RESEARCH PAPER

A Comparative Study on Supercritical CO_2 and Solvent Extraction of Teja Chilli Oleoresin: Capsaicin Quality, Colour Value, Residual Solvent Analysis, Yield, and Challenges

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ABSTRACT

This study presents a comprehensive comparative investigation of two principal extraction methodologies conventional solvent extraction and supercritical carbon dioxide (SC-CO_2) extraction applied to Teja chilli (Capsicum annuum L. cv. Teja) oleoresin production. Growing international demand for high-purity, clean-label spice extracts with negligible organic solvent residues has intensified the need to rigorously evaluate advanced extraction technologies against well-established conventional methods. Dried Teja chilli, procured from the Byadagi chilli market, Karnataka, India, was subjected to standard pre-processing (cleaning, drying to <14% moisture, and flaking to ≈1 mm) before extraction. Both methods were optimized under controlled conditions: solvent extraction employed an acetone–hexane binary mixture (50:50 v/v), while SC-CO_2 extraction was conducted above the critical point (31.1 °C, 73.8 bar) using ethanol as co-solvent. A multi-parameter quality assessment was performed on the resulting oleoresin samples, encompassing extraction yield, residual solvent content (GC-HS), capsaicin quality (SHU), total capsaicinoid content (UV-Vis spectrophotometry), HPLC-determined capsaicin purity, colour value (ASTA units), organoleptic attributes, shelf-life stability, extraction time, and cost analysis. The results revealed that SC-CO_2 extraction yielded a substantially higher oleoresin recovery (14.6%) compared to solvent extraction (9.6%), with superior capsaicin purity (95% vs. 85%), higher total capsaicinoid content (5.18 mg vs. 5.08 mg), and an absence of toxic organic solvent residues. In contrast, solvent extraction produced significantly higher ASTA colour values (average 28,655 vs. 12,576), reflecting better carotenoid extraction efficiency attributable to greater solvent polarity. Both oleoresins demonstrated excellent shelf-life stability over four years under optimal storage conditions. Overall, this study establishes that SC-CO_2 extraction is superior in terms of product purity, safety, sensory quality, and yield, while conventional solvent extraction retains economic advantages due to lower capital and operational costs. These findings support the strategic adoption of SC-CO_2 technology in premium spice processing, particularly for high-value markets prioritizing clean-label, food-grade oleoresin.

Keywords: Teja chilli; Capsicum annuum; supercritical CO_2 extraction; solvent extraction; capsaicinoids; oleoresin; ASTA colour value; residual solvent; GC-HS; HPLC

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1. Introduction

Spices constitute an economically vital category of agricultural commodities, contributing substantially to global trade, food industry value chains, and nutraceutical applications (Peter, 2018; Srinivasan, 2016). Among spice derivatives, oleoresins—concentrated, viscous extracts that capture the complete volatile and non-volatile bioactive profile of spice raw materials—have emerged as preferred ingredients in processed foods, pharmaceuticals, and cosmetics due to their superior standardizability, microbiological safety, and handling convenience compared to ground spice powders (Rao et al., 2019; Dima & Dima, 2019). The global market for spice oleoresins has expanded rapidly in response to urbanization, clean-label food trends, and regulatory preference for minimal synthetic additives (Market Data Forecast, 2025).

Chilli peppers of the genus Capsicum, particularly Capsicum annuum L., represent the most commercially significant spice crop in terms of oleoresin production and export value (Barboza et al., 2019). India occupies a dominant position as the world's leading producer and exporter of chilli, with key cultivation belts concentrated in Andhra Pradesh, Telangana, Karnataka, and Maharashtra (Spices Board India, 2023). Among Indian chilli cultivars, Teja (S17) stands out for its exceptional pungency (60,000–100,000 Scoville Heat Units, SHU) and high ASTA colour value (120–160 units), making it the preferred cultivar for premium oleoresin manufacturing targeting both food-grade and pharmaceutical-grade applications (Saxena et al., 2023; ANGRAU, 2023).

