated when a liquid passes through regions of acceleration, pressure reduction, and subsequent pressure recovery. Under these conditions, vapor or gas–vapor cavities may form, grow, and collapse, producing localized energy release [38–41].

In the recovery of bioactive and functional fractions, the mere occurrence of cavitation is not sufficient to define the value of the process. What matters is how cavitation events interact with the treated matrix. Potentially useful effects include cell disruption, mass-transfer enhancement, micromixing, interfacial renewal, and improved contact between the liquid phase and the plant-derived material [40–44].

These effects may promote the release of compounds located in plant tissues, cell walls, polysaccharide networks, or macromolecular structures. The same intensification, however, may also increase degradation, oxidation, loss of volatile compounds, or undesirable modification of proteins and pigments. Process value therefore depends on the balance between release and preservation of the target fraction.

Hydrodynamic cavitation should be interpreted as a modular intensification platform. In some applications, its main contribution is mass-transfer enhancement. In others, matrix disruption, dispersion, macromolecular modification, or integration into a continuous or recirculated process may be more relevant. This distinction is necessary to avoid a generic assessment of the technology.

4.1. Mechanisms Relevant to Bioactive and Functional Fraction Recovery

The mechanisms most relevant to bioactive and functional fraction recovery are those that modify matrix accessibility and transfer of the target compounds into the liquid phase. In plant-derived materials, compounds of interest may be located in vacuoles, membranes, cell walls, oil compartments, polysaccharide networks, or structures associated with proteins and pectins.

The mechanical action of cavitation may weaken cell walls, increase the surface area exposed to the liquid phase, and promote the release of intracellular or wall-associated compounds. This aspect is relevant for peels, fibrous residues, seeds, bark, and plant-derived matrices in which the target fraction is not freely accessible. Excessive disruption,

however, may increase turbidity, suspended solids, co-extraction of undesired compounds, and separation difficulties.

A second mechanism involves mass transfer. Cavitation may improve solvent penetration into the matrix, reduce diffusional resistance, and enhance solid–liquid contact. This is particularly relevant in aqueous or low-solvent processes, where the extraction capacity of the medium may be lower than that of more aggressive organic solvents.

A third mechanism involves micromixing and dispersion. In liquid or semi-liquid matrices, cavitation may improve the distribution of particles, droplets, macromolecules, and poorly soluble compounds. This effect can be useful for beverages, emulsions, protein dispersions, and pectin–polyphenol systems. Long-term stability, however, should be verified directly rather than inferred from improved initial dispersion.

Under intense conditions, cavitation may also generate reactive species or promote localized oxidative processes [42]. This effect may be useful in other application areas, but it requires caution in bioactive recovery. Polyphenols, carotenoids, pigments, volatile compounds, and proteins may be sensitive to oxidation or transformation. For this reason, the chemical effects of cavitation should not be automatically interpreted as beneficial.

Useful cavitation conditions are therefore those that improve accessibility or release while preserving target-fraction quality and avoiding non-selective effects, degradation, or unnecessary separation burdens.

4.2. Reactor Configurations and Operating Variables

The configurations used to generate hydrodynamic cavitation differ in geometry, distribution of active zones, pressure drop, dissipated energy, and scale-up potential. The main device families include Venturi tubes, orifice plates, vortex cavitators, cavitating jets, and rotational systems [45–53].

Venturi devices are particularly relevant because cavitation can be modulated through the geometry of the converging section, throat diameter, throat length, and diffuser design [45–47,51,52]. In the recovery of bioactive and functional fractions, this degree of controllability is useful when treatment intensity must be balanced against preservation of the target fraction.

Orifice plates are simple and easily implementable configurations. They can generate intense cavitation, often in more localized zones. This may promote matrix disruption, but it may also increase heating, pressure loss, or treatment non-uniformity.

Vortex devices and rotational systems provide different modes of cavitation generation. Vortex devices exploit vortical flow structures, whereas rotational systems generate rapid pressure and shear variations in mechanically active configurations [48–50,53]. These approaches may be promising for continuous processing, but they require assessment in terms of energy consumption, operational stability, solids handling, and quality of the recovered fraction.

Operating variables are as important as reactor geometry. Pressure, flow rate, cavitation number, temperature, treatment time, number of passes, solid-to-liquid ratio, particle size, solvent composition, and dissolved gases can all affect process outcomes. Nominal treatment time is poorly informative unless it is related to the actual exposure of the matrix to cavitating zones.

Temperature requires specific attention. A moderate temperature increase may favor diffusion and extraction, but it may also accelerate degradation, volatilization, or oxidation. To attribute a process advantage correctly to cavitation, thermal controls and comparisons with treatments conducted at equivalent temperature are needed.

Scale also changes the interpretation of results. A device that is effective with small volumes or dilute suspensions is not automatically transferable to concentrated matrices,

real process streams, or semi-industrial conditions. Scalability requires hydraulic-regime stability, temperature control, solids management, downstream separation, and assessment of specific energy input.

No reactor configuration is universally superior. Reactor selection should depend on the required process function. Moderate intensification may be sufficient for diffusion-limited matrices. Fibrous plant-derived materials may require a stronger mechanical contribution. For proteins, pectins, and colloidal systems, control of treatment severity becomes essential.

4.3. Process Functions in Bioactive and Functional Fraction Recovery

Hydrodynamic cavitation can perform different functions in the recovery and transformation of bioactive and functional fractions. The first is extraction intensification. In this case, the process aims to increase matrix accessibility, improve contact with the liquid phase, and accelerate the release of the target fraction.

A second function is cellular or structural disruption. This function is useful when the process is limited not primarily by compound solubility, but by physical accessibility within the matrix. The main risk is excessive non-selective disruption, which may increase co-extraction of undesired components and make clarification or downstream separation more difficult.

