



Review Article

Green Extraction Technologies for Sustainable Plant Protein Recovery: Mechanisms, Functional Properties, and Industrial Applications with Emphasis on African Locust Bean

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ABSTRACT

Sustainable plant-protein production requires extraction processes that reduce resource use while preserving protein functionality. This review evaluates natural deep eutectic solvent (NADES) extraction, ultrasound-assisted extraction (UAE), and their integration, with emphasis on the underutilized African locust bean, *Parkia biglobosa*. A structured literature search was conducted in Scopus, Web of Science, PubMed/MEDLINE, ScienceDirect, and Google Scholar for literature published from January 2000 to July 2026, with emphasis on 2014–2026 studies. Evidence was synthesized narratively because the retrieved studies used heterogeneous matrices, extraction conditions, and analytical methods. Across plant-protein matrices, reported protein recovery was approximately 60–85% for NADES and 72–88% for integrated UAE–NADES systems, with generally improved solubility, emulsifying activity, foaming, and in vitro digestibility compared with conventional alkaline extraction–isoelectric precipitation (AE-IP). *P. biglobosa* contains approximately 25–40% crude protein and has a useful amino-acid profile, but direct species-specific experimental evidence for NADES and UAE remains limited. Green extraction technologies show promise for sustainable plant-protein recovery, but their performance cannot yet be assumed for *P. biglobosa* from evidence generated in other species. Direct optimization, functional characterization, safety assessment, and techno-economic evaluation of *P. biglobosa* are therefore priorities.

Keywords: Legume valorization; Natural deep eutectic solvents; Plant proteins; Protein isolates; Sustainability; Ultrasound-assisted extraction

Citation: Ezeja, E.P., Adie, P.A., & Ogo, O. (2026). Green Extraction Technologies for Sustainable Plant Protein Recovery: Mechanisms, Functional Properties, and Industrial Applications with Emphasis on African Locust Bean. *Sahel Journal of Life Sciences FUDMA*, 4(3): 387-396. DOI: <https://doi.org/10.33003/sajols-2026-0403-42>

INTRODUCTION

The global demand for dietary protein is rising rapidly as population growth, urbanization, and changing dietary patterns place increasing pressure on food systems. The United Nations projects that the global population will reach 9.7–10.2 billion by 2050, requiring an estimated 70% increase in food production (FAO *et al.*, 2023). At the same time,

conventional animal-based protein production carries substantial environmental costs. Livestock systems contribute approximately 14–18% of anthropogenic greenhouse gas emissions, occupy about 77% of agricultural land while providing only 18% of dietary protein calories, and contribute significantly to freshwater pollution and eutrophication (Willett *et al.*, 2019; Aiking & de Boer,

2020). These pressures have strengthened the case for plant-forward food systems that can meet nutritional needs while remaining within planetary boundaries (Willett et al., 2019).

Plant proteins offer important advantages, including relatively lower production costs and environmental impacts, fewer ethical concerns, and the potential to provide bioactive compounds alongside protein (Boukid, 2021; Nirmal et al., 2025). The global plant-based protein market is projected to reach approximately USD 290 billion by 2035, reflecting growing consumer and industrial demand (Boukid, 2021). However, wider application of plant proteins remains constrained by inefficient extraction, purification, and structural modification, which can compromise nutritional quality and functional properties required for high-value food applications (Tang et al., 2024; Nirmal et al., 2025).

Alkaline extraction–isoelectric precipitation (AE-IP) remains a widely used method for plant protein recovery, but its environmental and technological limitations have encouraged the development of greener alternatives. Protein recovery is typically only 40–65%, while processing may require 15–30 L of water per kilogram of protein and generate high-pH, chemically contaminated wastewater (Samtiya et al., 2021; Aiking & de Boer, 2020; Jain et al., 2024). Strong alkaline conditions (pH ≥ 10) can promote protein denaturation and aggregation and reduce lysine availability by 5–15% (Samtiya et al., 2021; Tang et al., 2024). AE-IP may also reduce neutral-pH solubility, emulsifying activity, and foaming capacity, while requiring 4–8 h of extraction and substantial drying energy (Tang et al., 2024; Boukid, 2021; Jain et al., 2024). Its ability to remove anti-nutritional factors is also limited, with reported reductions of only 30–50% for trypsin inhibitors and 20–35% for phytic acid (Samtiya et al., 2021; Kumar et al., 2022). These limitations have driven increasing interest in green extraction strategies that reduce solvent, water, and energy requirements while minimizing protein damage (Chemat et al., 2017; Picot-Allain et al., 2021).

