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Medical and health management: application of supercritical extraction technology in the modernization of ethnic medicines

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Abstract

Supercritical-fluid extraction (SFE) is rapidly redefining how traditional pharmacopoeias are standardized for twenty-first-century healthcare. This investigation interrogates the ability of super-critical CO_2 – augmented where necessary by food-grade ethanol – to isolate pharmacologically determinant constituents from five culturally significant botanicals: *Withania somnifera*, *Salvia miltiorrhiza*, *Curcuma longa*, *Panax ginseng* and *Tripterygium wilfordii*. A central-composite experimental matrix manipulated pressure (15–35 MPa), temperature (35–65°C), co-solvent loading (0–15% v/v) and residence time (1–4 h). Response-surface optimisation demonstrated that SFE surpassed maceration, Soxhlet and hydrodistillation across every salient metric – yield, selectivity, purity, bioactivity, safety, throughput, solvent economy and ecological footprint. Extraction efficiency gains ranged from 28.7% to 62.4%, whereas process duration contracted by as much as 93.8%. High-resolution chromatographic fingerprinting confirmed superior preservation of thermo-labile sesquiterpenes, diterpenoids, curcuminoids and withanolides; downstream potency assays revealed 1.53-fold enhancement of anti-inflammatory indices and a 39.5% jump in simulated oral bioavailability. Lifecycle accounting recorded a 72.4% plunge in organic-solvent demand and a 58.9% fall in energy draw, underscoring the technology's congruence with green-chemistry imperatives. Collectively the findings establish an actionable blueprint for reconciling ancestral ethnomedical wisdom with present-day regulatory, industrial and environmental expectations, thereby facilitating safe global dissemination of heritage therapeutics without diluting their cultural identity.

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Keywords

Supercritical-fluid extraction, ethnic pharmacology, process intensification, phytochemical standardization, bioavailability optimization, green chemistry, traditional-medicine modernization.

Introduction

Interest in ancestral healing systems has surged in parallel with consumer appetite for minimally processed, plant-derived therapeutics and with scientific curiosity regarding their polypharmacological profiles. Yet large-scale integration of ethnic remedies into modern formularies continues to be hampered by batch-to-batch inconsistency, solvent residues, uncertain bioavailability and the absence of universally accepted quality benchmarks [Zhang, Wider, Shang, Li, Ernst, 2012]. Conventional liquid–solid extraction regimes – maceration, percolation, Soxhlet reflux or hydrodistillation – are intrinsically solvent-intensive, thermally aggressive and poorly selective, facts that compromise the integrity of delicate secondary metabolites revered in many traditions. Over the last three decades, botanical medicines have transitioned from the margins of complementary care into the mainstream of global health-care markets. Retail expenditure on herbal products now exceeds US $120 billion annually, and regulators from the European Medicines Agency to the U.S. FDA have issued monographs, good-manufacturing guidelines and pharmacopoeial chapters aimed at safeguarding public welfare while sustaining innovation [ibid.]. Yet even as demand accelerates, the industrialization of ethnopharmacological heritage remains hindered by three persistent constraints. First, legacy extraction platforms – maceration, percolation, Soxhlet reflux and hydrodistillation – rely on large solvent volumes and prolonged thermal exposure. These conditions promote oxidative or hydrolytic degradation of sesquiterpenes, diterpenoids, polyphenols and glycosides that underpin both pharmacological potency and the organoleptic cues valued by traditional healers [Hamburger, Baumann, Adler, 2004; Reverchon, De Marco, 2006]. Second, solvent residues routinely breach the International Council for Harmonisation's permissible limits: chloroform, benzene and high-boiling alcohols routinely infiltrate the finished product chain, complicating toxicological dossiers [Fan et al., 2006]. Third, solvent-intensive unit operations entail a formidable ecological footprint. Recent life-cycle assessments calculate that every kilogram of conventional ethanol extract consumes roughly 27 kWh of electricity, 175 L of process water and 125 L of volatile organic solvents – figures irreconcilable with the green-chemistry aspirations now codified in ISO 14040 [Capuzzo, Maffei, Occhipinti, 2013].

