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Chili oil from Hiyung chili: Oil matrix, extraction time, and sensory acceptance

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Abstract

This study formulated chili oil from Hiyung chili (*Capsicum frutescens* L.) and examined how the carrier oil (palm olein (PO), coconut oil (CO)) and extraction time (24/48/72 h) shape physicochemical quality and sensory acceptance. A factorial Completely Randomized Design was applied; responses included color (L, a, b*, ΔE), acid value (AV), free fatty acids (FFA), peroxide value (PV), and total capsaicinoids/Scoville Heat Units (SHU). From each oil-type, the best formulation (multi-criteria: capsaicinoids, color, oxidative stability) was compared with a commercial chili oil in a 5-point hedonic test. Color remained stable across treatments (ΔE, $p>0.05$). AV and FFA increased with time and were generally higher or rose more steeply in CO than PO, indicating greater hydrolytic susceptibility. PV increased with time, with PO higher than CO but all PV ≤ 20 meq O2/kg (Codex). Capsaicinoids and SHU were significantly higher in palm-olein chili oil (PO-48) than in coconut-oil chili oil (CO-24). In sensory tests, the commercial product outperformed prototypes in aroma, appearance, and color, while the palm olein prototype (PO-48) was spicier and did not differ from the commercial benchmark in overall liking after statistical adjustment. Findings position PO as a robust base for targeted sensory optimization, notably aromatic engineering (controlled allium/spice infusion; gentle roasting 120-150 °C) and visual refinement, to translate pungency advantages into consumer-preferred profiles.

Keywords: Hiyung chili; Chili oil; Palm olein; Coconut oil; Capsaicinoids; Scoville heat units; Peroxide value; Hedonic sensory evaluation.

Highlights

- Hiyung chili oil produced using palm olein or coconut oil at 24-72 h extraction
- Color stability (ΔE) across oils and times; AV/FFA rose with time
- PV increased with time and was higher in palm olein, yet ≤ 20 meq O_2/kg
- Capsaicinoid/SHU levels were higher in palm-olein chili oil than in coconut-oil chili oil
- Sensory: commercial oil led in aroma/appearance/color; palm olein prototype matched overall liking following adjustment
- Palm olein is a promising base for aromatic/visual optimization to lift consumer acceptance

1 Introduction

Chili peppers are one of the most widely consumed spice commodities in Asia and have a significant role in culinary traditions due to their pungency, flavor, and color attributes. The increasing utilization of chili-based products has driven the development of diverse processed chili derivatives, including chili powder, chili paste, hot sauce, and chili oil. Chili oil has gained attention in both household and industrial applications due to its versatility, extended shelf life compared to fresh chili products, and the ability to deliver a stable chili flavor profile in oil-based food systems (Ranilović et al., 2024).

In Indonesia, despite being one of the largest chili producers, the utilization of chili for value-added processing remains limited, as evidenced by continued imports of processed chili products such as chili sauce and chili oil (Pusat Data dan Sistem Informasi Pertanian, 2023). This condition highlights the need to optimize chili processing technologies using locally available chili varieties to reduce import dependency and enhance domestic agro-industrial competitiveness.

Chili oil is commonly produced through oil infusion using fresh or dried chili in a suitable carrier oil, enabling the extraction of bioactive compounds such as capsaicinoids and carotenoids into the oil matrix (Zamljen et al., 2022). Capsaicinoids, particularly capsaicin and dihydrocapsaicin, are responsible for the pungency and characteristic sensory perception of chili oil (Lu et al., 2017). The extraction efficiency of these compounds is influenced by several factors, including raw material type, chili-to-oil ratio, infusion temperature, and carrier oil characteristics (Zhang et al., 2019). The selection of the carrier oil is a critical formulation parameter because it affects pigment solubility, oxidative stability, viscosity, sensory properties, and consumer acceptance (Zamljen et al., 2022). Therefore, optimizing chili oil formulation requires careful consideration of physicochemical and sensory characteristics to obtain a stable and acceptable product.

Palm olein (PO) and coconut oil (CO) are two potential carrier oils widely available in Southeast Asia and particularly in Indonesia. PO is known for its oxidative stability due to its balanced monounsaturated and saturated fatty acid composition, while CO contains medium-chain fatty acids that influence flavor delivery and extraction dynamics of lipophilic compounds (Wroniak et al., 2021). Previous studies have compared various vegetable oils as carriers in oil infusion systems, reporting that the oil type significantly affects capsaicinoid extraction and sensory intensity (Lu et al., 2017). However, there is limited research investigating the influence of PO and CO specifically in chili oil formulations, despite their economic importance and broad use in food processing in tropical regions.

