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PROCESSING OPTIMIZATION AND SHELF-STABILITY ASSESSMENT OF *Hippophae rhamnoides* L. PRODUCTS IN THE COLD DESERT REGION OF LAHAUL-SPITI

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ABSTRACT

Seabuckthorn (*Hippophae rhamnoides* L.), locally revered as "Ladakh Gold," represents an underutilized nutritional resource thriving at 3,660 m in Lahaul-Spiti's cold desert. This study standardized low-cost processing protocols for jam, pulp, leaf tea ("Kaaru"), and fruit residue tea at Krishi Vigyan Kendra (KVK) Tabo during 2020-21, targeting sustainable livelihoods for remote producers lacking cold-chain infrastructure. Standardized protocols yielded three superior jam formulations from 2.5 kg fresh berries: T1 (whole fruit + sugar syrup) limited to 30-day shelf life due to high water activity; T2 (fine pulp + sucrose + 10 min boiling + 0.05% KMS) and T3 (pulp + 1g sodium bicarbonate) achieved 24-month ambient stability** with light orange color, semi-solid/soft texture, and sweet-acidic flavor profile. Sensory evaluation by 10 trained panelists (9-point hedonic scale) ranked T2 highest (overall acceptability: 8.1) due to optimal texture (8.1) and flavor balance (8.4), significantly superior to T1 (5.7 overall). Pulp processing produced three formulations: T1 (crushing + sieving) stable 12-18 months with vibrant orange pulpy texture; T2 (pulp + sugar + boiling + 0.03% KMS) and T3 (pulp + 0.03% sodium benzoate) achieved 2-year stability** with deep amber syrupy (T2) and bright orange liquid (T3) characteristics. 'Kaaru' leaf tea protocol utilized disease-free male leaves preferred for higher polyphenol content, processed through washing, shade drying (1 week), 3-4 minute boiling, and sugar finishing for optimal antioxidant extraction without bitterness. Zero-waste fruit residue tea converted pulp extraction skins/seeds via sun drying (1 week) into premium beverage with black tea, ginger, cardamom, and jaggery aromatics. KVK Tabo formulations require minimal equipment (manual crushing, domestic boiling) and locally available preservatives (KMS Rs. 200/kg, sodium benzoate Rs. 300/kg), ideal for Lahaul-Spiti women SHGs. T2 jam and T3 pulp offer immediate commercialization potential with >80% sensory acceptance and 24-fold shelf-life extension over traditional methods, achieving complete resource utilization and sustainable market viability for trans-Himalayan producers.

Keywords **:** Seabuckthorn, KVK Tabo, jam processing, pulp preservation, zero-waste tea, sensory evaluation, cold desert horticulture.

Introduction

Hippophae rhamnoides L., commonly known as sea buckthorn, stands as a remarkable deciduous shrub within the Elaeagnaceae family, serving critical ecological and economic functions across India's trans-Himalayan cold deserts, particularly in regions like Lahaul-Spiti (Stobdan *et al.*, 2011). This hardy plant flourishes at altitudes of 3,660–4,000 meters, enduring extreme conditions such as -40°C winters, minimal precipitation, and intense solar radiation in the Himalayan rain shadow (Singh, 2003). Its deep, anchor-like root system not only combats soil erosion in fragile arid landscapes but also fixes atmospheric nitrogen, enriching nutrient-poor soils and supporting associated flora and fauna vital to these ecosystems (Gupta *et al*., 2003; Sharma *et al*., 2015). Often revered locally as "Ladakh Gold," "Tirku," or the "Wonder Plant," sea buckthorn's berries cling resiliently to branches through prolonged frost, preserving their extraordinary nutritional bounty for harvest (Stobdan *et al*., 2017; Suo *et al*., 2025).

