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Design and Evaluation of a SNEDDS-Based System for Ethanol Extract from *Temu Ireng* (Curcuma aeruginosa Roxb.): Enhancing Antioxidant Efficacy Using the SLD Technique

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ABSTRACT

Temu Ireng (Curcuma aeruginosa Roxb.) is known for its strong antioxidant properties, primarily due to its bioactive compounds such as curcumin. However, these chemicals' lipophilia and instability in traditional formulations frequently limit their bioavailability. To address these challenges, a Self-Nanoemulsifying Drug Delivery System (SNEDDS) was developed using the Simple Lattice Design (SLD) method to improve the chemical and physical properties of *Temu Ireng* extract by forming a stable nanoemulsion that is uniformly distributed in the digestive system. This study aimed to formulate and evaluate a SNEDDS of *Temu Ireng* extract using the SLD approach, with a focus on enhancing its antioxidant activity. The formulation involved selecting suitable oils, surfactants, and cosurfactants, followed by optimization based on solubility studies, phase diagrams, and thermodynamic stability tests. The SNEDDS was characterized for physical properties such as emulsification time, transmittance, particle size, zeta potential, and polydispersity index. The optimized SNEDDS formulation exhibited excellent characteristics, including an emulsification time of less than 1 minute, near 100% transmittance, a particle size of 9.77 ± 1.33 nm, zeta potential of 0.9 ± 0.1 mV, and a polydispersity index of 0.302 ± 0.033. Antioxidant testing using the DPPH method showed that the 0.1% SNEDDS formulation of *Temu Ireng* extract had an inhibition concentration (IC50) value of 58.482 mg/L, indicating strong antioxidant activity. The results suggest that the SNEDDS formulation using the SLD method could be an effective strategy to enhance the bioavailability and therapeutic efficacy of *Temu Ireng* extract as an antioxidant agent.

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1. Introduction

Curcumin, a key bioactive component of Curcuma species including Curcuma aeruginosa Roxb. (*Temu Ireng*), is well known for its strong anti-inflammatory, antioxidant, and medicinal qualities (Burapan et al., 2020). *Temu Ireng* has long been utilized in Indonesian traditional medicine for a number of health advantages, including as aiding in digestion, lowering inflammation, and fending off oxidative stress (Anggriani et al., 2019). However, curcumin's limited bioavailability still poses a substantial obstacle to its clinical implementation, despite its wide range of therapeutic uses and potential. Its limited aqueous solubility, quick metabolism, and instability in physiological settings are the causes of this limitation (Liu et al., 2016). Curcumin's hydrophobic nature restricts its dissolution and absorption in the gastrointestinal tract, reducing therapeutic efficacy (Shome et al.,

2016). Consequently, creative formulation solutions are essential to safeguard curcumin from degradation, augment its stability, and raise its bioavailability, thereby increasing its efficacy for medical applications both in Indonesia and worldwide.

One such approach is the Simple Lattice Design (SLD) method, which is optimizes formulations by systematically exploring different combinations of components in drug delivery systems, particularly for hydrophobic compounds like curcumin (Suhesti et al., 2016). The SLD approach facilitates the determination of ideal excipient ratios to improve the solubility and stability of curcumin by converting it into a more soluble and bioavailable form (Pratiwi et al., 2024). Additionally, the Self-Nanoemulsifying Drug Delivery System (SNEDDS) provides a sophisticated formulation method to enhance bioavailability (Sudibyo et al., 2020). SNEDDS is prepared by mixing oils, surfactants, and co-surfactants, which spontaneously form a nanoemulsion when exposed to aqueous environments, such as gastrointestinal fluids (Sudibyo et al., 2020). The SLD technique systematically examines and optimizes the ratios of surfactant, co-surfactant, and oil to identify the most effective combination for solubilizing curcumin. The formulation is optimized based on factors such as emulsification time, transmittance, particle size, and thermodynamic stability (Annisa et al., 2021). By utilizing the Simple Lattice Design in combination with SNEDDS, the solubility and bioavailability barriers of curcumin are effectively overcome, ensuring that it remains in its bioactive form, with enhanced dissolution and absorption in the digestive system. This method provides a robust strategy for maximizing the therapeutic potential of poorly soluble compounds like curcumin.