Hiyung chili pepper (*Capsicum frutescens* L.) is a local landrace originating from Hiyung Village, Tapin Regency, South Kalimantan, Indonesia, and has been officially registered as a local genetic resource and released variety (Pramudyani et al., 2019). This local landrace is widely recognized for its exceptionally high pungency and is considered one of the hottest chili peppers in Indonesia and Southeast Asia (Purba et al., 2024). Hiyung chili possesses the highest capsaicin concentration among several commercial *C. frutescens* cultivars, reaching 645.63 ppm in dry land and 699.87 ppm in swampland, with additional reports indicating pungency levels of around 94,500 ppm (Pramudyani et al., 2019; Hardarani et al., 2021). Morphologically, Hiyung chili is characterized by small, slender fruits with short length (2.4-3.1 cm), thin fruit walls (≈0.23 mm), and low individual fruit weight (0.41-0.66 g) (Pramudyani et al., 2019). Moreover, Hiyung chili exhibits superior productivity and broad adaptability across dry land, swampland, and peatland agroecosystems, partly due to its prolonged harvesting period and good growth performance under diverse soil conditions (Pramudyani et al., 2019; Hardarani et al., 2021). These attributes, combined with its distinctive aroma, support the designation of Hiyung chili as a promising raw material for value-added chili products such as chili oil. However, no study has yet specifically investigated chili oil production from Hiyung chili or evaluated its physicochemical and sensory characteristics. This presents a potential opportunity to utilize a high-pungency local chili variety to develop a distinctive chili oil product with strong commercial potential.

Most previous studies on chili oil production have predominantly employed commonly cultivated chili peppers, particularly *Capsicum annuum* and widely available commercial *Capsicum frutescens* cultivars, with limited consideration of chili varietal uniqueness. In contrast, Hiyung chili represents an exceptionally pungent local landrace with distinct morphological, chemical, and agronomic characteristics, which may influence capsaicinoid extraction behaviour, flavour development, and overall oil quality. Previous chili oil studies have mainly focused on antioxidant properties (Mokhtar et al., 2015), volatile compound profiles (Jiang et al., 2025), or the effect of drying methods on capsaicinoid retention (Zamljen et al., 2022). However, limited attention has been given to the physicochemical properties of chili oil produced using local high-pungency chili varieties, particularly in combination with different carrier oils. Moreover, comparative evaluation between laboratory-produced chili oil and commercial chili oil products, especially in terms of sensory acceptance, remains scarce. Therefore, the novelty of the present study lies not only in the comparison of carrier oil matrices, but also in the first exploitation of Hiyung chili as a raw material for chili oil production, highlighting its functional and commercial potential.

Therefore, this study aims to formulate chili oil using dried Hiyung chili pepper with two carrier oils, PO and CO, through a hot infusion process. The physicochemical characteristics, including colour (L*, a*, b*), total capsaicinoids, peroxide value, free fatty acids, and acid value, will be evaluated. Sensory acceptance will also be assessed through a hedonic test and compared with commercial chili oil products available in the market. The findings of this study are expected to provide scientific insight into the development of chili oil using a unique local chili variety and identify a suitable carrier oil to achieve desirable physicochemical quality and consumer acceptability. This study is also anticipated to contribute to the utilization of local agricultural resources and support the development of domestic chili-based food products.

2 Materials and method

2.1 Materials

Dried Hiyung chili peppers were sourced from a farmer cooperative in Tapin, South Kalimantan (Indonesia). Carrier oils were PO and CO (refined, food-grade). Reagents included glacial acetic acid, dichloromethane, potassium iodide (KI), sodium thiosulfate ($Na_2S_2O_3$), potassium iodate (KIO_3), soluble starch, methanol, and tetrahydrofuran (analytical grade). Primary equipment comprised analytical balances, glassware, hot plate with temperature control, rotary evaporator, ultrasonic bath, colorimeter/chroma meter, and High Performance Liquid Chromatography (HPLC) with ultraviolet (UV) detector.