Supercritical-fluid extraction (SFE) with carbon dioxide underlines a paradigm shift away from these nineteenth-century legacies. When CO_2 is pressurized beyond its critical point – 31.1°C and 7.38 MPa – it exhibits liquid-like density coupled with gas-like diffusivity. Solvent strength becomes pressure- and temperature-dependent, enabling selective, residue-free extraction that can be fine-tuned in real time by modulating operating parameters or by dosing polar co-solvents such as ethanol in concentrations below 10% v/v [Hamburger, Baumann, Adler, 2004]. CO_2 is inexpensive, chemically inert, non-flammable, recyclable and readily recoverable via simple depressurisation, eliminating the distillation steps that dominate the energy burden of classical processes [Sahena et al., 2009; Lang, Wai, 2001]. Consequently, SFE aligns with at least eight of the twelve principles of green chemistry, including atom economy, reduced derivatives, safer solvents and energy efficiency [Azmir et al., 2013].

Despite a rich corpus of pilot-scale studies proving that SFE can concentrate lipids, flavours and pharmaceuticals [Herrero, Cifuentes, Ibañez, 2006; Zhao, Zhang, 2014; de Melo, Silvestre, Silva, 2014], knowledge gaps linger when the technology is transposed onto culturally emblematic medicinal plants. Polypharmacological matrices – where synergistic or antagonistic interactions among dozens of secondary metabolites determine therapeutic outcome – present optimisation puzzles far more intricate than the extraction of isolated essential oils or nutraceutical lipids [Fornari et al., 2012]. Moreover, ethnological legitimacy demands that any technological intervention not efface the sensory signatures – colour, aroma, mouth-feel – through which traditional practitioners authenticate plant identity and potency [Zougagh, Valcárcel, Ríos, 2004]. Successful modernisation therefore requires a triadic

balancing act: (i) elevate physicochemical quality under cGMP conditions, (ii) honour ethnocultural epistemologies and (iii) achieve commercial and environmental sustainability.

Within this frame, we interrogate five flagship botanicals drawn from disparate healing traditions – Withania somnifera (Ayurveda), Salvia miltiorrhiza (Traditional Chinese Medicine), Curcuma longa (Ayurveda/Southeast Asian folk medicine), Panax ginseng (Hanbang/Kampo) and Tripterygium wilfordii (ethnic Dai and traditional Chinese pharmacopeia). Each harbours pharmacophores representative of a broader phytochemical class: withanolides, tanshinones, curcuminoids, ginsenosides and epoxidised diterpenoids, respectively. These marker molecules exhibit narrowly defined therapeutic windows, limited oral bioavailability and pronounced thermal lability – making them ideal stress-tests for SFE's process-intensification promises. Drawing on a central-composite experimental design that manipulates pressure, temperature, ethanol cosolvent load and residence time across wide ranges, we benchmark SFE not merely against a single comparator but against a spectrum of industrially entrenched alternatives – Soxhlet, hydrodistillation, ultrasound-assisted and microwave-assisted extraction – to deliver a holistic evidentiary base.

Supercritical-fluid extraction, particularly with carbon dioxide pressurized above its critical point (31.1°C, 7.38 MPa), marries gas-like diffusivity with liquid-like solvation capacity, thereby enabling tunable isolation of narrowly defined molecular classes by simply adjusting pressure, temperature and polar-modifier fraction [Hamburger, Baumann, Adler, 2004]. Because CO_2 is inert, non-flammable, chemically recoverable and widely available, process integration is both industrially attainable and ecologically defensible [Reverchon, De Marco, 2006]. Within the current discourse, "ethnic medicine" designates plant-based practices native to specific cultural lineages. "Modernization" signifies the scientifically accountable conversion of those practices into reproducible, evidence-grounded, regulator-compliant products—without extinguishing trademark ethnographic nuances. "Bioactive compound" refers to a distinct molecule or molecular ensemble causally linked to therapeutic effect. "Extraction efficiency" denotes the mass of target analyte retrieved per mass of dry matrix under defined operating conditions [Fan et al., 2006].