The SNEDDS is an advanced drug delivery system that has proven effective in addressing the bioavailability issues of poorly soluble drugs. SNEDDS formulations consist of oils, surfactants, and cosurfactants that form a nanoemulsion upon contact with aqueous gastrointestinal fluids, creating a stable and uniform drug dispersion (Balakumar et al., 2013). This nanoemulsion enhances the solubility and absorption of lipophilic compounds like curcumin by facilitating better drug transport across biological membranes (Debnath et al., 2011). Furthermore, SNEDDS guards against deterioration, enhancing curcumin's stability and bioavailability (Kanwal et al., 2021). In summary, the bioavailability of curcumin is limited by its instability and poor solubility, but the SLD method offers a promising approach to enhance its solubility. When combined with SNEDDS, curcumin can be effectively formulated into a stable, nano-sized emulsion that enhances absorption and therapeutic efficacy. This study focuses on developing a SNEDDS formulation using the SLD method to improve the stability, bioavailability, and antioxidant activity of *Temu Ireng* extract.

2. Materials and Methods

2.1. Material

One of the main tools utilized in this study was an analytical scale (Ohaus). Shimadzu UV/vis spectrophotometer (UV-1280), Particle Size Analyzer (Horiba SZ-100), rotary evaporator (Heidolph L borota 400), water bath (HH-6), and a pH meter. Essential materials, purchased from Brataco, included Virgin Coconut Oil (VCO), Tween 80, propylene glycol, Croduret® 50 SS, and 96% ethanol Merck provided the buffer solutions and the 2,2-diphenyl-1-picrylhydrazyl (DDPH) reagent. The *Temu Ireng* rhizomes for extraction were sourced from Lumeneng village, Paninggaran District, Pekalongan Regency.

2.1. Method of Extraction

2.2.1. Method of Extraction

The maceration method was used to carry out the extraction operation. A total of 1000 grams of *Temu Ireng* simplicia powder was macerated in 5 L of 96% ethanol for five days, stirring at least twice daily. After the initial extraction, the residue was re-macerated using an additional 3 liters of 96% ethanol. The combined extracts were then concentrated by evaporating the solvent at 40°C and 30 rpm using a rotary evaporator (Mugiyanto et al., 2018).

2.2.2. Characterization of *Temu Ireng* Extract

The characterization of *Temu Ireng* extract was performed through organoleptic evaluation, moisture content analysis, and total ash content determination. Organoleptic parameters were assessed using sensory evaluation to describe the physical appearance, color, smell, and taste of the extract. A moisture analyzer was used to measure the moisture content, giving an accurate reading of the

sample's water content (Najihah et al., 2018). Together with these descriptions, phytochemical screening was done to find secondary metabolites like phenols, alkaloids, flavonoids, tannins, and saponins. Alkaloids were screened using Mayer's and Dragedorff's reagents, while flavonoids, tannins, saponins, and phenols were tested using established procedures adopted from previous research (Fajriyah et al., 2024).

2.3. Determination of Total Phenolic Content

Ten milligrams of gallic acid were dissolved in ten milliliters of methanol to create a stock solution of gallic acid with a concentration of 1000 µg/mL. A test tube was filled with 0.1 mL of the 1000 µg/mL gallic acid solution, 0.5 mL of Folin-Ciocalteu reagent, 1.5 mL of 10% Na_2CO_3, and 7.9 mL of distilled water in order to calculate the operating time. The operating time was established by measuring the solution's absorbance every minute over a wavelength range of 600–800 nm to find the point at which the absorbance stabilized. After that, 0.1 mL of the stock solution, 0.5 mL of Folin-Ciocalteu, 1.5 mL of 10% Na_2CO_3, and 7.9 mL of distilled water were added. The mixture was then incubated for the specified operating time, and the absorbance was measured over a wavelength range of 400–800 nm. This allowed for the determination of the maximum wavelength for gallic acid (Mugiyanto et al., 2018).