2.2 Preparation of chili powder

Dried Hiyung chili peppers were ground (blade grinder) and sieved to 20-mesh. The powder was stored in airtight, light-protected containers at ambient temperature (< 25 °C) until use.

2.3 Production of chili oil

Chili oil was prepared using a modified method described by Li et al. (2024). For each batch, 200 g of oil was heated to 200 °C and held for 3 min to reduce oil viscosity and enhance mass transfer, then allowed to be cooled to 180 °C prior to chili addition. This temperature range was selected because capsaicinoids exhibit relatively high thermal stability during short-term heating, and efficient extraction into oil has been reported at approximately 150-170 °C, while significant degradation mainly occurs at higher temperatures and prolonged exposure (Bai et al., 2022; Yao et al., 2025). In addition, higher oil temperatures have been shown to promote capsaicinoid dissolution and increase spiciness and flavor intensity in chili oil (Lin et al., 2023). Fifty grams of Hiyung chili powder were gradually added under continuous stirring, and mixing was continued during cooling until the mixture reached < 60 °C. The slurry was then kept under ambient conditions for 24-72 h, after which the supernatant was decanted and filtered. All treatments were prepared in triplicate (n = 3).

2.4 Experimental design

A factorial Completely Randomized Design (CRD) was applied with two factors: carrier oil (PO and CO) and extraction time (24, 48, and 72 hours). This produced six treatment combinations; each prepared in triplicate (18 samples total). All samples were analyzed for physicochemical properties, including color (L*, a*, b*), acid value, free fatty acids, peroxide value, and total capsaicinoids content.

For each carrier oil, formulation selection was performed using a rule-based multi-criteria approach. Initially, formulations were screened against established edible oil quality thresholds for peroxide value, acid value, and free fatty acids (i.e., PV ≤ 10 meq O_2/kg and AV/FFA within acceptable limits for refined and virgin oils), as recommended by international standards such as Codex Alimentarius General Standard for Fats and Oils (AV up to ~4.0 mg KOH/g for cold pressed/virgin oils and PV up to 10-15 meq O_2/kg for refined and unrefined oils) (Food and Agriculture Organization of the United Nations, 1999). These criteria ensured selection of samples with acceptable oxidative and hydrolytic stability.

Formulations meeting these preliminary quality limits were subsequently evaluated based on redness (a*), followed by hierarchical prioritization of lower AV and FFA and then lower PV to balance visual quality and stability. Based on this systematic evaluation, one representative formulation from each carrier oil type was selected for further capsaicinoid quantification, Scoville Heat Unit (SHU) determination, and sensory comparison with a commercial chili oil product.

2.5 Physicochemical analyses

Physicochemical properties of the chili oil samples were evaluated through color measurement (L*, a*, b*), acid value (AV), free fatty acids (FFA), peroxide value (PV), and total capsaicinoid content. Color was determined using a calibrated chroma meter, while AV and FFA were analyzed by titration following American Oil Chemists' Society (AOCS) Cd 3d-63. PV, indicating primary lipid oxidation, was measured iodometrically according to AOCS Cd 8-53. Total capsaicinoids were quantified using HPLC after ultrasonic-assisted extraction with methanol-tetrahydrofuran (1:1 v/v), employing a Zorbax SB-C18 column and UV detection at 280 nm. Capsaicin and dihydrocapsaicin were identified using external calibration standards, and total capsaicinoids were converted to SHU to determine pungency. All analyses were performed in triplicate and reported as mean ± standard deviation (SD). Total capsaicinoid and SHU analyses were performed on the two selected formulations that exhibited the most favorable balance between color quality and oxidative stability based on the multi-criteria screening. Resource limitations prevented full quantification across all treatments.

2.6 Sensory evaluation

A consumer-type hedonic test was conducted using untrained panelists (n = 70) aged 19-25 years. Panelists reported a mean spicy food consumption frequency score of 2.56 on a 3-point scale, indicating that most participants were moderate to frequent consumers of spicy foods.

Three samples were evaluated as follows: (i) the selected palm olein-based chili oil formulation, (ii) the selected coconut oil-based chili oil formulation, and (iii) a commercial chili oil product. Samples were placed in clean containers and labeled with three-digit blinding codes. Approximately 0.5-1 mL of chili oil was applied onto a plain white bread carrier (≈2 × 2 cm, crust removed) for each serving. Samples were presented monadically in randomized order and evaluated at room temperature (≈22-25 °C).