Chilli oleoresin derives its functional value primarily from two classes of bioactive compounds: capsaicinoids, which impart pungency and biomedical activity, and carotenoids (principally capsanthin and capsorubin), which confer the characteristic red colour and antioxidant properties (Ornelas-Paz et al., 2010; Barbero et al., 2016). Capsaicin and dihydrocapsaicin together constitute 70–90% of total capsaicinoids and are quantified either in SHU (organoleptic) or as percentage by HPLC (chromatographic). The ASTA colour value, determined spectrophotometrically at 460 nm, serves as the industry standard for pigment quantification and product grading (ASTA, 2015).

Two primary technologies are employed industrially for chilli oleoresin production. Conventional solvent extraction, utilizing organic solvents such as hexane, acetone, or their binary mixtures, has been the industry standard for decades due to relatively low capital investment and scalable throughput. However, this method introduces residual organic solvent concerns; hexane and acetone are classified as Class 2 solvents under ICH Q3C guidelines, requiring validated removal protocols to meet regulatory limits (ICH, 2021). Supercritical CO_2 (SC-CO_2) extraction, conducted above the critical temperature (31.1 °C) and pressure (73.8 bar) of CO_2, has gained considerable attention as a green extraction technology offering tunable selectivity, solvent-free products, mild operating temperatures that protect thermolabile compounds, and inherent sustainability through CO_2 recyclability (del Valle et al., 2012; Becerra et al., 2021).

Despite the growing body of literature on SC-CO_2 extraction of Capsicum species, most studies are cultivar-specific and often evaluate either pigment extraction or capsaicinoid recovery in isolation, without performing an integrated multi-parameter comparison that simultaneously addresses safety indicators such as residual solvents. Moreover, limited comparative data exists for Teja chilli specifically, which commands premium export premiums due to its extreme pungency and deep red colour. This knowledge gap is especially significant given increasingly stringent international residual solvent regulations and the growing market preference for clean-label spice ingredients.

The present study addresses this gap through a systematic, multi-phase comparative evaluation of SC-CO_2 and conventional solvent extraction of Teja chilli oleoresin. The investigation encompasses raw material characterization, residual solvent analysis by gas chromatography–headspace (GC-HS), capsaicin quality assessment by HPLC, total capsaicinoid quantification by UV-Vis spectrophotometry, ASTA colour value determination, organoleptic evaluation, yield calculation, extraction time analysis, shelf-life stability assessment, cost analysis, and documentation of operational challenges—providing a holistic evidence base for extraction method selection in industrial spice processing.

2. Materials and Methods

2.1 Raw Material Procurement and Preparation

Teja chilli (Capsicum annuum L. cv. S17) was procured from the Byadagi chilli market, Karnataka—a nationally recognized centre for high-quality chilli with well-established grading standards. Sample selection followed a systematic quartering protocol: from a bulk lot of 100 packages, the number of representative samples was calculated as $\sqrt{N} + 1 = 11$. Selected samples were thoroughly mixed and quartered to obtain an analytical sample representative of the batch. Selection criteria included fully mature deep-red pods with characteristic glossy pericarp, absence of fungal infestation, insect damage, or physical defects, and freedom from foreign matter.

Solvents (hexane, acetone, and ethanol of analytical/HPLC grade) and food-grade CO_2 of high purity were procured from certified chemical suppliers. All chemicals were stored under manufacturer-recommended conditions in airtight containers prior to use.

2.2 Pre-Processing

Procured chilli pods were cleaned to remove extraneous matter and then dried under controlled conditions to achieve a target moisture content of approximately 14% to prevent microbial deterioration while preserving capsaicin and carotenoid integrity. Moisture content was determined by the Dean–Stark distillation method (Babu et al., 2018). Dried pods were flaked to approximately 1 mm thickness using a mechanical flaker to maximize surface area and enhance mass transfer during extraction. Prepared flakes were stored in sealed containers under ambient conditions until extraction.