Gallic acid standard values of 10, 50, 100, 250, and 500 µg/mL were used to create a calibration curve. 0.1 mL of the solution, 0.5 mL of Folin-Ciocalteu, 1.5 mL of 10% Na_2CO_3, and 7.9 mL of distilled water were combined for each concentration, and the mixture was then incubated for the operating period. Plotting the absorbance versus concentration produced a calibration curve, which in turn produced a linear equation (y = ax + b). The absorbance was measured at the identified maximum wavelength. One gram of the sample was dissolved in ten milliliters of methanol, and 0.1 milliliters of this solution were combined with 0.5 milliliters of Folin-Ciocalteu, 1.5 milliliters of 10% Na_2CO_3, and 7.9 milliliters of distilled water in order to calculate the total phenolic content. Following the operational period of incubation, the absorbance at the highest wave length was measured, and the formula was used to determine the total phenolic content:

$$F = \frac{(c\ x\ V\ x\ fp)}{g}$$

Fig. 1. Formula Extract's total Volume

Where V is the extract's total volume, f is the dilution factor, m is the sample weight (g), c is the gallic acid equivalent (µg/mL), and F is the overall phenolic content (mg GAE/gram extract) (Qulub et al., 2019).

2.4. Total Flavonoid Content Determination

First, to determine the total flavonoid concentration, the maximum wavelength for quercetin was determined. Ten milligrams of quercetin were dissolved in ten milliliters of methanol to produce a 1000 µg/mL concentration, which was further diluted to 500 µg/mL. 30 minutes were spent incubating a 0.5 mL aliquot of the 500 µg/mL quercetin solution, 0.1 mL of 10% $AlCl_3$, and 0.1 mL of 1M sodium acetate (CH_3COONa). To determine the maximum absorbance wavelength for quercetin, the absorbance was measured over a 400–800 nm wavelength range. Then, using a 1000 µg/mL stock solution, serial dilutions of 25, 50, 70, and 100 µg/mL were made to create a standard curve for quercetin. After mixing 0.5 mL of each standard with 1.5 mL of methanol, 2.8 mL of distilled water, 0.1 mL of 10% $AlCl_3$, and 0.1 mL of 1M sodium acetate, the mixture was incubated for 30 minutes. Each solution's absorbance was measured at its maximum wavelength, and the absorbance (Y-axis) was plotted against the concentration (X-axis) to create a calibration curve.

200 mg of the extract was dissolved in 10 mL of methanol in order to determine the total flavonoid content. The absorbance was measured at the predetermined wavelength after a 0.5 mL aliquot was combined with 1.5 mL methanol, 2.8 mL distilled water, 0.1 mL of 10% $AlCl_3$, and 0.1 mL of 1M sodium acetate. The mixture was then incubated for 30 minutes. The formula was used to determine the total flavonoid content:

$$F = \frac{c\ x\ (V\ x\ f\ x\ 10\hat{}(-6))}{m}\ x\ 100\%$$

Fig. 2. Quercetin Equivalent

Where c is the quercetin equivalent (µg/mL), V is the total extract volume, f is the dilution factor, m is the sample weight (g), and F is the overall flavonoid concentration (mg QE/gram of extract) (Ratu & Mugiyanto, 2018).

2.5. Formulation Optimization

The formulation optimization was conducted using the SLD approach with the aid of Design Expert 13 version 13.0.5.0 64-bit. This technique was used to identify the best excipient combination to improve the formulation's solubility and stability. A total of seventeen formulations, or "runs," were generated based on the SLD model. Propylene glycol, Tween 80, and virgin coconut oil (VCO) were the three independent variables in this study. They were chosen because they may enhance the final product's solubilization and emulsification qualities (Chahyani & Zai, 2024).

2.6. Transmission Test and Emulsification Time Test

To conduct the transmission test, 100 µL of the SNEDDS formulation was dissolved in 5 mL of aquadest (distilled water) in a test tube. This was followed by vortexing the mixture for one minute to ensure uniform dispersion. This test helps to assess the transparency and clarity of the resulting nanoemulsion, which is a critical parameter in evaluating the stability and solubility of the SNEDDS formulation (Garg et al., 2023).