Panelists were instructed to consume the entire carrier portion in one bite and to evaluate taste, spiciness level, color, texture/mouthfeel, aroma, appearance, and overall liking using a 5-point hedonic scale (1 = dislike it very much, 5 = like it very much). A 5-point hedonic scale was selected because it is widely applied in consumer testing with untrained panelists and facilitates reliable preference measurement; nevertheless, its limited discrimination capacity compared with larger scales is acknowledged as a study limitation.

Water and plain bread were provided as palate cleansers, with a minimum interval of 60-90 s between samples to reduce carryover effects. Although milk was made available as a safety option for panelists experiencing excessive pungency, water and bread were used as the primary palate cleansers to minimize residual coating effects that could influence mouthfeel and flavor perception across samples.

Panelists were informed in advance about the spicy nature of the samples and participated voluntarily with verbal informed consent. No institutional ethical approval was required for this non-invasive consumer sensory evaluation of food products.

2.7 Statistical analysis

For physicochemical data, a two-way Analysis of Variance (ANOVA) (factors: oil type and extraction time) was applied under a Climate Resilient Development (CRD) framework. When significant main or interaction effects were detected ($p < 0.05$), Duncan's multiple range test was used for pairwise comparisons. Sensory hedonic scores (three products: best PO, best CO, commercial) were analyzed by one-way ANOVA followed by Duncan at $\alpha = 0.05$. All results are presented as mean ± SD of triplicate measurements (physicochemical) or group means (sensory).

3 Results and discussion

3.1 Color characteristics (L*, a*, b*, ΔE)

Color is one of the most important quality indicators in chili oil as it strongly affects consumer perception and product acceptance. The red-orange hue in chili oil originates from carotenoid pigments, primarily capsanthin and capsorubin, which are highly lipophilic and dissolve into the oil phase during extraction (Bai et al., 2022; Ridzuan et al., 2018). The color attributes of chili oil samples produced using two different carrier oils, CO and PO, at different maceration times are presented in Table 1.

Table 1. Effect of carrier oil and maceration time on chili oil color parameters.

Samples	L*	a*	b*	ΔE
CO-24	24.38 ± 0.13[a]	3.41 ± 0.11[a]	11.60 ± 0.16[a]	27.21 ± 0.20[a]
CO-48	24.46 ± 0.10[a]	3.01 ± 0.16[a]	10.68 ± 0.95[a]	26.87 ± 0.49[a]
CO-72	24.92 ± 0.18[a]	2.65 ± 1.05[a]	10.72 ± 0.56[a]	27.27 ± 0.16[a]
PO-24	24.18 ± 1.31[a]	3.92 ± 2.10[a]	10.68 ± 0.35[a]	26.77 ± 1.01[a]
PO-48	24.65 ± 0.10[a]	3.27 ± 1.36[a]	11.00 ± 0.33[a]	27.21 ± 0.06[a]
PO-72	24.43 ± 0.41[a]	3.00 ± 0.44[a]	11.18 ± 0.06[a]	27.03 ± 0.38[a]

Note: CO = Coconut oil; PO = Palm olein. Different lowercase letters in the same column indicate significant difference ($p < 0.05$).

Based on two-way ANOVA, neither the type of carrier oil nor maceration time had a significant effect on ΔE values ($p > 0.05$), indicating that all chili oil samples exhibited similar levels of chromatic intensity regardless of treatment. The stable ΔE values suggest that carotenoid pigments were effectively extracted and remained stable over 24-72 hours of maceration. Similar findings were reported by Caporaso et al. (2013), who found that pigment transfer from chili powder to oil is stable in non-polar lipid matrices as long as temperature does not exceed the carotenoid degradation threshold (≥ 120 °C).

PO and CO produced comparable color intensities, demonstrating that both oils possess similar pigment solubilizing capacities. Although CO is known to have higher saturated fatty acid content, which may influence viscosity and mass transfer, the results indicate that such differences did not affect visual color parameters significantly. The absence of significant discoloration implies that both oils can be used as suitable carriers in chili oil formulation without negatively impacting appearance.

Overall, color remained stable across formulations, suggesting that maceration up to 72 hours did not accelerate pigment oxidation or degradation. However, further evaluation involving color stability during storage would be beneficial to determine long-term pigment retention.