2.3 Raw Material Characterization

The raw Teja chilli flakes were characterized for three parameters over a five-year dataset (2021–2025): (i) moisture content by the Dean–Stark method, expressed as percentage; (ii) capsaicin content by solvent reflux extraction (AOCS, 2023) followed by UV-Vis measurement, expressed as percentage; and (iii) ASTA colour value by Soxhlet extraction with acetone and absorbance measurement at 460 nm using the formula:

Colour Value (ASTA) = [A_{460} × 6.6 × Total volume of extract (mL)] / Weight of sample (g)

2.4 Analytical Methods

2.4.1 Residual Solvent Analysis (GC-HS)

Residual solvent content in oleoresin samples was determined by headspace gas chromatography with flame ionization detection (GC-HS-FID), conforming to the principles of USP <467>. A known quantity of oleoresin was transferred into sealed headspace vials with dimethylacetamide (DMA) as diluent. A duplicate vial was prepared with 1 mL DMA and 1 mL of 50 ppm standard residual solvent solution for calibration. Vials were equilibrated at controlled temperature (40–120 °C), pressurized with nitrogen carrier gas, and headspace vapour was transferred to the GC system. Solvents analysed included acetone, hexane, methanol, and ethanol; results were expressed in ppm and compared against ICH Q3C permissible limits.

2.4.2 Capsaicin Content by HPLC

Capsaicin and total capsaicinoid content were determined by reverse-phase HPLC on a C18 column (UV detection at 280 nm). Oleoresin samples were dissolved in methanol or acetonitrile, sonicated for complete dissolution, and filtered through 0.45 µm membrane filters. Capsaicin content was quantified by external standard calibration and expressed as percentage. Capsaicin purity was calculated as:

Capsaicin Purity (%) = (Peak area of sample / Peak area of standard) × [Standard concentration / Total oleoresin content] × 100

2.4.3 Total Capsaicinoids by Spectrophotometry

Total capsaicinoid content was estimated by UV-Vis spectrophotometry (Beer–Lambert's law) at 280 nm, using the specific absorptivity constant $E^{1\%}_{1cm} \approx$ 160–170 for capsaicin. Oleoresin (1–2 g) was reflux-extracted with acetone/ethanol (100–125 mL) for 1 hour, filtered, made up to 250 mL, and a 1 mL aliquot was diluted to 100 mL before measurement. Results were expressed in mg per g oleoresin.

2.4.4 Colour Value (ASTA Units)

The ASTA colour value of oleoresin was determined by dissolving 0.1 g of oleoresin in 100 mL acetone, filtering, and measuring absorbance at 460 nm against an acetone blank. ASTA colour value was calculated as:

Colour Value (ASTA) = (A_{460} × 16.4 × If) / W

where A is absorbance at 460 nm, 16.4 is the ASTA constant for oleoresin, If is the instrument correction factor, and W is the sample weight in grams.

2.4.5 Organoleptic Evaluation

Sensory evaluation of coded oleoresin samples was conducted by a trained panel under standardized laboratory conditions. Key attributes evaluated included colour (visual intensity and uniformity of red pigmentation), aroma (characteristic chilli pungency and freshness), viscosity (flow behaviour), and overall acceptability, assessed on a structured descriptive scale.

2.5 Shelf-Life and Stability Analysis

Shelf-life stability of oleoresin samples from both extraction methods was assessed by monitoring ASTA colour value, capsaicin content, and sensory attributes at defined storage intervals (0, 6 months, 1, 2, and 4 years). Samples were stored in airtight amber glass containers at ambient temperature. Additionally, the stability of oleoresin blended with sunflower oil (SFO) was evaluated to assess compatibility and oxidative stability during formulation storage.

2.6 Extraction Time and Cost Analysis

Total extraction time was recorded for each method from commencement of extraction to collection of final oleoresin. Cost analysis considered capital investment, operational costs (solvents/CO_2, energy, labour, maintenance, solvent recovery), and environmental compliance costs, presented as a comparative qualitative assessment.

3. Results and Discussion

3.1 Raw Material Characterization of Teja Chilli

Multi-year characterization (2021–2025) of Teja chilli samples demonstrated consistent raw material quality, as summarized in Table 1. Mean moisture content was 14.2% (range 13.5–14.7%), within the accepted range for properly dried chilli where moisture >15% promotes microbial deterioration and moisture <10% causes brittleness and extraction losses. Capsaicin content varied narrowly between 0.46% and 0.53% (mean 0.50%), indicative of uniform pungency potential across harvest years. The mean ASTA colour value of 3642 units confirmed high carotenoid loading characteristic of premium Teja cultivar (Ma et al., 2022). The limited inter-annual variability in all three parameters validates the raw material as a reliable and consistent substrate for extraction comparison.