A third function is the reduction in organic solvent use. Cavitation may improve the effectiveness of water or low-solvent mixtures. This aspect is consistent with green recovery, but it is not sufficient on its own to demonstrate sustainability. Energy use, recovered-fraction concentration, microbiological stability, and downstream operations must also be considered.

A fourth function concerns macromolecular modification. Proteins, pectins, and polysaccharides may undergo changes in structure, size, aggregation state, or interaction with phenolic compounds. Some modifications may improve solubility, emulsification, or colloidal stability. Others may reduce functionality, digestibility, or reproducibility.

A fifth function concerns dispersion and emulsification. Cavitation may promote the distribution of particles, droplets, macromolecules, and poorly soluble compounds. This function is relevant to beverages, emulsions, colloidal systems, and functional ingredients. However, stability over time should be demonstrated rather than inferred from improved initial dispersion.

A sixth function concerns process integration. Hydrodynamic cavitation can be incorporated into continuous or semi-continuous lines and may combine extraction, mixing, size reduction, and suspension treatment. This perspective is relevant to sustainable processing and circular-resource use, but requires evidence on mass balance, energy use, water management, downstream separation, and reproducible quality of the recovered fraction [54–58].

Figure 2 summarizes this interpretation by positioning hydrodynamic cavitation as an upstream process module rather than as direct evidence of application efficacy.

The evidence gate includes stability, selectivity, safety, bioaccessibility, formulation compatibility, energy use, downstream operations, scale-up, and regulatory suitability. Recovered fractions should therefore be interpreted as candidate ingredients or functional intermediates, not as proof of final efficacy.

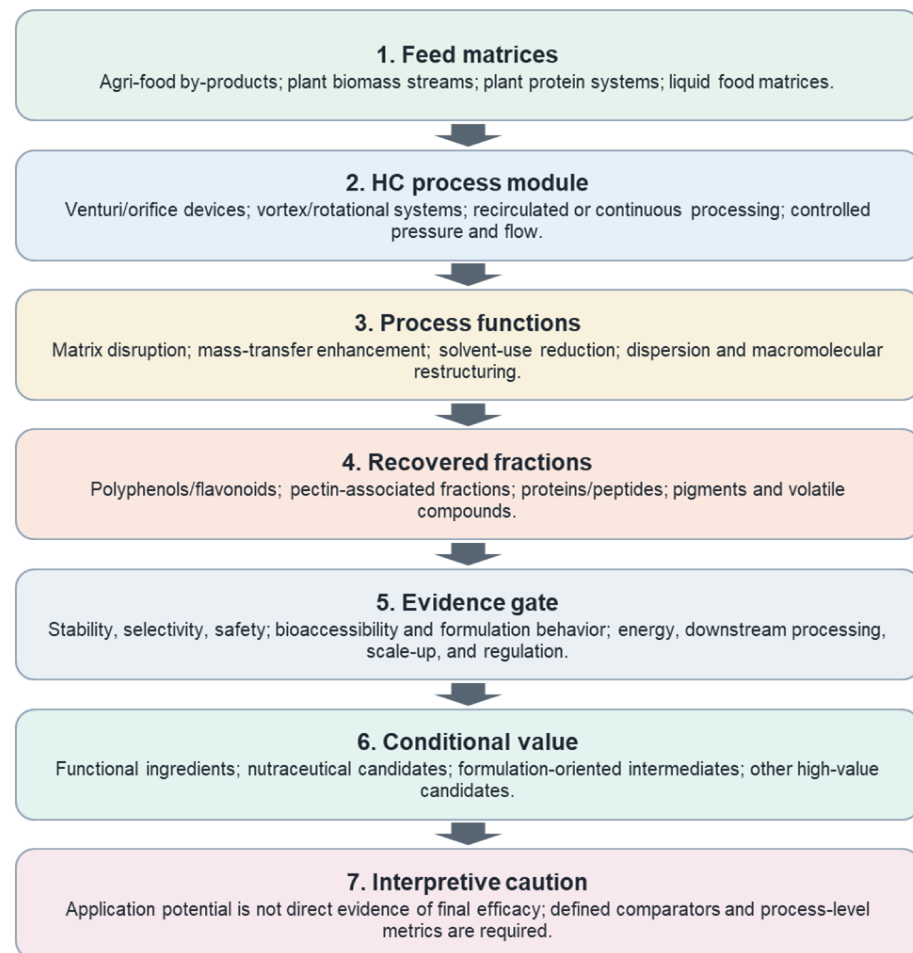


Figure 2. Hydrodynamic cavitation as a conditional platform for the sustainable recovery and transformation of bioactive and functional fractions.

5. Matrix-Specific Quantitative Evidence and Comparison with Alternative Technologies

Quantitative comparison is necessary to assess whether hydrodynamic cavitation provides a real advantage in the recovery or transformation of bioactive and functional fractions. However, cross-study comparison remains limited by differences in feedstock composition, moisture content, pretreatment, solvent system, reactor geometry, liquid-to-solid ratio, treatment time, temperature, analytical method, scale, and reporting basis. The evidence is therefore interpreted by matrix and target fraction, rather than through a single cross-technology ranking.

The discussion considers recovery yield, total phenolic content, flavonoid concentration, pectin or protein recovery, antioxidant response, solvent composition, treatment time, throughput, specific energy input, and available information on fraction quality or stability. This structure distinguishes cases where hydrodynamic cavitation shows a measurable advantage from cases where performance is comparable but less completely characterized, or where the evidence remains preliminary. Because the available studies do not report all parameters on a harmonized basis, quantitative values are interpreted within their matrix-specific context. Direct comparison is therefore based on the reported process conditions, target fraction, comparator technology, scale, energy or resource indicators, and quality-related endpoints, rather than on a single pooled numerical ranking.