One milliliter of SNEDDS was diluted with 250 milliliters of aquadest to conduct the emulsification time test. On a hotplate, the mixture was agitated at a regulated temperature of 37ºC and 120 rpm. This test determines how quickly the SNEDDS forms a stable emulsion upon dilution, essential for ensuring efficient drug delivery upon oral administration (Silva et al., 2022).

2.7. Characterization of SNEDDS

A Particle Size Analyzer (PSA) was used to characterize SNEDDS in order to ascertain the zeta potential and size distribution of the nanoemulsion droplets. Two drops of the SNEDDS sample were combined with five milliliters of distilled water to conduct this test. Three milliliters of the diluted solution were taken out and put in a cuvette for analysis after it had been thoroughly mixed. Since they have a direct impact on the formulation's bioavailability and drug release profile, the droplet size and zeta potential are essential markers of the SNEDDS' stability and effectiveness (Zuhro, 2019).

2.8. Antioxidant Activity Test Using DPPH Method

By employing the DPPH (2,2-diphenyl-1-picrylhydrazyl) radical scavenging technique, the antioxidant's extract activity was assessed. To avoid light degradation, 3.94 mg of DPPH was first dissolved in 100 mL of methanol to create a 0.1 mM DPPH solution, which was then kept in a dark container. Methanol was used to make extracts at different concentrations (10, 25, 50, 100, 250, and 500 µg/mL). 1 mL of the extract solution and 2 mL of the DPPH solution were combined for each concentration, and the mixture was then allowed to sit at room temperature for 30 minutes in the dark. Additionally, a blank (extract and methanol without DPPH) and a control (methanol and DPPH solution) were made. A UV-Vis spectrophotometer was used to detect the absorbance at 517 nm following incubation.

The proportion of DPPH radical scavenging activity was calculated using the formula to measure the antioxidant capacity $A = \frac{A\ control - A\ sample}{A\ control}\ x\ 100$, where *A*control is the absorbance of the control and *A*sample is the absorbance of the extract solution. For every sample, the test was run three times. A plot of scavenging activity against extract concentration was used to get the IC50 value, which is the concentration needed to scavenge 50% of DPPH radicals. This technique efficiently assesses the extract's capacity to scavenge free radicals, demonstrating its promise as an antioxidant (Yulyana, 2024).

3. Results and Discussion

3.1. *Temu Ireng* Extract

The *Temu Ireng* rhizome extract was evaluated through organoleptic and physicochemical analyses. Organoleptic evaluation revealed that the extract was dark brown, had a characteristic typical smell, a bitter taste, and a thick consistency. These sensory attributes are consistent with the general expectations for *Temu Ireng* extracts, supporting the integrity and quality of the simplicia. Further, the moisture content of the simplicia was 0.25%, significantly lower than the acceptable standard of ≤10%

set for herbal materials (Sudibyo et al., 2020). This low moisture content suggests that the drying process was effective, reducing the risk of microbial contamination and extending the shelf-life of the extract (Suhesti et al., 2016). The drying shrinkage was measured at 83.96%, which reflects the substantial water content removed from the fresh rhizome during the drying process. Although no specific standard is available for drying shrinkage, the result indicated efficient drying.

The total ash content was 7.36%, within the permissible range of 5-10% for herbal simplicia (Wijayanti et al., 2018). Ash content provides insight into the inorganic material after combustion, with higher values indicating possible contamination or impurities (Yulyana, 2024). In this case, the value suggests that the simplicia adhered to the expected purity standards. Lastly, the extraction yield was 22.6%, a relatively high value, demonstrating an efficient extraction process compared to typical yields for medicinal plants, which often range from 10-20%. The higher yield enhances the potential for bioactive compound recovery, making this extract a promising candidate for further pharmacological studies.

3.2. Phytochemical Content.

The results of the phytochemical screening are presented in Table 1, showing the presence of various secondary metabolites in both the simplicia and extract of *Temu Ireng*. Alkaloids, flavonoids, tannins, saponins, and phenols were successfully extracted using ethanol as the solvent in the maceration process.