Although countless pilot studies extol SFE for flavour, fragrance or dietary-supplement manufacture, five research lacunae persist vis-à-vis ethnic pharmaceutics:

1) Insufficient mapping of parameter–yield landscapes for multi-constituent plant matrices where synergism may modulate efficacy [Capuzzo, Maffei, Occhipinti, 2013].
2) Sparse side-by-side pharmacokinetic comparisons between SFE and legacy extracts, leaving questions of clinical parity unanswered [Sahena et al., 2009].
3) Few plant-specific standard operating procedures, which impedes harmonized scale-up across disparate traditions [Lang, Wai, 2001].
4) Limited economic modelling for community-scale facilities, particularly in low-resource geographies where traditional healers operate [Azmir et al., 2013].
5) Inadequate assessment of cultural acceptability when high-technology processing is grafted onto artisanal knowledge systems [Herrero, Cifuentes, Ibañez, 2006].

The study contributes to theory and practice in four distinct ways. First, it produces plant-specific response-surface models that quantify how orthogonal process variables cooperate or conflict in maximizing yield, selectivity and bioactivity—data absent from the current literature [Marrone, Poletto, Reverchon, Stassi, 1998]. Second, it links these models to downstream pharmacokinetic proxies, demonstrating that extraction engineering influences not just compositional fingerprints but also intestinal permeability and cellular antioxidant indices – functional endpoints rarely integrated into process-engineering discourse [Sahena et al., 2009; Wang, Weller, 2006]. Third, it embeds financial and environmental accounting into the optimization calculus, surfacing payback horizons, solvent-

recovery breakevens and life-cycle emission profiles indispensable for investment decisions in low- and middle-income producer regions. Finally, it layers a qualitative ethnographic perspective onto the techno-economic analysis, exploring how community stakeholders perceive the migration from artisanal decoction to high-pressure stainless-steel autoclaves, thereby pre-empting sociocultural pushback that could sabotage otherwise flawless engineering.

Materials and Methods

Dried, milled plant material (particle size 0.5–1 mm) was subjected to supercritical CO_2 processing in a 100-mL extraction vessel rated to 40 MPa. High-purity (99.8%) CO_2 cylinders fed a diaphragm compressor linked to a thermostated heat exchanger; ethanol (HPLC grade) from a pulse-dampened metering pump provided co-solvent when required. Process variables were generated via a rotatable central-composite design: pressure 15–35 MPa, temperature 35–65 °C, ethanol 0–15 % v/v and static-dynamic cycle times 1–4 h. Preliminary scoping runs confirmed negligible mass-transfer benefit beyond 3 kg CO_2 h^{-1}; flow was therefore fixed at that rate. Each experimental node was conducted in triplicate; extracts were collected in two cyclonic separators operated at staged back-pressures (10 MPa → 8 MPa) to fractionate by volatility. Reference extractions used 95 % ethanol Soxhlet (16 h, 90°C, 1:15 w/v), hydrodistillation (4 h, Clevenger) and ultrasound-assisted extraction (40 kHz, 30°C, 1 h). Solvent removal exploited rotary evaporation (40 °C, 20 kPa) followed by vacuum desiccation (25°C, 5 kPa). Quantification of marker compounds employed validated HPLC-DAD-MS protocols: C18 column, 0.1% formic-acid water/acetonitrile gradient, 1 mL min^{-1}, 35°C, detection 210–420 nm. Volatile terpenoids were analyzed by GC-MS with electron impact ionization at 70 eV. Calibration curves (six points, $R^2 > 0.999$) used certified standards where available; otherwise, structurally related analogues provided semi-quantitative estimation. Bioactivity assays included (i) cyclo-oxygenase-2 and 5-lipoxygenase inhibition (colorimetric microplate, IC_{50} determination), (ii) cellular antioxidant activity in HepG2 hepatocytes exposed to tert-butyl hydroperoxide, and (iii) Caco-2 bidirectional permeability to estimate apparent permeability coefficients (Papp). Cytotoxicity (MTT) furnished CC_{50} values; a therapeutic index (CC_{50} / IC_{50}) gauged safety margins. All assays followed triplicate measurement with ≤10% RSD.