The berries represent a nutritional powerhouse, boasting over 190 bioactive compounds that underscore their status as a "super healthy fruit". They deliver vitamin C at concentrations up to 275 mg/100g, roughly 10 times that of oranges or kiwi fruit, alongside vitamin A (432 IU/100g), vitamins E, K, and the full B-complex spectrum (Stobdan *et al*., 2017; Feng *et al*., 2023; Gutzeit *et al*., 2008). Minerals abound, including potassium (647 mg/L), calcium (177 mg/L), and iron (31 mg/L), complemented by a unique profile of all four major omega fatty acids: omega-3 (alpha-linolenic acid), omega-6 (linoleic acid), omega-7 (palmitoleic acid), and omega-9 (oleic acid) (Wang *et al*., 2022; Xia *et al*., 2023). These components confer potent antioxidant, anti-inflammatory, and immune-modulating properties, aiding in mucosal protection against gastric ulcers, alleviating arthritis symptoms, and potentially offering neuroprotective benefits through enhanced nervous system equilibrium and reduced oxidative stress. Seed oil stands out for its high oleic acid content (13–33%) and ideal omega-3/6 balance, ideal for cosmeceuticals and cardiovascular support. Meanwhile, leaves supply protein, tannins, flavonoids (e.g., quercetin, kaempferol, isorhamnetin), carotenoids, and sterols, forming the basis of traditional infusions with strong DPPH/ABTS scavenging activity (Marsiñach *et al*., 2019; Wang *et al*., 2022; Suo *et al*., 2025).

In India, sea buckthorn's natural distribution spans Ladakh (harboring over 13,000 hectares, the largest expanse), Kumaon-Garhwal in Uttarakhand, Lahaul-Spiti and Kinnaur in Himachal Pradesh, and northeastern states like Sikkim and Arunachal Pradesh (Wang *et al*., 2022; Husain *et al*., 2018). Within Himachal Pradesh's cold arid zone, Lahaul-Spiti exemplifies its potential as a naturally occurring wild resource with exceptional adaptability to local conditions (Bali *et al*., 2016). Traditional uses permeate local livelihoods: fruits yield juices, jams, preserves, compotes, beers, and teas; seeds and pulp produce medicinal oils; leaves brew "Kaaru" tea from disease-free male plants (boiled 3–4 minutes with sugar); and the entire shrub provides fencing, fuel, and remedies (Stobdan *et al*., 2017). Processed goods like multivitamin beverages, herbal teas, soft-gel capsules, and apricot blends tap into its nutraceutical and pharmaceutical promise, yet commercialization lags due to post-harvest hurdles (Sabir *et al*., 2005).

Harvesting demands precision amid the plant's thorny structure and berry delicacy: manual picking (25 kg/person/day) or pre-dawn rope-shaking (80% yield for allied species) occurs from late August to September, followed by immediate cooling to 4–6°C, short-term storage at 1–2°C (up to 30 days), or IQF freezing at -18°C for a year to safeguard nutrients. Processing involves crushing washed berries, sieving for juice (1.5 L from 2.5 kg), sun-drying residues/seeds for tea, boiling with sugar, and adding preservatives like potassium metabisulfite (KMS, 0.25–0.3 g/L) or sodium bicarbonate for jam/pulp stability in sterilized bottles. Despite these practices, challenges persist: rapid microbial proliferation, vitamin C/E degradation, omega fatty acid rancidity, and odor development from overripe fruit undermine shelf-life in remote, infrastructure-scarce cold deserts (Tiitinen *et al*., 2006; Khan *et al*., 2012; Geng *et al*., 2023; Zhang *et al*., 2023).

Shelf-stability emerges as pivotal for broadening consumer acceptance, market viability, and year-round nutritional security from this underutilized. This study, conducted during the 2020-21 season in Lahaul-Spiti, refines low-cost protocols for sea buckthorn jam (juice boiled with 0.5 kg sugar/kg, preserved for 2 years), pulp/juice (sieved extract with KMS), and leaf tea, ensuring maximal retention of vitamin C, E, antioxidants, and sensory qualities without deterioration to empower local producers and align with sustainable horticultural extension goals.

Material and Method

Study Location and Duration

The investigation was conducted during the 2020-2021 cropping season at Krishi Vigyan Kendra (KVK), Tabo, Lahaul-Spiti District, Himachal Pradesh, India. Located at 3,660 m above mean sea level (32°05'N, 78°00'E), the site represents typical cold arid desert conditions characterized by extreme temperature fluctuations (-35°C to +25°C), low annual precipitation (<250 mm), and short growing seasons. KVK Tabo operates under the administrative control of Dr. Y.S. Parmar University of Horticulture and Forestry, Nauni, Solan (HP).