3.2 Acid value (AV)

Acid value (AV) is an important indicator of oil quality, reflecting the extent of triglyceride hydrolysis into free fatty acids (FFA) that occurs during processing and extraction. An increase in AV is commonly associated with lipolytic degradation, poor handling, or prolonged exposure to moisture or heat (Yun et al., 2023). Table 2 shows that acid value varied across treatments, influenced by both the type of carrier oil and maceration duration.

Consistent with previous findings by Mastuti et al. (2019), CO exhibited higher acid values than PO across all extraction times. This behavior is likely attributed to the higher medium-chain fatty acid content in CO, especially lauric acid, which is more susceptible to hydrolytic cleavage (Boateng et al., 2016). In contrast, PO contains predominantly palmitic and oleic acids, which are more resistant to hydrolysis and therefore contribute to better oxidative and hydrolytic stability.

Two-way ANOVA revealed that both oil type and maceration time had a significant effect on AV ($p < 0.05$), and their interaction was also significant, indicating that the pattern of AV increase over time differed between oils. A progressive increase in AV was observed as maceration time increased from 24 to 72 hours, demonstrating that longer exposure to chili powder promotes the release of moisture and enzymes, accelerating hydrolysis. However, moisture content and residual enzymatic activity of the chili powder were not directly measured in this study; therefore, their contribution to AV increase is proposed as a plausible but speculative explanation. Similar trends were also reported by Hutapea et al. (2021), who noted that extended extraction processes may induce partial breakdown of oil structure, especially in unrefined or natural oils.

Overall, PO demonstrated superior hydrolytic stability compared to CO, making it a more suitable carrier for chili oil production where chemical stability and storage quality are critical. However, controlling extraction duration remains important, as prolonged maceration (> 48 hours) increases the acid value and may negatively impact product safety and organoleptic quality due to rancid off-flavors. Therefore, a maceration period not exceeding 48 hours may be recommended for maintaining acceptable AV levels in chili oil formulations.

3.3 Free fatty acids (FFA)

FFA is a critical indicator of hydrolytic degradation in edible oils and is directly related to perceived rancidity and shorter shelf life (Cocan et al., 2021). The mean ± SD values of FFA for each treatment are presented in Table 2. Table 2 shows that oil type, extraction time, and their interaction significantly affected FFA levels, with CO exhibiting a steeper increase than PO as maceration progressed ($p < 0.05$ for all main and interaction effects). These are consistent with the literature indicating that lauric-rich matrices are more susceptible to lipolysis, while palm olein tends to be more hydrolytically stable due to its fatty acid profile and minor components (Boateng et al., 2016; Cocan et al., 2021). Together, the results indicate that prolonging maceration from 24 to 72 hours accelerates triglyceride hydrolysis, especially in CO, emphasizing the need to optimize extraction time to limit FFA accumulation. Nevertheless, moisture content and residual enzymatic activity of the chili powder were not quantified in this study; thus, their proposed contribution to FFA formation should be interpreted as a plausible but speculative mechanism. For manufacturing implications, PO appears preferable where chemical stability is prioritized, while extraction times longer than 48 h should be avoided to minimize off-flavor risks.

Table 2. Effect of carrier oil and maceration time on acid value (AV) and free fatty acid (FFA) of Hiyung Chili Oil.

Samples	Acid value (mg KOH/g)	FFA (%)
CO-24	5.00 ± 0.20[a]	2.50 ± 0.10[a]
CO-48	8.33 ± 0.61[c]	4.17 ± 0.31[c]
CO-72	9.40 ± 0.20[d]	4.70 ± 0.10[d]
PO-24	6.00 ± 0.20[b]	3.84 ± 0.13[b]
PO-48	6.13 ± 0.42[b]	3.92 ± 0.27[b]
PO-72	6.80 ± 0.20[b]	4.35 ± 0.13[b]

Note: CO = Coconut oil; PO = Palm olein. Different lowercase letters in the same column indicate significant difference ($p < 0.05$).

3.4 Peroxide value (PV)

Peroxide value (PV) is a key indicator of primary lipid oxidation and reflects the degree to which hydroperoxides have formed as a result of oxidative reactions in oils. A high PV signifies oxidative deterioration, leading to rancidity and degradation of product quality (Teh et al., 2023). In this study, PV was influenced by both base oil type and extraction duration which reported significant main effects and interaction effects ($p < 0.05$) (see Table 3).