5.1. Citrus By-Products, Flavonoids, and Pectin-Associated Fractions

Citrus by-products are among the most representative matrices for evaluating hydrodynamic cavitation in the recovery of bioactive and functional fractions. Their relevance derives from the simultaneous presence of flavanones, phenolic compounds, pectins, essential oils, structural polysaccharides, and residual cellulosic material. This composition makes citrus residues suitable for assessing hydrodynamic cavitation not only as an extraction method, but also as an aqueous processing route for integrated residue valorization.

Hydrodynamic cavitation has been applied to orange peel at real scale, showing that wet citrus residues can be processed within an integrated resource-use strategy [59]. This point is important because wet processing can reduce the need for extensive drying and may improve compatibility with continuous or semi-continuous operation. The relevant indicators are therefore not limited to target-compound recovery, but also include recovered mass, treated volume, processing time, solvent or reagent demand, downstream separation, and energy input.

The most characteristic citrus application concerns pectin-associated fractions. In lemon, grapefruit, blood orange, and bitter orange residues, hydrodynamic cavitation has been associated with the recovery of fractions containing flavonoids, volatile compounds, and pectin-rich structural components [60–62]. These fractions should not be interpreted as simple phenolic extracts. Their potential value depends on combined composition and structure, including phenolic profile, pectin characteristics, volatile fraction, molecular properties, and stability.

Citrus fractions obtained by hydrodynamic cavitation have also been assessed for biological activity in experimental models [63–65]. These results support the interest of pectin–flavonoid systems, but they do not demonstrate final product efficacy. The transition from a recovered bioactive fraction to a food, nutraceutical, or formulation-oriented ingredient requires standardization, storage stability, safety assessment, bioaccessibility, formulation compatibility, and realistic dose evaluation.

A further process advantage concerns multiproduct valorization. Hydrodynamic cavitation has been proposed for obtaining biopolymers and micronized cellulose from citrus processing residues under aqueous conditions and with reduced reagent demand [66,67]. This expands the role of the technology beyond soluble-compound recovery. However, the strength of the evidence depends on mass balance, co-product quality, downstream separation, process water management, and comparison with established pectin, cellulose, or phenolic-extraction routes.

Recent interpretations of IntegroPectin systems and citrus flavonoid–pectin conjugates suggest that the recovered fraction may have a more complex functional structure than a conventional extract [68,69]. This perspective is promising, but it also increases the need to distinguish among composition, structure, biological activity, formulation behavior, and application readiness.

Comparison with alternative technologies remains essential in citrus matrices. A recent study directly compared ultrasound-assisted extraction and hydrodynamic cavitation for phenolic recovery from lemon by-products, showing that the outcome depends on solvent composition, operating conditions, and optimization criteria [70]. Additional cavitation-based work on citrus-waste valorization further confirms the potential of the technology, while also showing that the treatment objective must be defined precisely [71].

Overall, citrus residues provide one of the most developed matrix-specific cases for discussing hydrodynamic cavitation in the sustainable recovery of bioactive and functional fractions. Their main relevance lies in the possibility of treating wet matrices rich in flavonoids, pectins, and biopolymers within an integrated processing logic. The main

limitations remain protocol comparability, treatment-severity control, stability of sensitive fractions, downstream separation, energy reporting, and application-oriented validation.

5.2. *Pomegranate and Polyphenol-Rich Residues*

Pomegranate by-products provide a useful case for distinguishing recovery performance from application readiness. Peels, internal membranes, and processing residues contain ellagitannins, punicalagins, ellagic acid derivatives, and other phenolic compounds, making them relevant targets for polyphenol-rich fraction recovery. Hydrodynamic cavitation has been used to obtain antioxidant phytocomplexes from these residues, with reported *in vitro* biological activity [72]. In this context, the most informative indicators are not limited to total phenolic content, but also include recovered extract mass, target-compound profile, antioxidant response, solvent composition, treatment time, and reproducibility of the recovered fraction.

Further evidence indicates that pomegranate fractions obtained through hydrodynamic cavitation may produce biological effects in experimental cardiovascular models [73]. This supports the interest of the recovered fractions, but it also illustrates the need for careful interpretation. Biological response cannot be inferred from extraction yield or antioxidant activity alone. Composition, dose, bioaccessibility, stability, matrix compatibility, and the experimental model determine whether a recovered fraction can be considered application-relevant.

The broader literature on pomegranate-peel formulations and selected metabolites further supports the biological interest of this matrix in inflammatory, neurological, pharmacokinetic, and *in silico* contexts [74,75]. These studies are important because they place cavitation-derived fractions within a wider application rationale. At the same time, they confirm that compound identification, predicted activity, experimental bioactivity, and validated use represent different levels of evidence.

Comparison with alternative extraction routes remains necessary. Sustainable protocols for recovering bioactive compounds from pomegranate-processing by-products have been assessed in relation to process conditions and recovered compounds [76]. Hydrodynamic cavitation should therefore be evaluated against alternative green or intensified methods not only by total phenolic yield, but also by solvent demand, processing time, temperature, extract selectivity, stability, downstream requirements, and scale relevance.

Overall, pomegranate residues justify inclusion as a specific matrix class because they show both the potential and the current limits of hydrodynamic cavitation for bioactive-fraction recovery. The evidence supports recovery of antioxidant and polyphenol-rich phytocomplexes from a well-defined by-product matrix. It remains limited by incomplete cross-technology comparability, limited energy reporting, insufficient long-term stability data, and the need to connect recovered-fraction composition with realistic application conditions.

5.3. *Apple Residues, Coffee Grounds, and Lignocellulosic Matrices*

Apple residues, spent coffee grounds, conifer-derived materials, bark, softwood residues, and related plant matrices extend the assessment of hydrodynamic cavitation to heterogeneous and fibrous feedstocks. These systems are characterized by variable moisture, resistant cell-wall structures, mixed soluble and insoluble fractions, and stronger downstream constraints than softer fruit matrices.