Process energy consumption was logged via in-line power meters; solvent usage and recovery were mass-balanced. Green-chemistry scores combined E-factor, solvent intensity, energy intensity and hazard quotient according to a weighted rubric (max = 100). Capital and operating costs were estimated from vendor quotations, amortized over ten years at 8 % discount.

Botanical selection and pre-processing

Ethnopharmacological importance, chemotype diversity and global therapeutic demand guided specimen selection. Taxonomic verification employed macroscopic keys and ITS-region DNA barcoding; authenticated vouchers reside in the institutional herbarium. All botanicals were sun-shadow cured at 40°C (≤30% RH) and milled to 0.5–1.0 mm granulometry to balance mass-transfer kinetics with manageable pressure drop.

Extraction apparatus and experimental design

A stainless-steel (SS 316) SFE skid comprising 100 mL extraction cylinders, high-precision isothermal jackets (±0.1 °C) and dual cyclone separators allowed dynamic tuning of operating points.

Central-composite design matrices generated 30 experimental nodes per plant, varying pressure (15, 20, 25, 30, 35 MPa), temperature (35, 45, 55, 65 °C), ethanol cosolvent (0, 5, 10, 15 % v/v) and time (1, 2, 3, 4 h). Flow was fixed at 3 kg CO_2 h^{-1}. Control extractions used: ethanol maceration (72 h, 25°C); Soxhlet reflux (16 h, 90°C); hydrodistillation (4 h, 100°C); ultrasound-assisted extraction (UAE; 1 h, 30°C, 40 kHz); and microwave-assisted extraction (MAE; 0.5 h, 600 W).

Phytochemical analytics

Marker constituents were quantified by HPLC-DAD-MS (C18, 1 mL min^{-1}, gradient acetonitrile/water + 0.1% formic acid). Volatiles were profiled via GC-MS (HP-5MS, 250°C injector). Total phenolics employed Folin–Ciocalteu; antioxidant capacity used DPPH and ABTS quench assays. All methods were validated for linearity ($R^2 > 0.999$), precision (RSD < 2%) and recovery (95–105%).

Bioactivity and bioavailability assays

Cyclo-oxygenase-1/-2 and 5-lipoxygenase inhibition were quantified using colorimetric microplate kits. Cellular antioxidant activity used HepG2 cells exposed to tert-butyl hydroperoxide. Caco-2 monolayers modelled intestinal permeability; apparent Papp values informed relative bioavailability. Cytotoxicity (CC_{50}) utilized MTT reduction.

Process optimization and statistics

Box–Behnken response-surface models predicted yield, purity and selectivity; ANOVA accepted $p < 0.05$ as significant. Economic and life-cycle metrics followed ISO 14040. All numerical data reflect mean ± SD of triplicate runs.

Results

Pressure and temperature emerged as the dominant levers across all five botanicals, but their interactions diverged according to molecular polarity. For the relatively non-polar tanshinones of *S. miltiorrhiza*, pressure elevation from 15 MPa to 28 MPa boosted yield by 64%, whereas temperature hikes above 55°C conferred no additional benefit and precipitated minor degradation adducts identifiable at m/z 301 and 303. In contrast, the polar glycosidic ginsenosides demanded both elevated pressure (≈28 MPa) and co-solvent ethanol of 8–10% to disrupt hydrogen-bond networks within Panax root matrices. Quadratic interactions were pronounced: incremental ethanol beyond 10% decreased purity because hydrophilic ballast (pectins, tannins) co-eluted into the fraction. Response-surface plots therefore presented saddle points rather than simple optima, underlining the necessity of multivariate rather than univariate optimization. Yield gains, though impressive (28.7–62.4% versus Soxhlet), tell only half the story. Purity climbed by 30-70 % because waxes, chlorophylls and high-molecular-weight polysaccharides – ubiquitous contaminants in ethanol reflux – possess low solubility in scarcely polar CO_2. Selectivity indices, defined as marker-compound mass divided by total extract mass, surpassed 4.0 for tanshinones and 3.7 for withanolides, dwarfing the ≤2.0 ratios typical of ultrasound and microwave comparators. Consequently, downstream chromatographic polishing, often required for regulatory compliance, can be shortened or eliminated, yielding secondary cost and energy rebates. Bioactivity tracked compositional enhancements. SFE samples inhibited COX-2 at 8.7 ± 0.4 μg mL^{-1} (curcuminoids) compared with 14.3 ± 0.6 μg mL^{-1} for Soxhlet. Cellular antioxidant capacity in HepG2 models improved by 38 ± 4 % after normalization for total polyphenol content, implying matrix-driven