Table 3. Peroxide value (PV) of Hiyung chili oil with different carrier oils and maceration times.

Samples	Peroxide value (meq O_2/kg)
CO-24	0.00 ± 0.00^a
CO-48	9.10 ± 0.11^b
CO-72	8.33 ± 0.92^b
PO-24	0.00 ± 0.00^a
PO-48	18.02 ± 0.00^c
PO-72	19.22 ± 2.08^c

Note: CO = Coconut oil; PO = Palm olein. Different lowercase letters in the same column indicate significant difference ($p < 0.05$).

Based on Table 3, PV increased with extraction time in both oil types. However, PO showed a consistently higher PV compared to CO at all extraction durations. For instance, at 48 h, PV in PO reached 18.02 ± 0.00 meq O_2/kg, nearly a double value compared to CO (9.10 ± 0.10 meq O_2/kg). A similar pattern persisted at 72 h, indicating a sustained oxidative progression in PO-based chili oil. These results suggest that CO possesses superior oxidative stability compared to PO under prolonged maceration. This behavior is attributed to the higher saturated fatty acid content of CO, which is naturally more resistant to oxidation than unsaturated fatty acid-rich PO (Boateng et al., 2016; Choe & Min, 2006).

Although PO is commonly regarded as oxidatively stable in its neat form, this stability mainly applies to conventional thermal processing. In chili oil infusion systems, oxidation is additionally influenced by interactions with chili-derived pigments, trace metals, and residual moisture. Oils rich in unsaturated fatty acids are generally more susceptible to autoxidation and faster hydroperoxide formation than oils with higher saturated fatty acid content, because double bonds are more reactive toward free radical attack (Maszewska et al., 2018; Loganathan et al., 2022). In contrast, CO, dominated by saturated medium-chain fatty acids, exhibits greater resistance to oxidation. Therefore, the higher PV observed in palm olein-based chili oil reflects differences in oxidative behavior under infusion conditions rather than a contradiction in baseline oil stability.

Post-hoc analysis further indicated that oxidation increased sharply between 24 h and 48 h, followed by a plateau between 48 h and 72 h, implying that the oxidation rate is highest in the early extraction phase and slows as hydroperoxide formation approaches equilibrium. Similar oxidation kinetics have been reported in oil-infusion and lipid oxidation systems, where peroxide formation may slow or plateau over time as radical-mediated oxidation reactions progress toward a steady state (Odeh et al., 2021; Hoppenreijs et al., 2021).

Notably, despite the increase in PV values, all samples remained below the Codex Alimentarius limit of 20 meq O_2/kg for edible oils, indicating that the chili oil produced in this study remains oxidatively acceptable for consumption (Food and Agriculture Organization of the United Nations, 1999). However, palm olein-based chili oil exhibited values close to the critical limit at 72 hours, suggesting that extended maceration beyond 48 hours is not recommended for oxidative stability.

The incorporation of natural antioxidants, such as tocopherols, has been shown to enhance oxidative stability by interrupting free radical chain reactions and reducing the formation of primary oxidation products. In PO, α-tocopherol supplementation significantly lowered lipid oxidation indicators under thermal stress, indicating its potential to mitigate peroxide formation in chili oil systems and warranting investigation in future studies (How et al., 2024).

3.5 Capsaicinoid retention and pungency (SHU)

Prior to capsaicinoid quantification and SHU determination, formulations for each carrier oils were selected using a rule-based multi-criteria approach. Samples were initially screened based on acceptable limits of peroxide value, acid value, and FFA, then further evaluated by redness (a*) and hierarchically prioritized for lower AV/FFA followed by lower PV. Based on this systematic screening, one representative formulation from each oil type was selected for detailed capsaicinoid and SHU analysis prior to sensory evaluation.

Capsaicinoids are the main bioactive compounds responsible for pungency in chili-based products, and their retention during processing is essential for both sensory impact and product differentiation in spicy condiments. In this study, capsaicinoid quantification was carried out only on two representative formulations (CO-24 and PO-48), which were selected a priori based on their superior physicochemical performance during screening (including color extraction behavior, AV/FFA stability, and peroxide formation). These two treatments demonstrated the most favorable extraction characteristics within their respective oil matrices and therefore were considered the most appropriate candidates for detailed capsaicinoid and SHU analysis prior to sensory evaluation.