Conifer-derived and softwood materials contain phenolics, lignans, antioxidant fractions, antimicrobial components, free amino acids, cellulose, and other recoverable constituents [77–79]. Their compact lignocellulosic structure makes compound accessibility a central limitation. Hydrodynamic cavitation is therefore relevant mainly as a mechanical and aqueous intensification route, but recovery data must be connected with product func-

tionality, sensory quality, safety, and reproducibility, as shown by applications involving conifer-derived fractions in bakery products [80].

Spent coffee grounds provide a multiproduct example. Venturi-based hydrodynamic cavitation has been used for the simultaneous extraction of caffeic acid and production of cellulose microfibrils [33]. The value of this case lies in the combined recovery of soluble and solid fractions, although its practical significance depends on separation, energy demand, co-product quality, and overall process feasibility.

Apple by-products provide a scale-relevant case because pilot-scale extraction tests indicate that hydrodynamic cavitation can treat wet and compositionally variable processing streams [34]. This supports a realistic feedstock-handling perspective, but transferability still requires clearer reporting of solids content, treated volume, throughput, specific energy input, mass balance, fraction stability, and downstream processing.

Overall, these matrices show where hydrodynamic cavitation may be useful beyond simple extraction: wet-stream processing, tissue disruption, and multiproduct recovery. At the same time, they expose the main scale-up constraints more clearly than citrus or pomegranate systems.

5.4. Beverages and Liquid Food Systems

Beverages and liquid food systems represent a distinct application field because hydrodynamic cavitation can be integrated directly into the process stream. In these systems, the target is not only extraction from a solid matrix, but also mixing, precursor conversion, macromolecular modification, interfacial contact, stabilization, or preservation of selected bioactive compounds.

Brewing provides the most developed example. Hydrodynamic cavitation has been associated with process intensification, transformation of malt and hop components, gluten reduction, and retention or modulation of hop-derived bioactive compounds, including prenylflavonoids such as xanthohumol [81–86]. More recent studies have addressed dimethyl sulfide precursor conversion, hop alpha-acid isomerization, wort quality, and energy consumption [87,88]. These outcomes are important because they connect cavitation with real processing conditions, rather than only laboratory extraction.

Liquid plant-based systems provide a broader but less mature field. In these matrices, hydrodynamic cavitation may improve dispersion, homogenization, and contact among proteins, colloids, fibers, and soluble compounds. However, improved processing response must be assessed together with color, flavor, turbidity, colloidal stability, microbiological safety, storage behavior, and consumer-relevant quality.

Overall, beverages and liquid food systems support the role of hydrodynamic cavitation as a process-integration technology. Their main value lies in treating the matrix close to its final form or as a food intermediate. The main limitation is system specificity: results obtained in brewing or selected liquid matrices cannot be generalized without data on composition, stability, sensory quality, energy input, and shelf-life performance.

5.5. Plant Proteins, Peptides, and Antinutritional Factors

Plant proteins extend the role of hydrodynamic cavitation from small-molecule recovery to macromolecular fraction processing. In pea, oat, fava bean, seed-derived, and related matrices, the target is not only extraction yield, but also preservation or modification of solubility, digestibility, nutritional profile, and techno-functional properties.

Comparative studies have assessed hydrodynamic cavitation against ultrasound, high-pressure processing, and conventional techniques for protein recovery from plant matrices [89–91]. These comparisons are important because increased yield alone is insufficient

for protein ingredients. Structural integrity, aggregation, denaturation, amino-acid profile, functional behavior, and processability must be evaluated together with recovered mass.

Reduction of antinutritional factors provides an additional criterion. In pea-protein systems, hydrodynamic cavitation, ultrasound, and high-pressure processing have been compared for the reduction in undesirable components [92]. This effect is valuable only if it is not accompanied by loss of protein quality, digestibility, or functionality.

Other examples, including protein extraction from apple seeds, almond-beverage production, and gliadin modification, broaden the application field to seed matrices, liquid plant-based systems, and sensitive protein structures [93–95]. These cases support the potential of hydrodynamic cavitation for plant-protein processing, but they also require careful control of treatment severity, safety, nutritional quality, and reproducibility.

Overall, plant-protein systems provide a relevant but demanding evidence class. Hydrodynamic cavitation may improve extraction, dispersion, or functional modification, but application value depends on integrated reporting of yield, structure, solubility, digestibility, antinutritional factors, techno-functional properties, energy input, and downstream processing.

5.6. Protein–Polyphenol Systems and Functional Restructuring

Protein–polyphenol systems illustrate a further function of hydrodynamic cavitation beyond extraction: the modification of interactions among macromolecules, phenolic compounds, and colloidal structures. In these systems, process value is defined by changes in solubility, aggregation, interfacial behavior, antioxidant response, digestibility, and formulation stability, rather than by recovered mass alone.

Hydrodynamic cavitation and related intensified treatments may promote dispersion, exposure of binding sites, complex formation, or structural rearrangement in protein–polyphenol mixtures [96–99]. These effects can be useful for generating functional intermediates, but they must be distinguished from uncontrolled denaturation, precipitation, oxidation, or loss of nutritional quality.

This evidence remains preliminary. Application relevance requires stronger links among process conditions, molecular changes, colloidal behavior, nutritional quality, storage stability, and final-use performance.

5.7. Cross-Technology Interpretation and Evidence Limits

Cross-technology comparison is essential but must be interpreted with caution. Hydrodynamic cavitation, ultrasound-assisted extraction, microwave-assisted extraction, pulsed electric fields, subcritical or supercritical water extraction, natural deep eutectic solvents, and enzyme-assisted extraction act through different mechanisms and are often tested under non-equivalent conditions. Solvent composition, liquid-to-solid ratio, temperature, treatment time, energy input, feedstock preparation, and analytical endpoints can strongly affect the reported outcome.