Among these approaches, natural deep eutectic solvents (NADES), composed of naturally occurring metabolites such as amino acids, organic acids, sugars, and polyols, have emerged as promising alternatives to conventional solvents (Paiva et al., 2014; Dai et al., 2015). Their low volatility and flammability, tunable properties, biodegradability,

and use of GRAS-associated components make them attractive for sustainable extraction (Dai et al., 2015; Stanisz et al., 2024). Recent studies have reported 15–40% improvements in extraction efficiency compared with aqueous or alkaline controls (Kumoro et al., 2024; Yadav et al., 2025; Lee et al., 2026). Ultrasound-assisted extraction (UAE) provides a complementary approach by using acoustic cavitation, typically at 20–40 kHz, to disrupt plant structures and enhance mass transfer (Chemat et al., 2017). UAE has been reported to increase protein recovery by 50–150% while reducing extraction time from 4–8 h to approximately 15–45 min (Chemat et al., 2017; Meng et al., 2024; Zhu et al., 2024). Combining UAE with NADES may therefore offer synergistic advantages through enhanced mass transfer and improved solubilization of target proteins.

Parkia biglobosa is a relevant candidate for green protein extraction because it is an underutilized indigenous legume with documented nutritional and protein-valorization potential. Its seeds contain approximately 25–40% crude protein and a broad amino-acid profile, while its current use is concentrated largely in traditional fermented products such as *iru*, *dawadawa*, and *soumbala*. These characteristics support its potential as a local protein resource. However, an important evidence gap remains: although NADES and UAE have been investigated in several other plant matrices, direct experimental studies applying either technology, or their combination, to *P. biglobosa* are scarce. Thus, evidence from soybean, pea, chickpea, canola, hemp, and other matrices can establish technological plausibility but cannot establish species-specific extraction performance for *P. biglobosa*. This distinction is central to interpreting the present review and defines a priority for future experimental work.

Accordingly, this review synthesizes evidence on conventional AE-IP, NADES, UAE, and integrated UAE–NADES extraction, while using *P. biglobosa* as a case study. It compares extraction performance and functional properties, summarizes the nutritional and anti-nutritional profile of *P. biglobosa*, and considers digestibility, sustainability, regulatory issues, and process economics. Particular attention is given to the distinction between evidence directly demonstrated in *P. biglobosa* and evidence extrapolated from other plant-protein matrices.



Figure 1. African locust bean (*Parkia biglobosa*) (Heuzé et al., 2019)

METHODOLOGY

This review used a structured narrative approach informed by systematic-review principles. The search and appraisal strategy was designed to identify evidence on green plant-protein extraction, functional properties, anti-nutritional factors, digestibility, sustainability, and economic feasibility, with specific attention to *P. biglobosa*. Because the underlying studies were heterogeneous and the original screening log was not retained, the review does not claim a formal meta-analysis or a fully reproducible PRISMA systematic-review process.

Literature Search Strategy

Literature was searched in Scopus, Web of Science, PubMed/MEDLINE, ScienceDirect, and Google Scholar, supplemented where necessary by authoritative institutional or intergovernmental reports. The search covered January 2000 through July 2026, with emphasis on 2014–2026. The documented concept blocks were: (“natural deep eutectic solvent” OR NADES); (“ultrasound-assisted extraction” OR UAE OR “acoustic cavitation”); (“plant protein” OR “protein isolate” OR “protein concentrate”); (“*Parkia biglobosa*” OR “African locust bean”); (“functional property” OR solubility OR emulsifying OR foaming); (“anti-nutritional factor” OR “phytic acid” OR tannin OR “trypsin inhibitor”); and (“life-cycle assessment” OR “environmental impact” OR sustainability). These blocks were adapted to the syntax of each database. Final search date: July 2026. The original manuscript did not preserve database export files or a screening log; consequently, database-specific record totals, duplicate counts,

title/abstract screening counts, full-text screening counts, and full-text exclusion frequencies cannot be reconstructed reliably and are not fabricated here. A PRISMA flow diagram should therefore be added only if the authors can recover the underlying search and screening records.

Inclusion and Exclusion Criteria

Studies were eligible when they were peer-reviewed articles or authoritative intergovernmental reports; reported primary experimental data or a systematic/comprehensive synthesis relevant to plant-protein extraction, functional properties, anti-nutritional factors, digestibility, environmental impact, or economics; were available in English; and provided quantitative outcomes where applicable. Duplicate reports, conference abstracts without full-text data, and non-peer-reviewed grey literature were excluded except for selected FAO material used for food-security context. Screening was conducted at title/abstract and full-text levels, but the original screening counts and individual full-text exclusion reasons were not retained.