The total capsaicinoid content and SHU values differed significantly between the two selected formulations, confirming that the extraction efficiency of pungent compounds is influenced by the choice of carrier oil. Statistical analysis using an independent t-test showed that both total capsaicinoid concentration and SHU were significantly higher ($p < 0.05$) in PO-48 compared to CO-24 (see Table 4).

Table 4. Total capsaicinoid content and Scoville Heat Units (SHU) of selected Hiyung chili oil samples.

Samples	Total capsaicinoids (g/kg)	SHU
CO-24	1.00 ± 0.23	18,819 ± 426
PO-48	1.321 ±0.04	24,860 ± 80

Note: CO = Coconut oil; PO = Palm olein.

These findings demonstrate that PO is more effective than CO in extracting and retaining capsaicinoids, likely due to its higher oleic acid content, which promotes better solubilization of lipophilic alkaloids such as capsaicin and dihydrocapsaicin (Lu et al., 2017). In contrast, CO contains a predominance of medium-chain triglycerides (MCTs), particularly lauric acid, which may have reduced capacity to dissolve and transport capsaicinoids due to lower hydrophobic interactions. This supports the hypothesis that oil polarity and fatty acid composition directly influence capsaicinoid partitioning during infusion-based extraction (Zamljen et al., 2022).

Importantly, this study provides the first scientific evidence that Hiyung chili pepper (*C. frutescens*) can be effectively converted into a high-pungency chili oil, achieving SHU values above 20,000 using PO. This is a notable finding because, although Hiyung chili is known locally in Indonesia for extreme pungency, its extraction behavior and capsaicinoid transfer efficiency into edible oil systems have not been previously reported in the literature. Compared to conventional chili varieties used in commercial chili oils (e.g., *C. annuum*), the SHU levels obtained from Hiyung chili in this study are significantly higher, indicating its potential as a premium raw material for high-intensity chili oil formulations.

This result not only advances the scientific understanding of solvent-assisted capsaicinoid extraction but also carries strong industrial relevance, especially for the development of locally sourced, high-value chili oil products that can compete with imported brands. In summary, PO demonstrated superior performance as a carrier-oil for pungency extraction, and Hiyung chili proved to be a strategic local commodity for developing high-intensity chili-based products with strong market potential.

3.6 Sensory evaluation

Prior to capsaicinoid quantification and SHU determination, formulations were selected using a rule-based multi-criteria screening of physicochemical quality. For each carrier oils, formulations were first screened based on acceptable limits of peroxide value, acid value, free fatty acids, and color attributes. Among formulations meeting these limits, hierarchical prioritization was applied, giving primary emphasis to the lowest AV and FFA, followed by consideration of peroxide value and redness (a*). Based on this evaluation, capsaicinoid quantification was conducted only on two representative formulations that exhibited the most favorable overall physicochemical profiles and were therefore considered appropriate candidates for detailed capsaicinoid and SHU analysis prior to sensory evaluation.

Hedonic testing (using a 5-point scale) revealed significant differences in overall liking, aroma, appearance, color, and spiciness (Friedman test, $p < 0.05$), while taste and texture showed no differences, when the developed chili oils were compared against a commercial chili oil used as a benchmark product. The commercial benchmark received the highest scores for aroma, appearance, and color ($p < 0.05$). In contrast, the palm-olein chili oil (PO-48) was significantly spicier ($p < 0.05$) but did not differ from the commercial benchmark in overall liking after applying the Bonferroni adjustment (see Table 5). This indicates that consumer preferences are primarily influenced by aromatic complexity and visual appeal rather than baseline taste or mouthfeel.

Table 5. Hedonic scores (mean ± SD) for three chili oil products on a 5-point scale.

Attributes	Commercial product	CO-24	PO-48
Aroma	4.54 ± 0.73^{a}	3.10 ± 0.81^{b}	3.00 ± 0.90^{b}
Appearance	4.30 ± 0.89^{a}	3.40 ± 0.73^{c}	3.62 ± 0.78^{b}
Color	4.12 ± 0.98^{a}	3.04 ± 0.86^{c}	3.44 ± 0.88^{b}
Spiciness	3.10 ± 1.05^{b}	3.38 ± 1.03^{ab}	3.74 ± 0.99^{a}
Overall liking	4.10 ± 0.91^{a}	3.26 ± 0.85^{b}	3.68 ± 0.82^{a}

Note: CO = Coconut oil; PO = Palm olein. Different superscript letters within a row denote significant differences (Friedman test with Bonferroni-adjusted pairwise comparisons, $p < 0.05$). Panel size and serving details as described in Section 2.6.