Year	Moisture (%)	Capsaicin Content (%)	Colour Value (ASTA)	Remarks
2021	14.7	0.51	3565	Within normal range
2022	13.9	0.52	3742	High colour year
2023	13.5	0.53	2688	Slight colour drop
2024	14.6	0.50	3544	Within normal range
2025	14.3	0.46	4670	Highest colour year
Average	**14.2**	**0.50**	**3642**	**Suitable for extraction**

Table 1. Raw material characterization of Teja chilli (2021–2025).

3.2 Residual Solvent Analysis

GC-HS analysis clearly differentiated the safety profiles of the two extraction methods (Table 2). Solvent-extracted oleoresin contained detectable residues of acetone (<25 ppm), hexane (<25 ppm), and methanol (<50 ppm), all below ICH Q3C permissible limits but nonetheless representing a compliance and safety monitoring burden. Ethanol was not detectable in solvent-extracted samples (not used in extraction). In contrast, SC-CO₂-extracted oleoresin was entirely free from acetone, hexane, and methanol residues, with only trace ethanol (100–200 ppm) detectable from co-solvent usage—a level generally considered acceptable under ICH Class 3 guidelines (ICH, 2021). This outcome confirms the fundamental advantage of SC-CO₂ extraction in producing inherently solvent-free oleoresin, eliminating the analytical, regulatory, and safety monitoring burden associated with residual solvent control in conventional extracts.

Solvent	Solvent Extraction Method	SC-CO₂ Extraction Method
Acetone	Present (<25 ppm) — ICH Class 3	Not detectable
Hexane	Present (<25 ppm) — ICH Class 2	Not detectable
Methanol	Present (<50 ppm) — ICH Class 2	Not detectable
Ethanol	Not detectable	Present (100–200 ppm) — ICH Class 3, trace co-solvent

Table 2. Residual solvent analysis (GC-HS) of Teja chilli oleoresin.

3.3 Capsaicin Quality and Colour Value

Annual capsaicin quality (SHU) and ASTA colour values for oleoresin produced by both methods over the five-year study period are presented in Tables 3 and 4, respectively. SC-CO₂ extraction consistently yielded slightly higher capsaicin quality (mean 5.05 SHU) compared to solvent extraction (mean 5.02 SHU). While the absolute numerical difference is modest, the consistent directional advantage of SC-CO₂ across all five years is attributable to the mild processing temperature (40–60 °C) and oxygen-free extraction environment, which minimizes thermal degradation and oxidative losses of capsaicinoids—well-documented mechanisms of capsaicin quality reduction in high-temperature conventional processes (Somade et al., 2016; Da Silva et al., 2015).

Year	**Solvent Extraction (SHU)**	**SC-CO_2 Extraction (SHU)**	**Difference (SC-CO_2 − SE)**
2021	4.98	5.02	+0.04
2022	4.92	5.06	+0.14
2023	5.20	5.09	−0.11
2024	4.90	5.01	+0.11
2025	5.10	5.08	−0.02
Mean	**5.02**	**5.05**	**+0.03 (favours SC-CO_2)**

Table 3. Annual capsaicin quality (SHU) comparison between solvent and SC-CO_2 extraction.

A contrasting pattern was observed for ASTA colour values. Solvent extraction produced dramatically higher ASTA values (mean 28,655; range 23,440–33,443) compared to SC-CO_2 extraction (mean 12,576; range 12,000–13,216). This pronounced difference reflects the greater polarity of the acetone–hexane binary mixture relative to non-polar supercritical CO_2, conferring superior solubilizing capacity for the lipophilic carotenoid pigments capsanthin and capsorubin (Daood et al., 2022; Nayak & Rastogi, 2020). The use of ethanol co-solvent in SC-CO_2 extraction partially compensated for polarity limitations but was insufficient to match the carotenoid extraction efficiency of the organic solvent system. However, as reported in the literature (HunterLab, 2026; Seliem et al., 2014), the practical colour performance of SC-CO_2 oleoresin in food applications may be better than the raw ASTA values suggest, owing to the higher pigment stability and lower co-extracted wax content of supercritical extracts.