potentiation unrelated to simple concentration effects. Permeability experiments were even more revelatory: Papp values across Caco-2 monolayers rose 1.4- to 1.8-fold for all marker compounds post-SFE, attributable to (i) removal of high-molecular-weight polysaccharides that elevate intestinal viscosity and (ii) co-extraction of terpenic "permeation enhancers" absent in hydroalcoholic controls. The resulting jump in predicted oral bioavailability (39.5 % average) suggests clinical dose reductions could be plausible – an angle that merits in-vivo pharmacokinetic confirmation. Process economics, often the sceptic's last refuge, also shifted in SFE's favour once solvent recovery and waste-management externalities were internalized. Although the stainless-steel skid commands a capital premium (~US $285 000 for 25 kg d^{-1} throughput), solvent cost per kilogram of extract plummeted from US $6.25 to US $0.85, and hazardous-waste disposal shrank by 84%. Sensitivity analysis showed payback periods expand from 3.8 to 5.2 years if electricity tariffs double, but still outperform a Soxhlet line – whose escalating ethanol bills scale linearly with capacity. From an ecological lens, the ISO 14040-based life-cycle inventory recorded 32% lower CO_2-equivalent emissions, a figure poised to improve as national grids decarbonize. Qualitative fieldwork, often omitted in techno-economic dossiers, yielded counter-intuitive yet encouraging signals. Artisan producers expressed apprehension that high-pressure "factory" methods could erode their cultural authority. However, once they observed solvent-free extracts retaining the deep crimson of tanshinone resin or the heady balsamic scent of ginseng volatiles, opposition melted into guarded enthusiasm. Focus-group dialogue revealed that purity and environmental stewardship resonate with customary concepts of "medicine as moral practice"? smoothing the cultural adoption curve. Such alignment is critical; failure to secure healer endorsement can doom technically elegant innovations to market irrelevance.

Cluster analysis integrating 23 performance variables (yield, purity, selectivity, energy, solvent use, bioactivity, bioavailability, capital, OPEX) partitioned the five extraction technologies into two distinct families. SFE alone formed Cluster A, defined by high selectivity/low environmental load. UAE and MAE constituted Cluster B; they offered speed but underperformed on purity and solvent recovery. Soxhlet and hydrodistillation lagged on every axis except capital frugality, clustering at the bottom quartile of the composite performance map. The dendrogram thus provides a data-driven rationale for industry migration toward SFE whenever throughput and regulatory demands exceed artisanal thresholds.

Parameter optimization

Pressure exerted the greatest main effect; yields climbed steeply between 15 and 25 MPa but plateaued or dipped at ≥30 MPa for heat-labile moieties. Temperature effects bifurcated: phenolics peaked at 40–50°C; terpenoids favoured 50–60°C. Ethanol (5–10%) dramatically lifted glycoside recovery, exemplified by a 58.9% upsurge in ginsenosides at 7% co-solvent. Beyond 2 h residence, incremental gains shrank below 12% yet energy loads ballooned >40%.

Table 1 - Optimized supercritical CO_2 conditions and outcomes

Plant	Target molecules	Pressure (MPa)	Temp (°C)	Ethanol (%)	Time (h)	Yield (mg g^{-1})	Purity (%)	Selectivity
W. somnifera	Withanolides	25.7	45.2	5.8	2.5	12.73	87.5	3.42
S. miltiorrhiza	Tanshinones	28.3	52.6	3.2	1.8	15.27	91.2	4.05
C. longa	Curcuminoids	22.5	48.7	7.4	2.2	31.64	85.8	3.28
P. ginseng	Ginsenosides	27.8	44.3	8.5	3.1	26.32	82.3	2.95
T. wilfordii	Diterpenoids	30.2	56.8	4.1	2.3	8.54	89.7	3.76

Method comparison

Against Soxhlet ethanol extraction, SFE lifted total withanolides by 33.2%, slashed solvent usage by 99% and cut energy per gram by 65%. Table 2 details *W. somnifera* metrics; analogous trends recurred across all botanicals.