Seabuckthorn Plant Material and Propagation

Naturally occurring *Hippophae rhamnoides* L. populations were utilized for fruit harvesting. For future plantation programs, propagation protocols were standardized as follows:

Sexual Propagation (Seed-based)

Ripe berries were collected in October-November and processed to extract clean seeds following pulp maceration and open-shade drying. Seeds were stored in muslin bags at 4°C for up to 12 months. Pre-sowing stratification involved cold water soaking (daily water change) for 6 days to break dormancy. Sowing occurred mid-May in sunken nursery beds using sterilized media (sand:soil:FYM = 2:1:1) at 1.5 cm depth, 20 × 5 cm spacing. Polybag transplants used 5:3:1 media ratio. Management included grass mulching, partial shading, and sprinkler irrigation (twice weekly).

Asexual Propagation (Cuttings)

Semi-hardwood cuttings (9 cm, 2-year-old shoots) were collected during February-March and planted at 20 cm spacing in sand: soil: FYM (1:1:1) rooting medium. Rooting success averaged 68% after 8-10 weeks under intermittent mist.

Fruit Harvesting

Fruits ripened from late August through September (post May-June flowering). Harvesting constraints included thorny branches and delicate berry skin prone to mechanical injury. Two methods were employed:

- **Manual plucking**: Pre-dawn harvesting (25 ± 3 kg worker^{-1} day^{-1}) minimized berry damage
- **Mechanical shaking**: Rope-assisted shaking of *H. salicifolia* accessions yielded ~80% fruit drop before sunrise (efficiency declined >90% post-sunrise)

Overripe berries were avoided to prevent musky odor development. Harvested fruits were immediately field-washed.

Post-Harvest Handling

Fresh berries underwent rapid pre-cooling to 4-6°C within 2 hours to suppress microbial proliferation. Short-term storage (≤30 days) maintained 1-2°C, while long-term preservation employed Individual Quick Freezing (IQF) at -18°C (nutrient retention up to 12 months).

Product Development

Seabuckthorn Jam

From 2.5 kg fresh berries, fruits were washed, crushed, and juice extracted via muslin sieving (yield: 1.5 L). Fruit residue (pulp/seeds) was sun-dried for tea preparation. Juice was boiled with sucrose (0.5 kg L^{-1}) to 68°Brix, cooled, and preserved with potassium metabisulfite (KMS, 0.1% w/v) or sodium bicarbonate. Final product filled in pre-sterilized glass bottles (shelf-life: 24 months at ambient temperature).

Seabuckthorn Pulp/Juice

Berries (fresh weight basis) were washed, crushed, and pulp separated via sieving. Pulp yield averaged 60% fresh weight. Sugar adjusted to 15°Brix, KMS added (250-300 mg L^{-1}), hot-filled (85°C) into sterilized bottles (shelf-life: ≥24 months).

Seabuckthorn Leaf Tea ("Kaaru")

Disease-free male leaves (preferred over female due to superior biochemical profile) were collected, washed, shade-dried (40°C, 24h), and powdered. Preparation involved 1 tsp (2g) boiled in 150 mL water (3-4 min), sweetened with 1 tsp sugar. Traditional female leaf variants also prepared similarly.

Quality Parameters Assessed

Physical (yield, texture), chemical (TSS, acidity, vitamin C), microbial (total plate count), and sensory attributes monitored at 0, 6, 12, and 24 months storage under ambient (25±5°C) and refrigerated (4±1°C) conditions. Standard analytical methods followed (Ranganna, 2008).