Ultrasound-assisted extraction is the closest laboratory comparator because both technologies involve cavitation phenomena, although acoustic and pressure-driven cavitation differ in energy delivery, active volume, and scalability [100,101]. Microwave-assisted extraction is more closely linked to dielectric heating and rapid temperature increase [102,103]. Pulsed electric fields mainly act through membrane permeabilization and are therefore highly dependent on tissue structure, field strength, pulse conditions, and subsequent extraction steps [104,105]. Combined pulsed-electric-field and subcritical-water approaches, as well as pressing studies on citrus residues, further show that membrane permeabilization may act as a pretreatment rather than as a complete extraction route [106,107]. Broader

applications to aromatic plants and food by-products confirm that matrix conductivity, tissue state, and process integration strongly affect performance [108].

Subcritical or supercritical water extraction can improve solvent performance under high-temperature and high-pressure conditions, but may introduce thermal-severity and pressure-related constraints [109–111]. Pilot-scale, kinetic, and sequential studies on citrus residues show its relevance for flavonoid recovery, while also confirming the need to control temperature, pressure, degradation risk, and downstream processing [112,113]. Natural deep eutectic solvents improve solubilization and selectivity through solvent–solute interactions, although viscosity, solvent recovery, storage stability, and downstream compatibility remain important limitations [114–116]. Enzyme-assisted extraction offers biochemical selectivity under mild conditions, but depends on substrate specificity, enzyme cost, reaction time, and process control [117,118].

The available literature therefore does not support a universal ranking of these technologies. A meaningful comparison requires matrix-specific reporting of yield, target-compound profile, solvent demand, processing time, temperature, treated volume, throughput, specific energy input, fraction stability, downstream separation, and intended application. Under this framework, hydrodynamic cavitation is most clearly justified when recovery, functional modification, or wet-stream integration is achieved with acceptable energy demand and preserved fraction quality. It remains less mature when energy, stability, mass balance, or scale data are missing.

5.8. Quantitative Evidence, Scale-Relevant Indicators, and Reporting Limits

The matrix-specific evidence discussed above provides quantitative anchors, but their interpretation must remain tied to process function, reporting basis, and study context. Citrus by-products currently provide one of the most developed matrix-specific evidence domains. Real-scale water-based processing of waste orange peel showed that hydrodynamic cavitation can be applied to wet citrus residues at a scale involving several kilograms of raw material in more than 100 L of water, using water as the extraction medium [59]. In this domain, measurable outputs include pectin properties, phenolic recovery, flavonoid-rich pectin-associated fractions, volatile-compound behavior, and residual-solid valorization. One particularly reliable compositional indicator is the low degree of esterification reported for the isolated orange pectin, $17.05 \pm 0.60\%$ [59]. Direct comparison with ultrasound-assisted extraction in lemon by-products also showed higher values for selected phenolic and antioxidant indicators under the tested conditions [70]. These results support citrus residues as one of the most developed current cases for hydrodynamic cavitation, especially for wet residues, water-based processing, pectin-associated phenolic recovery, and integrated citrus-waste valorization. However, they do not justify a general claim of superiority because energy input, solvent conditions, volatile retention, concentration steps, storage stability, and downstream processing are not reported on a harmonized basis.

Pomegranate residues provide a second relevant case because hydrodynamic cavitation has been compared with conventional extraction, ultrasound-assisted extraction, and microwave-assisted extraction [72,76]. The reported evidence includes compositional markers such as punicalins, punicalagins, ellagic acid, total polyphenols, extraction yield, process time, and energy input. This supports the use of hydrodynamic cavitation as a recovery route for polyphenol-rich fractions. However, biological or nutraceutical relevance remains conditional on fraction stability, bioaccessibility, dose realism, formulation compatibility, and application-specific testing.

Scale-relevant information is particularly important for wet and fibrous matrices. Apple by-products show that hydrodynamic cavitation can be assessed not only in terms of extract composition, but also in terms of biomass loading, process temperature, cavitation

regime, treatment time, and energy requirement for producing a defined amount of dry extract [34]. Spent coffee grounds further illustrate a multiproduct logic, where phenolic recovery and cellulose-rich solid fractions can be considered within the same process [33]. These examples support hydrodynamic cavitation as a wet-stream and multiproduct processing tool, rather than only as a single-compound extraction method.

Beverages and liquid food systems represent a different type of evidence. In these cases, hydrodynamic cavitation is not used only to extract target compounds from a solid residue, but also to intensify liquid-phase operations such as mixing, precursor conversion, macromolecular modification, dispersion, stabilization, and process integration. Process-oriented studies on wort boiling, hop-compound transformation, and almond beverages indicate that hydrodynamic cavitation can reduce treatment time or energy demand while preserving relevant quality attributes under defined conditions [87,88,94]. In almond beverage production, energy consumption was estimated below 50 Wh/L before bottling, after dilution to beverage concentration [94]. This is a useful quantitative anchor because it links energy input to a product-oriented processing basis. However, liquid food applications remain system-specific and require sensory, shelf-life, microbiological, and scale-up validation.

Plant-protein systems expand the interpretation beyond phenolic recovery. Hydrodynamic cavitation improved protein recovery or protein content in pea, faba bean, and oat-hull systems and was also associated with changes in antinutritional-factor distribution in pea protein isolates [89–92]. These results are important because they connect extraction performance with nutritional and functional quality. Nevertheless, pH adjustment, precipitation, drying, digestibility, antinutritional-factor partitioning, and residue valorization remain essential reporting items. Protein extraction yield alone is therefore insufficient to establish application readiness.

Hydrodynamic cavitation can also modify macromolecular interactions. In protein–polyphenol systems, cavitation has been reported to increase protein–polyphenol binding and to modify selected functional properties of the resulting complexes [96,97]. This evidence indicates that hydrodynamic cavitation may act not only as an extraction tool, but also as a structuring or functionalization technology. However, model-system results should not be transferred directly to real food matrices unless stability, sensory quality, digestibility, bioaccessibility, and regulatory constraints are evaluated.