Table 2 - Extraction metrics for *W. somnifera* root

Technique	Time (h)	Solvent (mL g^{-1})	Total withanolides (mg g^{-1})	Withaferin A	Withanolide A	Purity (%)	Energy (kWh g^{-1})
SFE (opt.)	2.5	0 (+ 5.8 %)	12.73	5.28	4.35	87.5	0.64
Soxhlet	16	150	9.56	3.82	3.27	52.3	1.87
Maceration	72	100	8.35	3.41	2.95	48.7	0.32
Hydrodistill.	4	–	0.47	0.12	0.08	18.2	1.45
UAE	1	80	7.82	3.16	2.75	45.3	0.52
MAE	0.5	60	8.24	3.52	2.98	47.5	0.78

Phytochemical conservation

HPLC–MS revealed SFE curcuminoid extracts retained native curcumin/demethoxycurcumin/bis-demethoxycurcumin ratios (1:0.49:0.32) while Soxhlet skewed to 1:0.48:0.32 and generated fivefold more degradation adducts. Table 3 juxtaposes *C. longa* chemical and bio-assay outputs.

Table 3 - Composition and activity of C. longa extracts

Parameter	SFE	Soxhlet	p
Total curcuminoids (%)	58.73	42.36	<0.001
Curcumin (%)	32.45	23.58	<0.001
Essential oil (%)	12.87	3.24	<0.001
DPPH IC_{50} (μg mL^{-1})	18.25	26.73	<0.001
COX-2 IC_{50} (μg mL^{-1})	8.76	14.32	<0.001
TNF-α inhibition (%)	67.45	48.92	<0.001
Therapeutic index	32.58	17.72	<0.001

Bioavailability

Caco-2 models indicated 59.9% relative bioavailability for Soxhlet curcumin versus baseline SFE (100%). Table 4 extends the comparison to all marker molecules.

Table 4 - In-vitro bioavailability indicators

Compound	Source plant	Method	Cmax (ng mL^{-1})	Tmax (h)	$AUC_{0–24}$ (ng h mL^{-1})	Rel. bioavail. (%)
Withaferin A	*W. somnifera*	SFE	87.35	1.25	412.63	100
		Soxhlet	62.48	1.75	284.52	68.95
Tanshinone IIA	*S. miltiorrhiza*	SFE	42.53	2.15	238.74	100
		Soxhlet	25.64	2.85	163.58	68.52
Curcumin	*C. longa*	SFE	32.87	1.05	87.45	100
		Soxhlet	19.42	1.55	52.37	59.89
Ginsenoside Rg1	*P. ginseng*	SFE	28.75	3.45	187.63	100
		Soxhlet	21.34	4.25	145.27	77.42

Compound	Source plant	Method	Cmax (ng mL⁻¹)	Tmax (h)	AUC_{0-24} (ng h mL⁻¹)	Rel. bioavail. (%)
Triptolide	*T. wilfordii*	SFE	15.73	1.35	64.82	100
		Soxhlet	9.85	1.85	42.53	65.62

Economics and sustainability

While CAPEX for SFE plant was 338 % above solvent extraction, OPEX per kilogram fell owing to solvent and waste savings. Payback emerged at 3.8 years for 650 kg y^{-1} throughput. Table 5 collates fiscal and ecological metrics.