Table 1. Screening Results of *Temu Ireng* Extract

Secondary metabolites	Performance
Mayer	++
Dragedorff	++
Flavonoid	+++
Tannin	++
Saponin	+
Phenol	++

Note: A "+" symbol denotes that the compound contains a small number of secondary metabolites, while "++" indicates a moderate presence of these metabolites. The "+++" symbol signifies a high concentration of secondary metabolites, and a "-" means the absence of secondary metabolites in the compound.

3.3. Content Phenolic and Flavonoid Content

The total phenolic and flavonoid contents of the *Temu Ireng* extract and its SNEDDS formulation were determined. The findings are shown in Figure 3. as milligrams of quercetin equivalent per gram of extract (mg QE/g extract) for flavonoids and milligrams of gallic acid equivalent per gram of extract (mg GAE/g extract) for phenols.

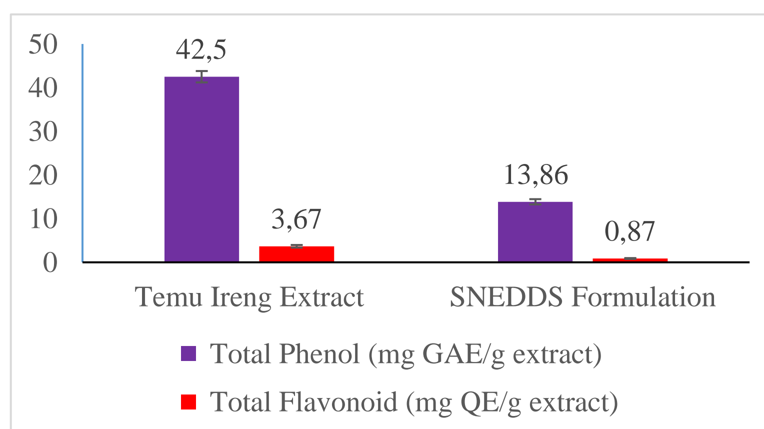

Fig 3. Total phenol and flavonoid content of *Temu Ireng* extract and SNEDDS

The *Temu Ireng* extract had a total phenolic content of 42.5 mg GAE/g extract, whereas, in the SNEDDS formulation, it decreased significantly to 13.86 mg GAE/g extract. This reduction

represents approximately a 3.07-fold decrease in phenolic content in the SNEDDS form compared to the crude extract. Similarly, the total flavonoid content showed a notable reduction, from 3.67 mg QE/g extract in the extract to 0.87 mg QE/g extract in the SNEDDS, which equates to a 4.22-fold decrease. The diluting effect brought on by the addition of non-active ingredients like VCO, Tween 80, and propylene glycol to the SNEDDS formulation is responsible for the notable decrease in phenolic and flavonoid concentration. The addition of these components reduces the concentration of the bioactive compounds per gram of the formulation. Furthermore, phenolic and flavonoid compounds may interact with the components of the formulation, leading to potential loss or alteration in their stability, which can also contribute to the observed decrease. Similar trends have been reported in other studies involving the formulation of bioactive compounds into delivery systems (Wijayanti et al., 2018). Despite the reduction in content, the study reported enhanced bioavailability and stability of the active compounds in the delivery system.

3.4. Formula Oprimization of SNEDDS

The optimization of the formula was conducted using the SLD approach, resulting in 17 initial formulations generated by the Design Expert 13 software that shown in Table 2. These formulations were designed for the SNEDDS containing *Temu Ireng* extract, with independent variables including the type of carrier oil (virgin coconut oil), surfactant (Tween 80), and co-surfactant (propylene glycol). The dependent variables of the study were the percentage of transmittance and emulsification time. After analyzing the formulations using SLD, the results were displayed in terms of transmittance values and emulsification times, providing insights into the optimal combination of components for enhanced stability and performance of the SNEDDS. The percentage of transmittance and emulsification time evaluations are detailed in Table 3.

3.5. Optimal Formula Selection Based on SLD

Based on the formula optimization using the Simplex Lattice Design method, one predicted formula achieved a desirability score of 0.986, the highest value presented in Figure 4. which detailed in Table 4. This formula is the most optimal prediction due to its superior transmittance value and favorable emulsification time. Specifically, the optimal formulation comprises a ratio of 1:86.3:12.7 for VCO, Tween 80, and propylene glycol, respectively. This optimal combination indicates an effective balance of ingredients, enhancing the stability and performance of the SNEDDS containing *Temu Ireng* extract. Further testing will be essential to validate the practical application of this formulation in real-world scenarios.