Comparator technologies also show strong but mechanism-specific advantages. Ultrasound-assisted extraction, microwave-assisted extraction, pulsed electric fields, subcritical or supercritical water extraction, natural deep eutectic solvents, and enzyme-assisted extraction may outperform hydrodynamic cavitation for specific targets when the dominant limitation is acoustic disruption, microwave heating, electroporation, solvent-polarity modulation, solvent–solute affinity, or enzymatic selectivity [100–105,109,114–118]. For example, pulsed-electric-field treatment of lemon residues increased the recovery of hesperidin and eriocitrin under defined electric-field and pressing conditions [104,105]. Enzyme-assisted extraction can also improve essential-oil release from citrus peels through cell-wall degradation, while producing fermentable sugars as an additional valorization stream [118]. These examples reinforce the need for a conditional comparison rather than a universal hierarchy.

The representative evidence domains and their interpretation limits are summarized in Table 2. The table identifies the quantitative indicators considered in the literature and the main boundaries for comparison, rather than establishing a numerical ranking among technologies.

Table 2 indicates that quantitative comparison is useful only when recovery indicators are assessed together with process conditions, energy or resource demand, recovered-fraction quality, downstream steps, and application requirements.

Table 2. Matrix-specific quantitative indicators, comparative interpretation, and reporting limits for hydrodynamic cavitation and comparator technologies.

Evidence Domain	Quantitative Anchors Considered	Main Interpretation	Main Reporting Limit
Citrus by-products	Process scale, water-based operation, pectin properties, phenolic recovery, flavonoid-rich pectin-associated fractions, volatile behavior, and HC-UAE comparison	Most developed matrix-specific evidence for HC in wet citrus residues, pectin-associated phenolic recovery, and integrated citrus-waste valorization	Energy input, volatile retention, concentration steps, storage stability, downstream separation, and application-oriented performance are not harmonized
Pomegranate residues	Target polyphenols, extraction yield, process time, energy input, and comparison with CE, UAE, and MAE	Supports recovery of polyphenol-rich fractions under defined study conditions	Bioaccessibility, dose realism, long-term stability, formulation compatibility, and final application remain conditional
Apple residues, coffee grounds, and fibrous matrices	Biomass loading, process temperature, cavitation regime, treatment time, energy estimate, phenolic recovery, and cellulose-rich co-products	Supports wet-stream handling, tissue disruption, rapid extraction, and multiproduct valorization	Solids handling, mass balance, specific energy allocation, downstream separation, and co-product quality remain incomplete
Beverages and liquid food	Precursor conversion, process time, energy demand, product quality, and liquid-phase integration	HC can act as an integrated process-intensification step in liquid systems	Sensory quality, shelf life, foaming behavior, microbiology, and industrial transfer require case-specific validation
Plant proteins	Protein recovery, protein purity, extraction efficiency, antinutritional-factor distribution, and selected functional indicators	HC may improve extraction and selected nutritional-quality indicators	pH adjustment, precipitation, drying, digestibility, antinutritional-factor partitioning, and residue use must be reported together
Protein–polyphenol systems	Binding level, structural modification, emulsifying properties, and antioxidant response	HC may also function as a macromolecular structuring technology	Evidence remains mainly model-system based and requires validation in real matrices
Comparator technologies	UAE, MAE, PEF, SWE/SCWE, NADES, and EAE, each with technology-specific parameters, mechanisms, and endpoints	HC is most defensible when the limitation is hydrodynamic, diffusional, related to wet-matrix handling, or linked to combined extraction and physical restructuring	No universal ranking is justified across different solvents, temperatures, pressures, scales, endpoints, and downstream requirements

Note: The table summarizes representative quantitative anchors and reporting limits across heterogeneous studies. It is not intended as a meta-analytical ranking, proof of sustainability, demonstration of technological superiority, or validation of application readiness. Interpretation depends on matrix type, target fraction, operating conditions, comparator quality, recovered-fraction stability, downstream requirements, scale relevance, and intended use. References supporting each evidence domain are cited in the corresponding paragraphs of Section 5.8 and in the matrix-specific subsections above.

These data support a conditional rather than absolute interpretation. Hydrodynamic cavitation is most defensible when the process limitation is related to wet-matrix handling, mass transfer, cell or tissue disruption, suspension processing, liquid-phase intensification, or combined recovery and restructuring. It may be equivalent to other technologies when similar recovery is obtained without a clear advantage in energy use, solvent demand, fraction stability, treated volume, or downstream processing. It may be less suitable when the dominant requirement is high chemical selectivity, specific solvent–solute interac-

tion, targeted electroporation, enzymatic specificity, or temperature- and pressure-driven solvent modulation.

Economic comparison remains premature in most cases because formal techno-economic data are rarely reported on a comparable basis. The most useful economic proxies are treated volume, throughput, liquid-to-solid ratio, solvent or reagent demand, specific energy input, process time, concentration requirement, separation burden, equipment utilization, and final product concentration. These parameters should be reported before claims of cost-effectiveness, scalability, or industrial superiority are made.

The main limitation is therefore not the absence of quantitative outcomes, but their non-uniform reporting. Future studies should report at least feedstock condition, solvent system, liquid-to-solid ratio, reactor configuration, pressure or flow conditions, treatment time, temperature, treated volume, energy input, recovery yield, target-compound concentration, fraction stability, and downstream processing. Without these elements, claims of sustainability, cost-effectiveness, scalability, or technological superiority remain premature. This interpretation avoids overgeneralization and distinguishes measurable process advantages from unsupported claims of universal technological superiority.

6. Application Requirements: Stability, Safety, Functionality, and Scale Relevance

Recovery yield alone does not establish application value. Fractions obtained from agri-food residues and plant-derived matrices must retain chemical stability, functional performance, safety, reproducibility, and compatibility with the intended use. This requirement is particularly important for hydrodynamic cavitation, because treatment intensity may promote release, dispersion, or structural modification, but may also affect sensitive compounds, macromolecular integrity, colloidal behavior, and downstream processability.