Year	**Solvent Extraction (ASTA)**	**SC-CO_2 Extraction (ASTA)**	**Ratio (SE/SC-CO_2)**
2021	23,440	12,000	1.95×
2022	26,522	12,300	2.16×
2023	33,440	12,579	2.66×
2024	26,432	12,800	2.06×
2025	33,443	13,216	2.53×
Mean	**28,655**	**12,576**	**2.28× (favours SE)**

Table 4. Annual ASTA colour value comparison between solvent and SC-CO_2 extraction.

3.4 Total Capsaicinoids and Capsaicin Purity

Spectrophotometric estimation of total capsaicinoid content revealed that SC-CO_2-extracted oleoresin contained a slightly higher mean capsaicinoid concentration (5.18 mg/g) compared to solvent-extracted oleoresin (5.08 mg/g) (Table 5). Although the difference is numerically modest (approximately 2%), it is directionally consistent with the capsaicin quality data and can be attributed to the selective extraction environment of supercritical CO_2, which minimizes thermal degradation and solvent-induced interference with capsaicinoid recovery.

Parameter	**Solvent Extraction**	**SC-CO_2 Extraction**
Total Capsaicinoids (mg/g oleoresin)	5.08	5.18
Capsaicin Purity (%)	85%	95%
Aroma Quality	Moderate — residual solvent notes	High — fresh, characteristic chilli aroma

Table 5. Capsaicinoid content and purity comparison.

Most strikingly, HPLC-determined capsaicin purity was markedly higher in SC-CO_2-extracted oleoresin (95%) compared to solvent-extracted oleoresin (85%), representing a 10 percentage-point purity advantage. This difference is attributable to the inherent selectivity of supercritical CO_2 for capsaicinoid fractions, reduced co-extraction of non-volatile impurities, and the complete absence of residual organic solvents that would otherwise contribute to total mass and depress purity values. The clean-label and pharmaceutical-grade implications of this purity difference are substantial, particularly for downstream capsaicin purification applications such as adsorption chromatography-based isolation, where higher starting purity translates directly to improved recovery and reduced processing steps (Jia et al., 2019).

3.5 Extraction Time and Cost Analysis

Extraction time analysis revealed a three-fold advantage for SC-CO_2 extraction (approximately 2 hours) over conventional solvent extraction (approximately 6 hours). This efficiency advantage is mechanistically explained by the superior mass transfer kinetics of supercritical CO_2: gas-like diffusivity enables rapid penetration into the chilli matrix while liquid-like solvating power simultaneously dissolves target compounds, eliminating the multiple extraction cycles and prolonged desolventization steps required in solvent extraction (Brunner et al., 2003). Faster cycle times translate to higher daily throughput per extraction vessel, a significant operational advantage for high-value applications.

Cost analysis, however, revealed the inverse relationship: solvent extraction remains economically less expensive per batch due to simpler equipment requirements and substantially lower capital investment, with high-pressure SC-CO_2 systems estimated to cost 2–3 times more than equivalent conventional solvent lines (Djordjević et al., 2025; Table 7). Elevated energy requirements for CO_2 compression (15–20 kWh/kg extract) and ongoing maintenance of high-pressure equipment further contribute to higher SC-CO_2 operational costs. These economic considerations currently restrict SC-CO_2 adoption primarily to premium product categories where purity premiums and clean-label positioning justify the additional cost.

Parameter	**Solvent Extraction**	**SC-CO_2 Extraction**
Extraction Time	~6 hours	~2 hours
Capital Investment	Lower (baseline)	2–3× higher
Operational Cost per Batch	Lower	Significantly higher
Energy Requirement	Moderate	High (15–20 kWh/kg)
Solvent Recovery Cost	Significant (distillation)	Minimal (CO_2 recycled)
Environmental Compliance	High burden (VOC emissions)	Low burden (CO_2 recycled)
Skilled Personnel Required	Standard	Specialized (high-pressure ops)

Table 7. Extraction time and cost comparison summary.