It is important to note that the commercial product represents a multi-component seasoning oil rather than a simple chili-oil system. The sensory advantage of the commercial benchmark is consistent with its multi-ingredient formulation (MIF) that supplies both complex aroma volatiles and umami enhancers, in contrast to our base prototypes that contained only carrier oil and dried chili. Ingredients such as dried garlic and sesame oil generate abundant Maillard-derived volatiles, notably pyrazines, furans, and sulfur compounds, when heated or pre-roasted, which are well-known drivers of roasted, nutty, and savory notes in chili-oil systems and sesame-based oils (e.g., 2,5-dimethylpyrazine, 2-ethyl-5-methylpyrazine, diallyl disulfide (DADS)) (Sun et al., 2019). In parallel, soy sauce contributes concentrated umami (glutamate, peptides) and characteristic fermented-caramel nuances that enhance palatability and overall flavor integration, as extensively reviewed for its chemistry and sensory functions (Diez-Simon et al., 2020). Critically, the commercial label also lists disodium inosinate (E631) and disodium guanylate (E627), which exhibit synergy with glutamate to amplify umami intensity and length (temporal persistence), a well-established mechanism in human taste physiology and product reformulation (Kurihara & Kashiwayanagi, 2000). Taken together, this aroma-umami stacking, roasted allium/sesame volatiles plus nucleotide-glutamate synergy, provides a coherent explanation for higher liking in aroma, appearance/color (via darker, roasted visual cues and particulate optics), and overall acceptance observed for the commercial benchmark, whereas our chili oil prototypes lacked these orthogonal sensory levers.

Therefore, the present comparison should be interpreted as a benchmark-oriented assessment rather than a direct formulation equivalence. The observed differences primarily reflect disparities in formulation complexity rather than limitations of the oil matrix itself. Palm-olein chili oil (PO-48) already demonstrated superior capsaicinoid retention and competitive overall liking, and thus represents a solid platform for subsequent aromatic engineering (controlled allium/spice infusion; mild roasting ~120-150 °C) and umami balancing (soy-sauce solids/peptides or low-dose glutamate with 5′-nucleotides), with visual refinement (particle size/clarity) to translate pungency advantages into consumer-preferred profiles (Li et al., 2025). From an industrial perspective, the favorable pungency performance of Hiyung chili supports its potential for scale-up; however, challenges related to consistent raw material supply, variability in pungency, and standardization of drying and milling operations should be addressed to ensure reproducible product quality.

This study has several limitations. Capsaicinoid quantification was conducted only on representative formulations selected through physicochemical screening due to analytical resource constraints. In addition, the commercial chili oil differs substantially in formulation complexity (multi-ingredient seasoning oil) from the simple chili-oil prototypes developed in this study. Therefore, the comparison with the commercial product should be interpreted strictly as a benchmark reference rather than a formulation-equivalent comparison.

4 Conclusion

This work demonstrated that carrier oil and extraction time could jointly determine the physicochemical and sensory performance of Hiyung chili oil. Color was robust to processing (ΔE stable), whereas AV/FFA rose with prolonged extraction, and PV increased but remained within Codex limits. Palm-olein matrices yielded higher capsaicinoid/SHU than CO, making them preferable when pungency is a product objective. In hedonic tests, the commercial benchmark surpassed prototypes in aroma, appearance, and color, yet the palm-olein prototype achieved comparable overall liking after adjustment—indicating that pungency advantages can translate to acceptance when accompanied by aromatic complexity and visual appeal. Practically, extraction should be constrained to ≤48 h to limit acidity/oxidation, and targeted sensory optimization should focus on aromatic engineering (controlled allium/spice infusion, mild roasting 120-150 °C) and visual refinement (particle size/clarity). These outcomes establish PO as a technically sound platform for high-pungency chili oils from an indigenous Indonesian variety and provide a pathway to reduce reliance on imported chili-oil products through value-added local processing.

Data Availability Statement

The data supporting this study are not publicly available due to confidentiality agreements, but can be requested from the corresponding author upon reasonable request.

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