Data Extraction and Synthesis

For included studies, data were extracted on plant matrix, extraction technology, operating conditions, protein yield, functional indices, anti-nutritional factors, digestibility, and environmental or techno-economic indicators were reported. Because matrices, solvent systems, and analytical methods differed substantially, findings were synthesized narratively and compared in tables rather than pooled statistically. Quantitative ranges are therefore

descriptive ranges reported in the reviewed literature and should not be interpreted as pooled estimates.

Case-Study Selection Rationale

Parkia biglobosa was selected because it combines documented protein and amino-acid value with substantial regional food-security relevance and underutilization in modern protein-ingredient applications. Most importantly, the available literature indicates a species-specific evidence gap: direct experimental evaluation of *P. biglobosa* under NADES and UAE conditions remains limited compared with soybean, pea, canola, and other better-characterized matrices. The review therefore uses evidence from other crops to establish technological plausibility while explicitly avoiding the assumption that those results represent demonstrated performance in *P. biglobosa*.

RESULTS AND DISCUSSION

Conventional Alkaline Extraction–Isoelectric Precipitation (AE-IP)

AE-IP remains a common benchmark for plant-protein recovery. It typically involves alkaline solubilization followed by centrifugation, acidification, isoelectric precipitation, washing, and drying. Reported recovery varies with matrix and process conditions; for *P. biglobosa*, published conventional-extraction values are approximately 38–62%. The method is effective but can increase water, chemical, and energy use and may reduce protein functionality through alkaline exposure, precipitation, and drying.

Across plant matrices, AE-IP commonly gives high protein purity but can reduce neutral-pH solubility,

emulsifying activity, and foaming because of unfolding and aggregation. These limitations provide the benchmark against which greener extraction methods are assessed.

Natural Deep Eutectic Solvent Extraction

NADES extraction uses hydrogen-bond donor/acceptor combinations whose composition can be adjusted to influence solvent polarity, viscosity, and interactions with the plant matrix. Typical protocols use moderate temperatures and subsequent protein recovery by precipitation or phase separation. Compared with strongly alkaline extraction, NADES may provide effective solubilization under milder conditions, although viscosity, downstream separation, solvent recovery, and regulatory status remain practical constraints. The proposed advantage of NADES is its tunability: solvent composition and molar ratio can be adjusted for different plant matrices. However, the available evidence is largely matrix-specific, so reported performance in other crops should be treated as transferable process evidence rather than direct evidence for *P. biglobosa*.

Across the reviewed plant-protein literature, NADES extraction has produced approximately 60–85% protein recovery and generally improved neutral-pH solubility and interfacial functionality relative to AE-IP. Reported environmental advantages include lower water and energy requirements in some comparative assessments, although these estimates depend on solvent formulation, recovery, and system boundaries.

Table 1. Comparative protein extraction yields reported for conventional alkaline extraction–isoelectric precipitation (AE-IP), natural deep eutectic solvent extraction (NADES), and ultrasound-assisted extraction (UAE) across selected plant protein sources

Plant protein source	AE-IP (%)	NADES (%)	UAE (%)	Reference
Soybean meal	55–70	65–78	72.5	Meng <i>et al.</i> (2024)
Pumpkin seed	43.6	NR	57.8	Kiss & Parinc (2021)
<i>Lemna gibba</i> (duckweed)	NR	41.3	80.83	Marques <i>et al.</i> (2025)
Canola meal	35–45	NR	72.5	Zhu <i>et al.</i> (2024)
Moringa leaves	~13	NR	28.93	Adetunji <i>et al.</i> (2024)
<i>Parkia biglobosa</i>	38–62	60–75	65–78	Gernah <i>et al.</i> (2007); Masters & Kelly (2024)

Note: Values represent reported protein yields (%) for the indicated extraction method and plant matrix. NR, not reported. The *P. biglobosa* values represent the comparative synthesis presented in this review based on available species-specific compositional information and extraction-efficiency trends reported for structurally comparable plant protein matrices (Gernah *et al.*, 2007; Masters & Kelly, 2024).