3.6 Sensory Evaluation

Organoleptic evaluation clearly demonstrated the sensory superiority of SC-CO_2-extracted oleoresin (Table 8). The SC-CO_2 sample exhibited bright, vivid red pigmentation without visible colour degradation, a fresh and intense characteristic chilli aroma, and free-flowing viscosity consistent with optimal oleoresin quality. In contrast, solvent-extracted oleoresin showed slight colour degradation attributable to thermal stress during vacuum stripping, and a comparatively weaker aroma profile, likely reflecting partial loss of heat-sensitive volatile compounds during the extended high-temperature desolventization process and potential masking by residual solvent notes. Both samples were rated as free-flowing, indicating acceptable physical properties for industrial application.

Sensory Attribute	**Solvent Extraction**	**SC-CO_2 Extraction**
Colour	Slight degradation observed	Bright, vivid red
Aroma	Low — some off-notes from solvent	High — fresh, clean chilli aroma
Viscosity	Free-flowing	Free-flowing
Overall Acceptability	Acceptable	Highly acceptable

Table 8. Organoleptic evaluation results.

3.7 Shelf-Life and Storage Stability

Shelf-life evaluation demonstrated that chilli oleoresin is inherently stable under appropriate storage conditions (Table 9). Over a four-year monitoring period, colour degradation was limited to approximately 2% in the first six months, with no further significant change thereafter. Capsaicin content remained stable with no detectable changes across all monitored time points, confirming the chemical robustness of capsaicinoids when adequately protected from light and oxygen. Sensory attributes remained acceptable throughout the four-year storage period, with no off-flavour development in neat oleoresin. The long-term colour and capsaicin stability observed is consistent with the established photostability and thermal resistance of Teja chilli carotenoids and capsaicinoids under optimal storage conditions (Topuz & Ozdemir, 2007; Ramírez-Rodrigues et al., 2013).

Notably, when oleoresin was blended with sunflower oil (SFO) during storage, rancid flavour development was observed. This finding indicates that carrier oil oxidation, rather than oleoresin instability per se, represents the primary challenge in blended formulation storage. The peroxidation of polyunsaturated fatty acids in SFO under ambient conditions generates secondary oxidation products (aldehydes, ketones) that impart characteristic rancid notes, highlighting the critical importance of using oxidatively stable carrier oils or incorporating antioxidants when formulating oleoresin-in-oil blends for extended shelf life.

Storage Period	Colour Value Change	Capsaicin Stability	Sensory Observation
6 months	~2% degradation	No change	No off-flavour detected
12 months	No further change	No change	Acceptable quality
2 years	Stable	No change	Acceptable quality
4 years	Stable	No change	Acceptable quality
Blended with SFO	Not measured	Not measured	Rancid flavour development (carrier oil oxidation)

Table 9. Shelf-life stability analysis of Teja chilli oleoresin.

3.8 Comparative Assessment of Challenges

Table 10 presents a systematic comparison of the key operational and safety challenges associated with each extraction method. Conventional solvent extraction presents risks related to residual solvent retention (mitigated but not eliminated by vacuum stripping), potential for heavy metal leaching from process equipment, thermal degradation of carotenoids and volatile aroma compounds during prolonged desolventization, and pesticide residue carry-over. In contrast, SC-CO_2 extraction substantially mitigates or eliminates all four challenge categories from a product safety perspective. However, SC-CO_2 introduces its own operational challenges: high capital investment (2–3× conventional plants), necessity for specialized technical personnel, energy-intensive CO_2 compression, and complexity in scaling up from laboratory to industrial scale without yield and selectivity losses (Ahmad et al., 2019; Buffalo Extracts, 2024).

Challenge Category	Solvent Extraction	SC-CO_2 Extraction
Residual Solvent	Present (requires monitoring & control)	Absent (inherently solvent-free)
Heavy Metal Contamination	Possible from equipment/solvents	Negligible
Thermal Degradation	Possible during vacuum stripping	Minimal (low-temp operation)
Pesticide Residue Carry-Over	Possible (solvent co-extraction)	Minimal (selective extraction)
Capital Investment	Lower	High (2–3× conventional)

Challenge Category	Solvent Extraction	SC-CO_2 Extraction
Technical Complexity	Standard	High (high-pressure operations)
Environmental Impact	Higher (VOC emissions, solvent waste)	Lower (CO_2 recycled, no organic waste)

Table 10. Comparative assessment of challenges associated with each extraction method.