The stability issue is compound- and matrix-specific. Polyphenols, carotenoids, volatile compounds, proteins, and pectin-associated fractions may respond differently to cavitation intensity, temperature rise, oxidation, residence time, and downstream stabilization. Application assessment should therefore move from analytical recovery to product-oriented validation.

Preservation should therefore be assessed through compound- and fraction-specific indicators rather than through global recovery alone. For phenolic and flavonoid-rich fractions, relevant indicators include target-compound profile, total phenolic or flavonoid content, antioxidant response, and evidence of degradation or transformation during processing and storage. For volatile compounds and essential-oil-related fractions, retention and loss should be considered together with temperature rise, residence time, and downstream stabilization. For proteins, useful indicators include recovery, purity, solubility, digestibility, structural integrity, antinutritional-factor distribution, and techno-functional properties. For pectin-associated fractions, degree of esterification, molecular properties, associated phenolics, and storage behavior are more informative than yield alone, as shown by citrus pectin-associated systems and by broader formulation-oriented stability requirements [59–69,119–125].

In pectin- and protein-associated systems, relevant properties include molecular structure, interaction behavior, gastrointestinal stability, and storage response, because functionality may depend on the organization of the recovered fraction rather than on compound concentration alone [119,120]. For emulsions and colloidal systems, additional criteria are required, including particle size, physical stability, oxidative stability, retention of associated compounds, and performance in real matrices [121–125].

Food incorporation provides a direct test of application relevance. Citrus-derived pectin-associated fractions have been evaluated in gluten-free biscuits, where the recovered

material is assessed within a product matrix rather than only as an extract [126]. Fruit by-product extracts have also been incorporated into gluten-free and vegan cookies, making technological behavior and product compatibility central criteria [127]. Conifer-derived ingredients have been tested in enriched bread, further showing that recovery must be connected with sensory quality, stability, and matrix performance [128].

Other high-value formulation-oriented applications require a cautious interpretation. Hesperidin from orange peel has been discussed as a skincare bioactive, with relevance depending on extraction, stability, delivery, and formulation performance [129]. Pomegranate-derived extracts have also been examined in skin-related and photoprotective contexts, supporting biological plausibility and formulation interest rather than direct evidence for cavitation-derived products [130,131]. Broader literature on plant-based antioxidants further supports their cosmetic and dermocosmetic relevance, while confirming that safety, bioavailability, stability, and claim substantiation belong to later development stages [132–136]. Within this framework, hydrodynamic cavitation should be interpreted as an upstream recovery or structuring technology that may generate candidate ingredients or functional intermediates.

Material and product specifications should therefore be defined before application relevance is inferred. For recovered fractions, relevant specifications include composition, marker compounds, purity, moisture or dry-matter basis, degradation markers, microbial or contaminant-related safety indicators, and storage stability. For product-oriented uses, additional specifications include dose, incorporation level, matrix compatibility, sensory or physical stability, functional performance, and compliance with the intended application requirements.

Scale relevance remains a separate requirement. Treated volume, throughput, specific energy input, solvent or water demand, feedstock variability, mass balance, and downstream separation should be reported together with recovery and quality endpoints. Without these data, laboratory or pilot-scale results remain difficult to transfer to industrial processing, even when recovery yield or biological activity appears promising.

7. Sustainability, Scale-Up, and Evidence Requirements

Sustainability and scale relevance must be assessed at the level of the complete recovery pathway, not only at the level of the cavitation step. Reduced solvent use, aqueous processing, or shorter treatment time can support a sustainability argument only when they remain meaningful after energy demand, water use, recovered-fraction concentration, downstream operations, residue management, mass balance, and comparison with appropriate alternatives are considered [11]. An apparent advantage during extraction may be reduced or lost during filtration, clarification, concentration, drying, stabilization, or formulation.

7.1. Solvents, Water, and Energy

Reduced organic-solvent use is a relevant potential advantage of hydrodynamic cavitation, especially for food, nutraceutical, formulation-oriented, and other high-value applications. However, solvent reduction should be evaluated together with water demand, extract dilution, concentration requirements, stabilization, and downstream processing. Aqueous processing may reduce solvent-related burdens, but large liquid volumes or dilute recovered fractions can shift the burden to separation, concentration, or drying.

Energy should be reported on a comparable and function-specific basis. Useful indicators include energy per mass of treated matrix, energy per unit of recovered compound, and energy per yield increase relative to an appropriate control. Pressure, flow rate, recirculation, number of passes, temperature rise, reactor configuration, and treated volume

should be reported together with recovery data because they determine both cavitation intensity and process efficiency [12–15]. Without these parameters, environmental advantage remains potential rather than demonstrated.

7.2. Scale-Up and Process Integration

Scale-up is a decisive requirement for hydrodynamic cavitation because performance depends on hydraulic regime, cavitation distribution, residence time, solids content, pressure drop, heating, wear, and operational stability. Increasing treated volume is therefore not equivalent to demonstrating transferability. The quality and stability of the recovered fraction must remain reproducible when reactor size, flow rate, and feedstock properties change [137–139].

Process integration is one of the most promising features of the technology. Hydrodynamic cavitation may be incorporated into recirculated or continuous lines in which pumping, mixing, suspension treatment, extraction, or beverage processing are already present. This advantage is meaningful only if integration reduces process time, solvent demand, resource use, or downstream complexity, rather than adding an additional unit operation without a system-level benefit.

Scale-up claims are therefore strongest when treated volume, continuity of operation, solids handling, thermal control, product quality, and downstream steps are reported together. In their absence, larger treated volume or pilot-scale operation should be interpreted as scale-relevant evidence, not as proof of industrial readiness.

At present, industrial implementation should therefore be interpreted through scale-relevant and economic proxies rather than through formal cost-effectiveness ranking. The most informative proxies include throughput, operating continuity, specific energy input, solvent or reagent demand, concentration burden, separation steps, equipment utilization, final product concentration, and reproducibility of recovered-fraction quality. These parameters are necessary before hydrodynamic cavitation can be compared economically with UAE, MAE, PEF, SWE/SCWE, NADES, or EAE.