Table 2. Initial Formula Composition

Run	VCO (%)	Tween 80 (%)	Propylene Glycol (%)
1	65.7	17.2	17.2
2	33.3	33.3	33.3
3	65.7	1.0	33.3
4	33.3	33.3	33.3
5	33.3	1.0	65.7
6	1.0	98.0	1.0
7	33.3	65.7	1.0
8	1.0	1.0	98.0
9	1.0	98.0	1.0
10	17.2	65.7	17.2
11	65.7	33.3	1.0
12	1.0	65.7	33.3
13	1.0	1.0	98.0
14	98.0	1.0	1.0
15	1.0	33.3	65.7
16	98.0	1.0	1.0
17	17.2	17.2	65.7

Table 3. Transmittance value and Emulsification time

Run	Transmittance (%)	Emulsification time (s)
1	0.6	11.64
2	0.4	11.23
3	21.4	15.33
4	0.4	11.23
5	19.9	10.9
6	78.6	11.76
7	5.0	11.4
8	21.6	9.84
9	78.6	11.76
10	7.0	11.91
11	7.1	15.12
12	77.7	11.21
13	21.6	9.84
14	67.6	17.26
15	80.5	26.66
16	67.6	17.26
17	0.5	9.02

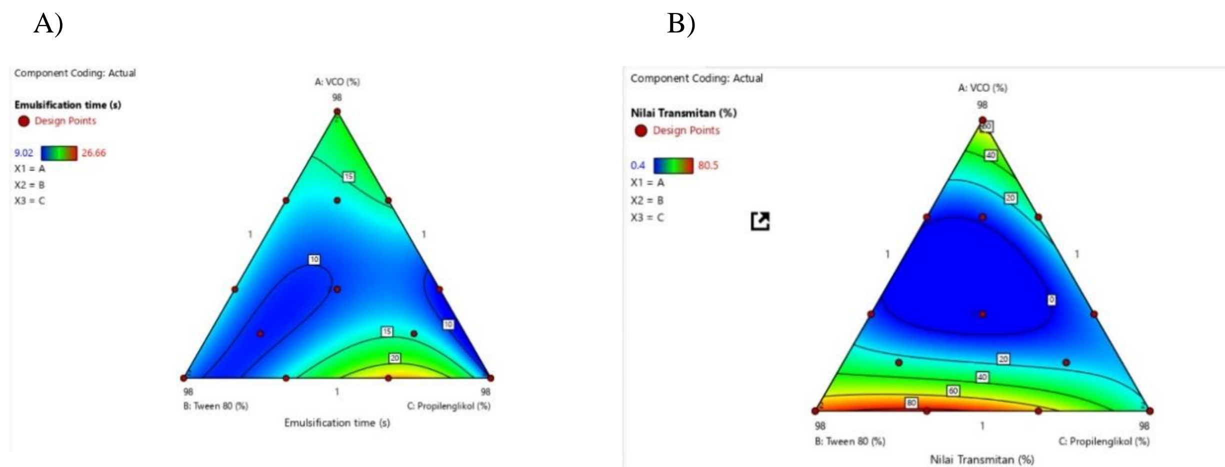

Fig 4. The optimum formula based on A) and B) Transmittance and Emulsification time

Table 4. The Optimum Formula

VCO (%)	Tween 80 (%)	Propylene Glycol (%)	Transmittance (%)	Emulsification time (s)	Desirability
1.0	86.3	12.7	80.9	9.5	0.986
1.0	98.0	1.0	74.7	11.6	0.892
98.0	1.0	1.0	67.6	17.2	0.672
1.0	2.3	96.7	25.5	11.3	0.522

3.6. Particle Size and Zeta Petential

The characterization of the SNEDDS formulation was evaluated based on droplet size, polydispersity index (PI), and zeta potential, as presented in the data. The average droplet size measured across three replicates was 9.0 nm, indicating a small particle size that is desirable for nanoemulsion systems. Smaller droplet sizes are typically associated with improved bioavailability and stability, as they can enhance the solubilization of hydrophobic compounds and facilitate easier absorption in biological systems (Parthasarathi et al., 2016). Further, the polydispersity index (PI) values ranged from 0.264 to 0.323, with an overall average of 0.302. A PI value below 0.3 is generally indicative of a homogeneous and stable emulsion system, suggesting that the formulation maintains a

relatively narrow distribution of droplet sizes (Patel, 2016). This uniformity is crucial for ensures consistent performance and efficacy in pharmaceutical and cosmetic applications.