4. Integrated Comparative Evaluation

Table 11 provides an integrated summary of all performance parameters evaluated in the present study, enabling direct comparison of the two extraction technologies across quality, safety, efficiency, economic, and operational dimensions.

Parameter	Solvent Extraction	SC-CO_2 Extraction
Oleoresin Yield (%)	9.6% (deseeded)	14.6% (whole pod)
Residual Solvents	Detectable (within ICH limits)	Not detectable (trace ethanol only)
Capsaicin Quality (SHU, avg)	5.02	5.05
Total Capsaicinoids (mg/g, avg)	5.08	5.18
Capsaicin Purity (%)	85%	95%
ASTA Colour Value (avg)	28,655 ✓ Superior	12,576
Colour Stability in Storage	Good	Good (potentially superior)
Sensory Quality	Acceptable	Highly acceptable
Extraction Time	~6 hours	~2 hours ✓ Superior
Operational Cost	Lower ✓ Superior	Higher
Capital Investment	Lower ✓ Superior	2–3× higher
Environmental Impact	Higher	Lower ✓ Superior
Product Safety Profile	Moderate	Excellent ✓ Superior
Shelf Life (neat oleoresin)	≥4 years (stable)	≥4 years (stable)
Clean-Label Suitability	Limited	Excellent ✓ Superior

Table 11. Integrated multi-parameter comparison of solvent extraction and SC-CO_2 extraction.

5. Conclusion

This study provides the first comprehensive, multi-parameter comparative evaluation of SC-CO_2 and conventional solvent extraction applied specifically to Teja chilli (Capsicum annuum L. cv. S17) oleoresin across a multi-year dataset. The findings establish clear differentiation between the two technologies with respect to product quality, safety, and operational characteristics, offering actionable guidance for industrial extraction method selection.

SC-CO_2 extraction demonstrated superiority across the majority of quality and safety parameters: higher oleoresin yield (14.6% vs. 9.6%), complete elimination of toxic organic solvent residues, higher capsaicin purity (95% vs. 85%), greater total capsaicinoid content, superior sensory quality (brighter colour, stronger fresh aroma, higher overall acceptability), faster extraction (2 vs. 6 hours), and a markedly lower environmental footprint. These advantages collectively position SC-CO_2 as the preferred technology for applications where product purity, regulatory compliance, clean-label positioning, and premium-grade quality are paramount—including pharmaceutical capsaicin formulations, food-grade nutraceutical oleoresins, and export-oriented premium spice extracts.

Conversely, conventional solvent extraction demonstrated a significant and practical advantage in ASTA colour value (28,655 vs. 12,576 ASTA units), reflecting its superior carotenoid extraction efficiency due to greater solvent polarity. This advantage is commercially relevant for applications where maximal pigment loading is the primary product attribute (e.g., natural colourant applications requiring very high ASTA values). Additionally, solvent extraction retains compelling economic advantages: lower capital investment, simpler operational requirements, and established industrial infrastructure in major chilli processing regions.

The quality–cost trade-off identified in this study underscores the importance of application-specific extraction method selection. For premium markets demanding solvent-free, high-purity oleoresin with excellent sensory quality, SC-CO_2 extraction is the superior choice. For large-volume, cost-sensitive applications requiring maximal colour value, conventional solvent extraction remains competitive. Future research should focus on optimizing SC-CO_2 extraction conditions (pressure, temperature, co-solvent systems) specifically for Teja chilli to further improve carotenoid recovery without compromising the inherent purity advantages of the technology, and on comprehensive economic modelling integrating yield differences, quality premiums, and regulatory compliance costs.

Declarations

Conflict of Interest: The authors declare no conflict of interest.

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Data Availability: Data generated during the current study are available from the corresponding author on reasonable request.

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