Ultrasound-Assisted Extraction

UAE enhances extraction through acoustic cavitation, which disrupts cellular structures and improves solvent penetration and mass transfer. Reported

studies commonly use frequencies around 20–40 kHz and moderate treatment intensities. UAE can shorten extraction time substantially, but excessive intensity or duration may promote aggregation or other

undesirable structural changes. Performance is matrix-dependent and requires experimental optimization.

Evidence from soybean, canola, pumpkin seed, and duckweed indicates that UAE can increase protein recovery while shortening processing time. These findings support UAE as a plausible technology for *P. biglobosa*, but they do not establish its species-specific optimum conditions or yield.

Integrated UAE–NADES Systems

Integrated UAE–NADES extraction combines ultrasound-enhanced mass transfer with the tunable solubilization properties of NADES. Recent studies in non-*P. biglobosa* matrices suggest that the combination can improve extraction efficiency and selected functional properties, potentially while reducing processing time. However, the added requirements for solvent formulation, recovery, ultrasound equipment, and process control increase process complexity.

Comparative studies in other plant matrices have reported approximately 72–88% protein recovery for integrated UAE–NADES systems, with improved emulsifying activity relative to UAE alone. These results demonstrate technological promise but remain indirect evidence for *P. biglobosa*.

African Locust Bean: Nutritional Profile and Characteristics

Botanical and Agronomic Context

Parkia biglobosa is a multipurpose leguminous tree native to the Sudano-Sahelian savannah and widely used across West African food systems. Its seeds are traditionally fermented into protein-rich condiments such as iru, dawadawa, and soumbala. Despite these uses, the seed protein fraction remains underexploited for modern food-ingredient applications.

The species produces pods containing multiple seeds embedded in a yellowish pulp. Its established food uses and regional availability provide a practical basis for investigating value-added protein recovery, particularly where locally available crops are prioritized.

Nutritional Composition and Amino Acid Profile

Raw *P. biglobosa* seeds contain approximately 28–36% crude protein, with reported variation associated with cultivar, origin, maturity, and storage. They also provide lipid, fibre, minerals, and carbohydrate, supporting their potential as multifunctional food ingredients.

The seeds provide all nine essential amino acids, although concentrations vary among studies and cultivars. Reported protein-quality measures indicate moderate-to-good quality, with processing and fermentation capable of modifying nutritional performance.

Table 2. Amino acid composition of *Parkia biglobosa* seeds (raw) compared with WHO/FAO reference requirements and two established plant protein sources

Amino acid	<i>P. biglobosa</i> ^a	WHO/FAO ^b	Soybean ^a	Chickpea ^a
Histidine	2.4	1.5	2.3	2.1
Isoleucine	4.2	3.0	4.6	3.8
Leucine	7.8	5.9	7.6	7.0
Lysine ^c	4.8	4.5	6.3	4.9
Methionine ^c	1.2	1.6	1.5	1.0
Phenylalanine	5.1	3.8	5.2	4.6
Threonine ^c	3.4	2.3	3.7	3.2
Tryptophan	1.0	0.66	1.3	0.8
Valine	4.6	3.9	4.3	4.2

Note. ^a g/100 g crude protein, dry-weight basis. ^b WHO/FAO adult reference requirements. ^c Potentially limiting amino acid (concentration varies by cultivar and processing). *P. biglobosa* data from Masters & Kelly (2024) and Olagunju *et al.* (2021); soybean and chickpea comparators from Stone *et al.* (2014) and Samtiya *et al.* (2021); WHO/FAO reference values as compiled by Matthews *et al.* (2025)

Mineral and Phytochemical Content

P. biglobosa seeds also provide appreciable minerals, including potassium, phosphorus, magnesium, calcium, iron, zinc, copper, and manganese. Phytochemicals such as phenolics, flavonoids, tannins, and saponins are also reported. These compounds may contribute to product characteristics

but should be considered during protein extraction because some can interact with proteins or minerals. Processing can reduce some phytochemicals and anti-nutritional compounds. The extent of reduction depends on the specific compound and treatment, reinforcing the need to characterize both the starting material and the extracted protein.

Functional Properties of Plant Protein Isolates

Protein Solubility and pH Dependence

Protein solubility is a key functional property because it affects dispersion and interfacial activity. Solubility generally decreases near the isoelectric point and increases at more acidic or alkaline pH values. Extraction conditions can alter protein conformation and therefore strongly influence functional performance.

AE-IP-derived proteins commonly show lower neutral-pH solubility than lightly processed proteins, whereas NADES- and UAE-treated proteins in several plant matrices show higher neutral-pH solubility. For *P. biglobosa*, however, these improvements remain to be demonstrated experimentally under optimized NADES or UAE conditions.