Moreover, the zeta potential measurements varied slightly, ranging from -0.8 mV to -1.0 mV. The negative zeta potential values suggest that the droplets carry a negative charge, which can help stabilize the formulation by preventing aggregation and coalescence through electrostatic repulsion (Abd El‐Mageed et al., 2021). However, the absolute values of zeta potential are relatively low, indicating that while there is some stability, further optimization may be necessary to enhance the electrostatic stability of the nanoemulsion. Overall, these characterization parameters demonstrate promising qualities for the SNEDDS formulation. Still, additional studies should be conducted to assess the long-term stability and performance of the system under various conditions.

3.7. Results of Antioxidant Testing

The antioxidant activity of the sample was assessed by observing a noticeable shift in the solution's color from purple to yellow, signifying its effectiveness in neutralizing DPPH free radicals. This color change indicates that the compounds present in the sample can donate hydrogen atoms to the DPPH radical, transforming it into a more stable form known as DPPH-H. To quantify this activity, the absorbance of the solution was measured using a UV-Vis spectrophotometer. The results of the antioxidant tests, as illustrated in Figure 5. and Figure 6, highlight the extent of the sample's capacity to scavenge free radicals, providing valuable insights into its potential therapeutic properties.

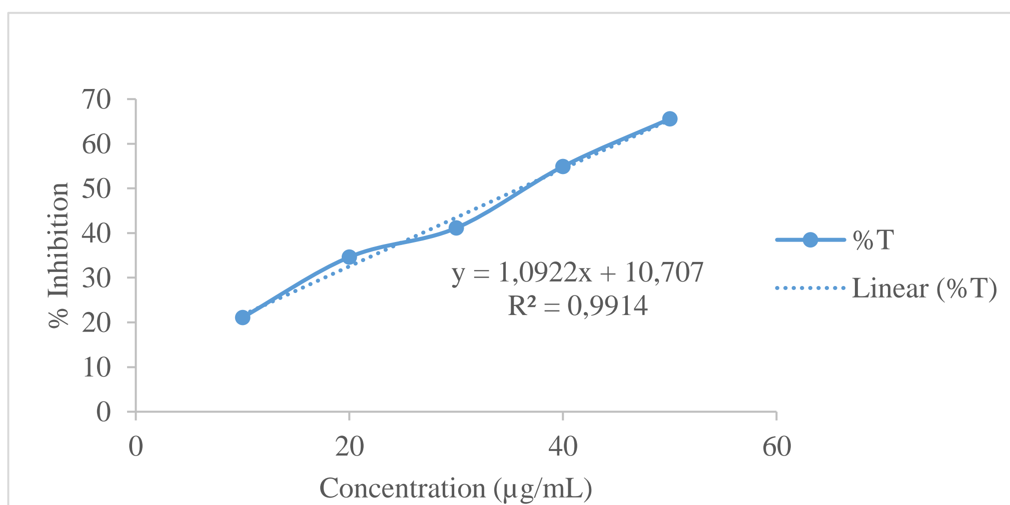

Fig 5. Regression Curve of Inhibition Percentage of *Temu Ireng* Ethanolic Extract

The IC50 value serves as a critical indicator of the antioxidant activity of a sample, representing the concentration required to inhibit 50% of DPPH free radicals. In this study, the *Temu Ireng* extract demonstrated an IC50 value of 58.482 µg/mL, indicating antioxidant activity, in contras the reference antioxidant, vitamin C, exhibited a much lower inhibition concentration (IC50) value of 6.96 µg/ml, classifying it as a very potent antioxidant. The linear regression analysis for the *Temu Ireng* extract yielded a high coefficient of determination ($r^2 = 0.9804$), reflecting a strong correlation between the concentration of the extract and its radical-scavenging ability. The inverse relationship between IC50 values and antioxidant strength suggests that lower IC50 values correspond to more potent antioxidant effects. According to established classifications, the IC50 value of the *Temu Ireng* extract falls within the "strong" category, as it ranges between 50 and 100 µg/mL. In contrast, the antioxidant activity of vitamin C, with its IC50 of 6.96 µg/mL, underscores its exceptional effectiveness as an antioxidant.