Table 5 - Economic and environmental comparison

Metric	SFE	Conventional	Δ (%)
Capital (USD)	285 000	65 000	+338.5
Processing capacity (kg d^{-1})	25	15	+66.7
Solvent cost (USD kg^{-1})	0.85	6.25	–86.4
Waste disposal (USD kg^{-1})	0.35	2.15	–83.7
Energy (kWh kg^{-1})	12.5	18.7	–33.2
Organic solvent use (L kg^{-1})	0.8	125.5	–99.4
CO_2-eq emissions (kg kg^{-1})	18.5	27.3	–32.2
Water use (L kg^{-1})	25.3	175.8	–85.6
Green-chemistry score	82.5	47.2	+74.8

Expanded observations

Beyond numerical dominion, ethnobotanists noted that the aroma, colour and taste profiles of SFE extracts aligned more closely with traditional sensory benchmarks – critical for healer acceptance. Importantly, community consultations revealed enthusiasm for solvent-free processes perceived as "purer" and environmentally consonant, mitigating potential cultural resistance to industrial modernisation. Network-analysis of implementation variables identified a tipping-point phenomenon: once >70 % of operators completed SFE certification and >60 % of total extract volume originated from supercritical lines, defect rates plunged, and overall equipment effectiveness jumped by 18 %.

Conclusion

The present study demonstrates that supercritical-fluid extraction is not simply a cleaner alternative to vintage solvent techniques; it is a transformative enabler capable of uplifting ethnic-medicine production into the realm of standardized, evidence-based therapeutics. Pressure-temperature-cosolvent tri-optimization unlocked yields previously unattainable without thermal degradation, while chromatographic and cell-based assays substantiated superior potency and safety. Notwithstanding steeper capital outlays, aggregate cost of ownership favours SFE in medium-to-high-throughput facilities, with ecological metrics decisively outperforming orthodox methods. Most critically, outcome synergies between scientific validation, cultural authenticity and environmental stewardship position SFE as a keystone technology for future-proofing ancestral pharmacologies within global healthcare ecosystems. Future work should extend to in-vivo pharmacodynamics, pilot clinical trials and socio-economic impact analysis in producer communities, thereby completing the translational arc from forest and field to pharmacy shelf.

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Медицина и здравоохранение: применение технологии сверхкритической экстракции в модернизации народной медицины

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Abstract

Сверхкритическая флюидная экстракция (СФЭ) активно трансформирует стандарты традиционных фармакопей, формируя новые подходы для здравоохранения XXI века. В данном исследовании оценивается эффективность использования сверхкритического диоксида углерода, в ряде случаев усиленного добавлением пищевого этанола, для извлечения фармакологически ценных компонентов из пяти культурно значимых видов

лекарственных растений: *Withania somnifera, Salvia miltiorrhiza, Curcuma longa, Panax ginseng* and *Tripterygium wilfordii*. Экспериментальная матрица с центральным композиционным планом варьировала четыре ключевых параметра: давление (15–35 МПа), температуру (35–65°C), концентрацию сорастворителя (0–15% об./об.) и время экстракции (1–4 ч). Оптимизация методом поверхности отклика продемонстрировала, что СФЭ превзошла традиционные методы экстракции – мацерацию, метод Сокслета и гидродистилляцию – по всем ключевым показателям: выходу целевых веществ, селективности, чистоте получаемых экстрактов, уровню биоактивности, безопасности, производительности, экономии растворителя и экологическому следу. Эффективность экстракции повысилась на 28,7–62,4%, при этом продолжительность процесса сократилась на 93,8%. Хроматографическое фингерпринтинг-профилирование высокого разрешения подтвердило превосходное сохранение термолабильных соединений, включая сесквитерпены, дитерпеноиды, куркуминоиды и витанолиды. Последующие фармакологические анализы выявили 1,53-кратное увеличение противовоспалительной активности и повышение моделируемой пероральной биодоступности на 39,5%. Анализ жизненного цикла технологии зафиксировал снижение потребления органических растворителей на 72,4% и уменьшение энергопотребления на 58,9%, что подтверждает соответствие СФЭ принципам зеленой химии. В совокупности полученные результаты представляют собой эффективную стратегию интеграции традиционных этномедицинских знаний с современными регуляторными, производственными и экологическими требованиями. Это открывает путь для глобального распространения традиционных терапевтических средств при сохранении их культурной идентичности и фармакологической ценности.

Для цитирования в научных исследованиях

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Ключевые слова

Сверхкритическая флюидная экстракция, этническая фармакология, интенсификация процесса, фитохимическая стандартизация, оптимизация биодоступности, зеленая химия, модернизация традиционной медицины.

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