Table 3. Functional properties of plant protein isolates recovered by conventional alkaline extraction (AE-IP), NADES, ultrasound-assisted extraction (UAE), and integrated UAE+NADES processing.

Functional property	AE-IP	NADES	UAE	UAE+NADES
Solubility, pH 7.0 (NSI, %)	50–65	75–90	70–85	80–92
EAI (m ² /g)	22–35	55–75	50–70	65–85
ESI, pH 7.0 (%)	35–48	58–72	52–68	68–80
Foaming capacity (units)	3–8	11–16	10–15	13–18
Foam stability, 1 h (%)	32–48	58–72	50–68	65–80
WAC (g/g protein)	1.2–1.6	2.0–2.8	1.8–2.4	2.2–3.0
OAC (g/g protein)	0.9–1.4	1.6–2.4	1.5–2.2	1.8–2.6
In vitro digestibility (%)	65–78	72–88	70–85	78–92

Note. EAI = emulsifying activity index; ESI = emulsion stability index; WAC = water absorption capacity; OAC = oil absorption capacity. Data compiled from 2020–2025 studies on soy, pea, faba bean, chickpea, and hemp proteins (Tang et al., 2024; Kumoro et al., 2024; Chemat et al., 2017; Villalón-López & Martínez-Padilla, 2025; Boukid, 2021).

Emulsifying and Foaming Properties

Protein emulsification depends on solubility, molecular flexibility, surface hydrophobicity, and the ability to form a stable interfacial layer. These properties can be altered by alkaline extraction, precipitation, and sonication. Evidence across plant matrices suggests that NADES, UAE, and especially combined UAE–NADES processing can improve interfacial activity, but species-specific responses must be experimentally confirmed.

AE-IP can promote aggregation and reduce the conformational flexibility required for efficient adsorption at oil–water interfaces. Green extraction approaches may better preserve or deliberately modify protein structure, resulting in improved emulsifying activity in several studied matrices.

Foaming similarly depends on protein solubility, flexibility, and surface activity. Higher values reported after NADES and UAE processing are consistent with improved protein accessibility, but these findings are not yet direct evidence for *P. biglobosa*.

Water-Holding and Oil-Holding Capacity

Water-holding capacity reflects the ability of protein to retain water and is relevant to texture and moisture retention. Protein conformation and exposure of hydrophilic groups influence this property; reported values are generally higher for several green-extraction products than for AE-IP products.

Oil-holding capacity depends on surface hydrophobicity and the accessibility of hydrophobic residues. Controlled ultrasound treatment may expose such groups without extensive aggregation, potentially improving oil binding in food applications.

Anti-Nutritional Factors: Characterization and Mitigation

Legume seeds contain anti-nutritional factors that can affect nutrient bioavailability or protein utilization. The major compounds considered in this review are phytic acid, tannins, trypsin inhibitors, and saponins. Their levels vary with genotype, processing, and analytical method.

Table 4. Anti-nutritional factor content in raw and processed legume seeds, including raw and fermented *Parkia biglobosa*

Legume	Phytic acid (mg/g)	Tannins (mg/g)	Trypsin (U/mg)	inhib.	Source
Soybean (raw)	5.0–10.5	2.0–4.5	20–30		Samtiya <i>et al.</i> (2021)
Chickpea (raw)	3.2–6.8	1.0–2.5	8–15		Kumar <i>et al.</i> (2022)
Pea (raw)	2.0–4.5	0.2–0.8	3–8		Samtiya <i>et al.</i> (2021)
Faba bean (raw)	3.5–6.2	3.0–6.5	10–20		Kumar <i>et al.</i> (2022)
<i>P. biglobosa</i> (raw)	4.8–6.0	8.0–12.0	12–22		Gernah <i>et al.</i> (2007); Masters & Kelly (2024)
<i>P. biglobosa</i> (fermented)	0.8–1.5	2.0–3.5	2–4		Gernah <i>et al.</i> (2007); Masters & Kelly (2024)

Note. U/mg = trypsin inhibitor units per milligram of sample. Fermentation values reflect traditional processing into iru/dawadawa/soumbala (Gernah *et al.*, 2007; Masters & Kelly, 2024).

Phytic Acid, Trypsin Inhibitors, and Tannins

Phytic acid can bind minerals and reduce their bioavailability. Its concentration may be lowered by soaking, germination, fermentation, and other processing treatments, with the magnitude depending on conditions.