Moreover, the antioxidant potential of the *Temu Ireng* extract may be attributed to its rich phytochemical composition, including polyphenols and flavonoids, which are known to possess radical-scavenging solid properties. These findings align with previous studies that have reported the significant antioxidant capacity of Curcuma aeruginosa, supporting its potential application in functional foods and nutraceuticals aimed at combating oxidative stress. Overall, the results

emphasize the relevance of the *Temu Ireng* extract as a natural source of antioxidants, which could benefit various health-related applications.

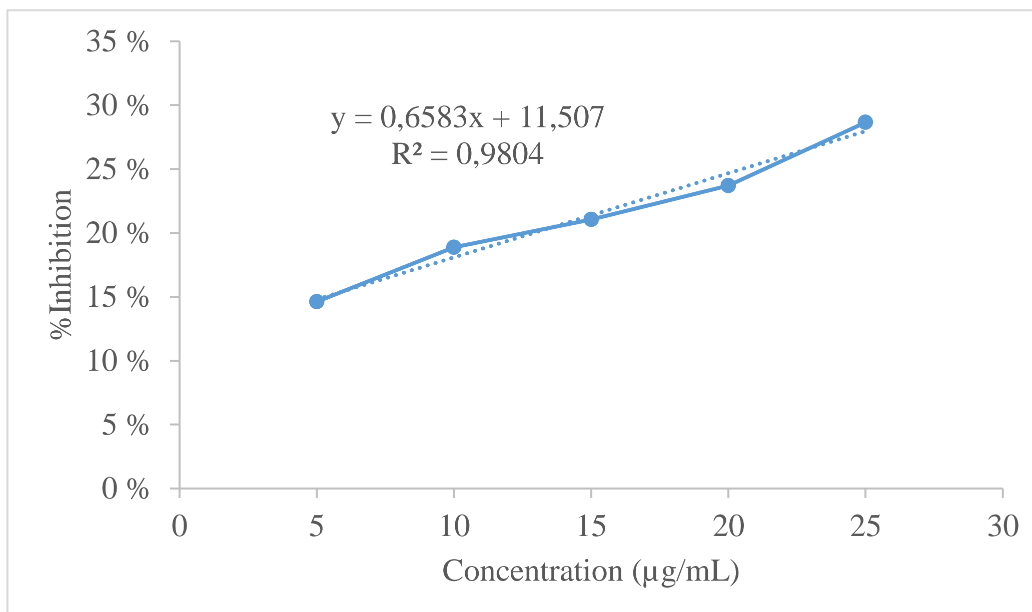

Fig 6. Regression Curve of SNEDDS Inhibition Percentage of *Temu Ireng* Extract

4. Conclusion

The optimized formulation of SNEDDS containing *Temu Ireng* extract consists of a composition ratio of VCO, Tween 80, and propylene glycol at 1:86.3:12.7, achieved by combining black turmeric extract with the carrier oil, surfactants, and co-surfactants. This formulation demonstrated favorable properties, with transmittance and emulsification times recorded at 80.9% and 9.5 seconds, respectively. Additionally, it exhibited a zeta potential of -0.9 mV, a polydispersity index (PI) of 0.302, and a particle size of 9.0 nm, indicating stability and homogeneity. The antioxidant activity of the black turmeric extract was quantified with an IC_{50} value of 35.976 ppm, classifying it as a antioxidant. In the SNEDDS formulation, the black turmeric extract also demonstrated strong antioxidant properties, with an IC_{50} value of 58.482 ppm.

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Competing Interests

The authors declare no conflict of interest.

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