Result and Discussion

Sea buckthorn Jam Processing

The experimental data reveals a significant improvement in storage stability when transitioning from whole fruit immersion to pulp-based processing. While the whole fruit treatment (T1) exhibits a limited shelf life of only one month due to high intrinsic moisture and the absence of preservatives, the jam formulations (T2 and T3) remain stable for up to six months. This extended durability in T2 is primarily driven by the addition of 0.05% Potassium Metabisulphite (KMS), which effectively inhibits microbial proliferation and enzymatic degradation. In terms of visual and color attributes, a distinct transition is observed from the Dark Orange of the unprocessed fruit in T1 to a Light Orange hue in the processed jams. This color shift is a characteristic result of the pulping process and the 10-minute thermal treatment, which induces pigment oxidation and incorporates air, resulting in a lighter visual profile. The textural evolution highlights the structural breakdown required to achieve a spreadable consistency. T1 maintains a Solid state by preserving the whole berry structure. In contrast, T2 achieves a Semi-solid consistency typical of standard fruit jams. Interestingly, T3 yields a Soft texture; the inclusion of Sodium Bicarbonate acts as an alkaline agent that modifies the natural pectin gelation, resulting in a more delicate set compared to the firmer structure of T2. Finally, the flavor profile undergoes a significant enhancement. The natural, intense acidity of the Sea Buckthorn berry remains dominant and sour in T1, as the sugar syrup fails to neutralize the internal acids of the whole fruit. However, the pulping and boiling involved in T2 and T3, combined with sugar addition, create a balanced "Sweet with acidic blend." This synergy effectively tempers the fruit's harsh tartness, significantly increasing its overall palatability for commercial consumption.

Table 1: Physical and sensory characteristics of Sea Buckthorn jam (*Hippophae* spp.) under different processing treatments

Treatments	Shelf life	Color	Texture	Flavor
T1 -Wash sea buckthorn fruit + dip in sugar syrup	1 month	Dark Orange	Solid	Sour
T2 -Sea buckthorn fine fruit pulp + add sugar + boil for 10 min + add 0.05%KMS	2 years	Light orange	Semi solid	Sweet with acidic blend
T3 -Sea buckthorn fine fruit pulp + add Sodium bicarbonate (1g)	2years	Light orange	Soft	Sweet with acidic blend

Table 2: Sensory Evaluation of Sea Buckthorn Jam Formulations (9-point Hedonic Scale)

Attributes	T1 (Whole Fruit)	T2 (Pulp + 0.05% KMS)	T3 (Pulp + $NaHCO_3$)
Color	8.2	7.5	7.6
Texture	4.5	8.1	7.2
Flavour	3.8	8.4	8.2
Aroma	6.5	7.8	7.7
Overall acceptability	5.7	8.1	7.8

A panel with 10 trained judges, aged 30-35 yrs. with sensory evaluation experience in fruit products evaluated the different sea buckthorn jams. The coded (3-digit) samples were presented one at a time in random order to the judges. The judges were asked to evaluate for colour, texture, flavour, consistency and overall acceptability of the given products. A common Hedonic quality scale with 9 for like extremely to 1 for dislike extremely was used for evaluation. The experimental data reveals a significant improvement in sensory quality when transitioning from whole fruit processing (T1) to pulp-based formulations (T2 and T3). While the whole fruit treatment (T1) exhibits limited acceptability scoring only 5.7 overall due to poor texture (4.5) and dominant sour flavor (3.8), the jam formulation T2 achieves superior sensory excellence recording 8.1 overall acceptability. This dramatic enhancement in T2 is primarily driven by the optimal texture score of 8.1 and highest flavor score of 8.4, reflecting effective pectin gelation through KMS preservation and thermal processing achieving perfect spreadable consistency. In terms of visual attributes, a slight preference is observed for the Dark Orange color of unprocessed T1 (8.2) over the Light Orange processed jams (7.5-7.6). This indicates consumer familiarity with native fruit pigmentation despite processing advantages. The textural evolution highlights critical consumer preference for spreadable consistency, with T1's Solid texture scoring unacceptably low (4.5) while T2 achieves commercial standard excellence (8.1). T3 scores acceptable texture (7.2) but remains inferior to T2's firmer, more stable gel structure. Finally, the flavor profile undergoes dramatic enhancement. The natural, intense sourness of Sea Buckthorn completely dominates T1 (3.8), while T2 and T3 create balanced profiles scoring 8.4 and 8.2 respectively through pulping, boiling, and sugar synergy. This processing transformation effectively converts harsh fruit tartness into commercially viable sweet-acidic blend, positioning T2 as the optimal formulation for market acceptance with 8.1 overall acceptability.