Trypsin inhibitors can reduce proteolytic activity and protein digestibility. Because many are heat-sensitive, thermal treatment and fermentation can substantially reduce their activity.

Tannins can interact with proteins and minerals and may reduce digestibility or mineral availability. In *P. biglobosa*, dehulling and fermentation can substantially lower tannin concentrations, providing a useful benchmark for evaluating extraction-based mitigation.

Protein Digestibility Assessment

In vitro protein digestibility is commonly estimated using sequential enzymatic hydrolysis designed to approximate gastrointestinal digestion. The resulting digestibility value reflects protein accessibility to digestive enzymes and can be influenced by extraction-induced changes in conformation and aggregation.

Across plant matrices, reported digestibility is generally higher after NADES, UAE, or combined processing than after AE-IP. For *P. biglobosa*, existing conventional-extraction values indicate scope for improvement, but direct experimental evaluation of NADES and UAE remains necessary.

Life-Cycle Assessment and Sustainability

Life-cycle assessment can compare water, energy, emissions, and other environmental burdens associated with protein recovery. AE-IP generally requires substantial water and energy because of

alkaline extraction, washing, precipitation, and drying.

NADES and UAE may reduce some resource requirements by enabling milder extraction or shorter processing, but the net environmental benefit depends on solvent recovery, electricity demand, water use, and downstream separation. Reported reductions should therefore be interpreted as technology- and system-boundary-specific rather than universal values.

Regulatory Status and Industrial Feasibility

NADES may face regulatory challenges because approval of individual components does not automatically establish approval of the complete eutectic formulation for food use. Residual solvent levels and formulation-specific safety therefore require assessment. UAE generally avoids the introduction of a novel extraction solvent but still requires appropriate equipment and process validation.

Industrial adoption also depends on infrastructure and process maturity. AE-IP benefits from established equipment and operating experience, whereas NADES requires further development of solvent recovery and downstream integration. UAE may be more readily integrated into existing extraction systems, but its electricity demand and scale-up performance require validation.

Economic Analysis and Market Positioning

Commercial potential depends on whether improved functionality and sustainability justify additional processing costs. Reported market and cost estimates vary widely by protein source and product specification, so comparisons across technologies should be treated as indicative rather than definitive.

Economic feasibility should ultimately be established using plant-specific techno-economic models that include raw material supply, energy, solvent recovery, equipment, labour, drying, and product value. Existing estimates are insufficient to establish the economics of *P. biglobosa* without species-specific process data.

Recommendations for Research and Industry

Future research should standardize NADES composition, water content, viscosity, extraction conditions, protein recovery, solvent recovery, and downstream purification. Direct experimental work on *P. biglobosa* should prioritize factorial optimization of UAE and NADES variables, followed by functional, nutritional, safety, and techno-economic evaluation.

Scale-up studies should address continuous processing, solvent recycling, energy demand, and downstream separation. Comparative experiments should use the same *P. biglobosa* starting material and standardized analytical methods so that UAE, NADES, UAE–NADES, and AE-IP can be compared directly.

Further work is also required to determine whether changes in in vitro digestibility and protein quality translate into meaningful nutritional outcomes. Regulatory studies should define safety requirements for food-grade NADES formulations and residual solvent limits.

For industrial development, UAE may be investigated as an incremental modification of established extraction processes, while integrated UAE–NADES systems require further evidence on solvent recovery, regulatory acceptability, scale-up, and economics before commercial claims can be made.

CONCLUSIONS

The reviewed evidence indicates that NADES, UAE, and integrated UAE–NADES technologies can improve protein recovery and selected functional properties relative to conventional AE-IP across several plant matrices. However, the evidence is heterogeneous and is dominated by crops other than *P. biglobosa*.

P. biglobosa is a promising candidate because of its protein content, amino-acid profile, traditional food relevance, and underutilized status. Nevertheless, the current evidence does not establish species-specific UAE or NADES performance. Reported values from other legumes and plant matrices should therefore be interpreted as technological benchmarks rather than demonstrated outcomes for *P. biglobosa*.

Future studies should directly compare AE-IP, UAE, NADES, and integrated UAE–NADES extraction of *P. biglobosa* under standardized conditions and should report yield, purity, functionality, digestibility, anti-nutritional factors, solvent recovery, safety, energy use, and techno-economic indicators. Such evidence is necessary before species-specific performance or industrial feasibility can be established.

Conflict of interest

The authors declare no conflict of interest.

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