7.3. Raw-Material, Regulatory, and Standardization Requirements

Application-oriented recovery also requires control of the starting material. Agri-food residues and plant-derived matrices may vary with cultivar, season, origin, industrial processing history, storage, moisture, particle size, microbial load, pesticide residues, contaminants, or undesired compounds. Hydrodynamic cavitation does not remove the need for raw-material qualification, traceability, and analytical control.

Standardization is equally important. A recovery process intended for food, nutraceutical, formulation-oriented, or other high-value applications should produce fractions characterized by defined composition, stability, safety-related properties, and functional performance. Natural origin and reduced solvent use are not sufficient to support application claims without evidence on dose, compatibility, bioaccessibility, formulation behavior, and the applicable regulatory framework [20].

7.4. Evidence Gaps and Future Priorities

The main evidence gaps concern protocol comparability, hydraulic reporting, specific energy input, mass balance, recovered-fraction characterization, storage stability, bioaccessibility, formulation behavior, downstream operations, and scale-up. These gaps are decisive because higher recovery does not necessarily imply a better technology if recovered-fraction quality, resource demand, water use, separation burden, or application performance remains unresolved.

Future studies should therefore connect matrix type, reactor configuration, process function, recovery performance, fraction quality, energy and water demand, downstream

processing, and intended use. Integrated approaches, including cavitation-assisted recovery of biopolymers and extractives from lignocellulosic materials, are promising but require complete process-balance assessment [140]. Robust evidence is obtained only when hydrodynamic cavitation is evaluated as part of a defined recovery pathway, not as an isolated treatment step.

The minimum reporting and evidence requirements are summarized in Table 3.

Table 3. Minimum reporting requirements for hydrodynamic cavitation studies on bioactive and functional fraction recovery.

Domain	Information to Report	Purpose	Interpretation Boundary
Feedstock	Origin, matrix type, moisture, particle size, pretreatment	Support reproducibility	Avoid generalization across matrices
Target fraction	Target class, markers, profile, co-products	Distinguish recovery from valorization	Avoid equating extraction with selectivity
HC setup	Reactor type, geometry, flow, pressure, cavitation number	Enable hydraulic comparison	Avoid generic attribution to HC
Conditions	Medium, ratio, time, temperature, pH, recirculation	Separate cavitation from other effects	Avoid attributing uncontrolled effects to cavitation
Controls	No-HC, thermal, conventional, green comparator	Support process claims	Avoid unsupported superiority claims
Fraction quality	Yield, selectivity, purity, degradation, assays	Link yield to usable quality	Avoid equating yield with value
Resource use	Energy, water, solvent, reagents, mass balance, throughput, and concentration burden	Assess efficiency	Avoid green claims from solvent reduction alone
Downstream steps	Separation, concentration, stabilization, residues	Identify hidden burdens	Avoid judging only the HC step
Application relevance	Stability, bioaccessibility, formulation behavior, safety-related data, material specifications, and product-oriented requirements	Connect fractions to realistic use	Avoid inferring functionality from composition alone
Scale-up	Volume, continuity, stability, solids handling, integration	Assess transferability	Avoid equating laboratory feasibility with scale-up readiness

Note: HC, hydrodynamic cavitation. The table is a minimum reporting and evidence checklist, not a scoring system, maturity scale, proof of sustainability, or demonstration of technological superiority. Robust interpretation depends on matrix characterization, recovered-fraction quality, resource demand, downstream processing, scale relevance, and integration within a defined process or application pathway.

Table 3 emphasizes that progress depends on complete and comparable reporting. The central question is not whether hydrodynamic cavitation produces a measurable effect, but whether that effect is useful, reproducible, resource-efficient, and relevant to a defined matrix, process function, and intended use.

8. Conclusions

Hydrodynamic cavitation can be considered a conditional process-intensification platform for the recovery and transformation of bioactive and functional fractions from agri-food residues, food-processing by-products, and plant-derived matrices. Its value does not derive from cavitation generation alone, but from the ability to improve a defined process function relative to an appropriate comparator while preserving target-fraction quality. The most developed evidence concerns citrus by-products, pectin-associated fractions, wet processing streams, plant protein matrices, and liquid food systems, where

hydrodynamic cavitation may support recovery, dispersion, functional modification, or process integration.

Comparison with ultrasound-assisted extraction, microwave-assisted extraction, pulsed electric fields, subcritical or supercritical water extraction, natural deep eutectic solvents, and enzyme-assisted extraction confirms that no universal technology ranking is supported. Hydrodynamic cavitation is most clearly justified when physical accessibility, mass transfer, wet-stream handling, liquid-phase integration, or combined recovery and restructuring represent the main process limitation. Other technologies may be preferable when controlled heating, membrane permeabilization, solvent selectivity, or biochemical specificity is required.

Application relevance requires caution. Higher recovery yield, increased total phenolic content, or biological activity in preliminary assays does not demonstrate stability, bioaccessibility, formulation performance, safety, or efficacy in a final product. Recovered fractions should therefore be regarded as candidate ingredients or functional intermediates until evidence is available on composition, stability, dose, compatibility with real matrices, downstream processing, and intended use.

Further progress requires complete and comparable reporting of matrix properties, reactor configuration, operating conditions, treated volume, throughput, specific energy input, mass balance, recovered-fraction quality, stability, downstream operations, and scale relevance. These requirements are necessary to distinguish promising process effects from demonstrated technological advantage. Hydrodynamic cavitation can contribute to sustainable recovery strategies when its mechanical and hydrodynamic effects address a specific limitation of the matrix or process. Its application maturity will depend on integrated evidence connecting recovery performance with fraction quality, resource demand, scalability, downstream compatibility, and final-use requirements.

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