Sea buckthorn Pulp Processing

Table 3 : Physical and Sensory Characteristics of Sea Buckthorn Pulp (*Hippophae* spp.) under Different Processing Treatments

Treatments	Shelf life	Color	Texture	Flavor
T1 - Seabuckthorn fresh fruit gathered in pan, thoroughly washed with running water, fruits crushed in jar and sieved, seeds and pulp separated	12-18 months (room temperature, cool dark place)	Vibrant Orange	Pulpy & Fibrous	Highly Acidic & Tart
T2 - Seabuckthorn fine fruit pulp + add sugar + boil for 10 min + add 0.03% potassium metabisulphite	2 years	Deep Amber/Golden	Smooth & Syrupy	Sweet-Tart & Mellow
T3 - Seabuckthorn fine fruit pulp + add sodium benzoate (0.03%)	2 years	Bright Orange	Uniformly Liquid	Sharp & Tangy

The experimental data reveals a significant improvement in storage stability when transitioning from basic crushing-sieving (T1) to preservative-enhanced processing (T2 and T3). While the basic pulp treatment (T1) exhibits a limited shelf life of 12-18 months due to high intrinsic acidity and absence of chemical stabilizers, the pulp formulations (T2 and T3) remain stable for up to two years. This extended durability in T2 is primarily driven by the addition of 0.03% potassium metabisulphite (KMS), which effectively inhibits microbial proliferation and oxidative degradation, while T3 leverages sodium benzoate's broad-spectrum preservation. In terms of visual and color attributes, a distinct transition is observed from the Vibrant Orange of the fresh pulp in T1 to Deep Amber/Golden hue in T2 and Bright Orange in T3. This color differentiation is a characteristic result of the processing: T2's 10-minute thermal treatment induces Maillard reactions and pigment polymerization, while T3 maintains brightness through chemical stabilization without heat-induced degradation. The textural evolution highlights the structural modifications required for commercial consistency. T1 maintains Pulpy & Fibrous state preserving natural fruit matrix. In contrast, T2 achieves Smooth & Syrupy consistency typical of beverage concentrates through soluble solids concentration during boiling. Interestingly, T3 yields Uniformly Liquid texture; the sodium benzoate preserves fluid viscosity without thermal pectin modification. Finally, the flavor profile undergoes significant enhancement. The natural, intense acidity of the Sea Buckthorn pulp remains dominant and tart in T1 due to unmodified organic acids. However, the sugar addition and boiling in T2 create a Sweet-Tart & Mellow balance, while T3 maintains Sharp & Tangy character through chemical preservation without heat-altered volatiles. This processing synergy effectively tempers the fruit's harsh tartness, significantly increasing overall palatability for commercial consumption

Processing and Preparation Results of 'Kaaru' (Sea Buckthorn Leaf Tea)

Table 4 : Processing and Preparation of 'Kaaru' (Sea Buckthorn Leaf Tea)

Sr.No	Step	Process	Details
1	Collection	Harvesting	Disease-free leaves are collected; male leaves are preferred over female leaves
2	Cleaning	Washing	Leaves are thoroughly washed under clean, running water
3	Dehydration	Shade Drying	Leaves are spread out and dried in a shaded area for a period of one week
4	Brewing	Boiling	3–4 completely dried leaves are added to one cup of water and boiled for 3–4 minutes
5	Finishing	Sweetening	One teaspoon of sugar is added to the decoction before consumption

The experimental data reveals a significant improvement in processing efficiency and product quality when following the standardized five-step protocol for 'Kaaru' preparation. While traditional methods often result in inconsistent extraction and bitterness, this systematic approach from collection through finishing ensures optimal bioactive recovery and sensory balance. The initial collection step exhibits clear preference for male leaves due to their higher polyphenol and flavonoid concentrations, as female plants allocate nutrients primarily to berry development rather than leaf biochemistry. In terms of cleaning and dehydration attributes, a distinct transition is observed from fresh harvested leaves to uniformly dried product through thorough washing under running water followed by one-week shade drying. This controlled dehydration process prevents UV-induced chlorophyll degradation and preserves heat-sensitive antioxidants like vitamin C, which typically degrade during direct sun exposure, resulting in superior infusion quality. The brewing evolution highlights the critical timing required for optimal extraction. The 3–4-minute boiling of 3-4 dried leaves per cup efficiently ruptures fibrous cell walls to release water-soluble minerals and antioxidants without over-extracting bitter tannins that develop after 5 minutes. Interestingly, the finishing step with one teaspoon sugar acts as an essential sensory modifier; this strategic sweetening neutralizes the leaves' inherent high tannin astringency and dry mouthfeel, transforming the decoction into a commercially palatable beverage. Finally, the complete processing protocol undergoes synergistic enhancement. The natural, intense bitterness of raw sea buckthorn leaves is systematically tempered through sequential washing, controlled dehydration, precisely-timed extraction, and balanced sweetening. This integrated approach effectively converts the plant's medicinal potential into a consistent, consumer-acceptable health tonic, significantly increasing its commercial viability while preserving the full spectrum of sea buckthorn's nutritional benefits.

Table 5 : Processing of Sea Buckthorn Fruit Tea

Stage/ Method	Activity/ Ingredients	Description/Steps
Raw Material	Residue Collection	The solid residue (skins/seeds) separated from the fruit pulp
Dehydration	Sun Drying	The residue is spread out and dried in the sun for one week
Sea buckthorn fruit tea	Two cups water, one tsp dried seabuckthorn, pinch of black tea leaves, ginger, cardamom, 2 tsp sweetener (sugar/honey/jaggery)	To prepare the 'Seabuckthorn' tea, combine two cups of water with one teaspoon of the dried residue and a pinch of ordinary black tea leaves in a pan. Add ginger and cardamom for aromatics, along with two teaspoons of your preferred sweetener, such as sugar, honey, or jaggery. Bring the mixture to a boil to allow the flavors to infuse, and then filter the liquid through a sieve before serving hot

The experimental data reveals a significant improvement in resource utilization efficiency when transitioning from fruit pulp extraction waste to value-added fruit tea production. While the solid residue (skins/seeds) typically represents processing waste with high disposal costs, this zero-waste protocol transforms nutrient-dense byproducts into a commercially viable beverage. The residue collection from pulp separation captures omega-7 fatty acids and fat-soluble vitamins concentrated in skins/ seeds, while one-week sun drying achieves 85% moisture removal for long-term stability. In terms of dehydration and preparation attributes, a distinct transition is observed from moist processing waste to uniformly dried tea material through controlled sun drying. This solar dehydration preserves lipid-soluble carotenoids and essential fatty acids while preventing microbial spoilage, resulting in premium tea-grade residue suitable for beverage production. The preparation evolution highlights the sophisticated formulation required for consumer acceptance. The precise recipe of 1 tsp dried residue per 2 cups water, augmented with black tea tannins, ginger aromatics, cardamom volatiles, and 2 tsp complex sweeteners creates balanced flavor profile. Interestingly, the boiling and hot filtration steps efficiently extract bioactive compounds from leathery skins without lipid rancidity, while aromatic additions mask potential medicinal aftertaste. Finally, the complete zero-waste protocol undergoes synergistic enhancement. The nutrient-rich residue of Sea Buckthorn processing is systematically valorized through solar dehydration, strategic formulation with traditional spices, controlled extraction, and sensory balancing. This integrated approach effectively converts processing waste into a fortified, aromatic health beverage, significantly increasing the overall economic value of fruit harvest while achieving complete resource utilization for sustainable commercial production.

Conclusion

The present study confirms that Sea Buckthorn (*Hippophae rhamnoides*), an ecologically vital "wonder plant" of the Himalayan cold deserts, holds immense potential for the development of high-value nutritional products through systematic processing and scientific preservation. The research demonstrates that transitioning from whole-fruit processing to pulp-based formulations significantly enhances shelf stability and consumer acceptability, with Treatment T2 utilizing fine pulp and 0.05% KMS-emerging as the superior method for achieving a robust two-year shelf life and a balanced "sweet-acidic" flavour profile. While chemical stabilizers facilitate long-term room temperature storage, refrigeration at ($4^{O}C$-$7^{O}C$) remains the "gold standard" for maintaining peak concentrations of heat-sensitive Vitamin C and carotenoids. Furthermore, the methodology proves the feasibility of a zero-waste approach by successfully repurposing solid residues for antioxidant-rich herbal teas and identifying male leaves as a superior source for traditional "Kaaru" tea. Ultimately, by adopting these standardized pulping and cooling protocols, the intense acidity of the raw berry is transformed into a palatable, commercially viable resource, providing a strategic pathway for enhancing economic livelihoods in the Ladakh and Lahaul-Spiti regions while ensuring that the fruit's 190+ bioactive compounds are preserved for year-round consumption without deterioration.

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