

Comparative Extraction Yield, Phytochemical profile, and Bioactivity of Essential oil and Oleoresin from Seeds/placenta, pericarp, and whole fruit of Nsukka Yellow pepper (*Capsicum annuum* L.)

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Comparative Extraction Yield, Phytochemical profile, and Bioactivity of Essential oil and Oleoresin from Seeds/placenta, pericarp, and whole fruit of Nsukka Yellow pepper (*Capsicum annuum* L.)

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Abstract

Oxidative deterioration and microbial contamination remain critical challenges in food preservation, driving demand for clean-label natural antioxidants and antimicrobials. This study compared the extraction yield, phytochemical composition, antioxidant capacity, and antimicrobial activity of essential oil and oleoresin from seeds (including placenta), pericarp, and whole fruit of Nsukka yellow pepper (*Capsicum annuum* L.). Essential oils were obtained by steam distillation and oleoresins by hexane-ethanol maceration. Total phenolic, flavonoid, and carotenoid contents were quantified spectrophotometrically. Antioxidant activity was assessed by ferric-reducing antioxidant power (FRAP) and DPPH radical scavenging assays. Antimicrobial activity against *Escherichia coli*, *Staphylococcus aureus*, *Candida albicans*, and *Aspergillus flavus* was evaluated using agar well diffusion and broth macrodilution method. Seed essential oil exhibited the highest yield among essential oils, whereas whole pepper oleoresin yielded the highest among oleoresins. Oleoresins consistently outperformed essential oils in antioxidant capacity. Seed oleoresin demonstrated the strongest radical scavenging activity (IC₅₀ = 10.87 µg/mL) and the highest phenolic content (320.00 mg GAE/100 g extract). Pericarp oleoresin contained the highest carotenoid concentration (260.99 mg/100 g extract), while seed extracts were richest in flavonoids. Whole pepper oleoresin exhibited the broadest antimicrobial spectrum, with a minimum inhibitory concentration (MIC) of 6.25 % against all tested organisms. Nsukka yellow pepper oleoresins, particularly from seeds and pericarp, are potent sources of natural antioxidants and antimicrobials with emerging applications in functional foods and clean-label preservation systems.

Keywords: *Capsicum annuum*; essential oil; oleoresin; antioxidant activity

Introduction

Diet-induced chronic diseases represent a major global health burden, with oxidative stress, microbial infections, and inflammation recognized as central contributing factors (Nikam et al., 2024). The long-term health implications of heavily processed diets containing synthetic additives have intensified consumer demand for natural, health-promoting ingredients (Whelan et al., 2024; Rafaqat et al., 2025). Consequently, the food and nutrition industries are increasingly exploring plant-derived bioactive compounds that align with the clean-label paradigm.

Plants belonging to the genus *Capsicum* (family Solanaceae) are cultivated worldwide for their nutritional, sensory, and medicinal properties (Anaya-Esparza et al., 2021). Pepper fruits are rich in phytochemicals, including phenolics, flavonoids, carotenoids, capsaicinoids, essential oils, and oleoresins, that confer pungency, aroma, colour, and health-promoting attributes (Dias et al., 2016). These bioactives mitigate the risk of cardiovascular disease, diabetes, neurodegeneration, and cancer by neutralizing reactive oxygen species and enhancing endogenous antioxidant defenses (Lu et al., 2020; Mahboubi, 2021; Dłudla et al., 2023). Furthermore, pepper extracts exhibit documented antimicrobial effects against foodborne bacteria and fungi, highlighting their potential as natural preservatives for shelf-life extension (Maurya et al., 2021; Romero-Luna et al., 2023).

The distribution of phytochemicals within pepper fruit is anatomically heterogeneous. The pericarp is predominantly enriched with carotenoids, whereas the seeds and placental tissues accumulate higher concentrations of flavonoids and capsaicinoids (Gómez-García & Ochoa-Alejo, 2013; Dias et al., 2016). Extraction methodology further dictates chemical profile and bioactivity: essential oils capture volatile, polar fractions, whereas oleoresins retain both volatile and non-volatile (non-polar) constituents, including phenolics and pigments (Singh et al., 2013; Baenas et al., 2019). Despite these known variations, systematic comparisons of bioactivity across anatomical parts and extraction methods remain limited for indigenous pepper varieties.

Nsukka yellow pepper, native to southeastern Nigeria, is distinguished by its bright golden-yellow colour, sharp pungency, and unique aroma, and it is widely used in traditional cuisines of the region (Dias et al., 2016). Although preliminary evidence suggests that this landrace is rich in carotenoids, capsaicinoids, and flavonoids (Mahboubi, 2021), comprehensive biochemical and functional characterization is lacking. This knowledge gap limits its exploitation in nutraceutical and functional food applications.

Therefore, this study was designed to: (i) compare the extraction yield of essential oil and oleoresin from whole pepper, seeds/placenta, and pericarp; (ii) evaluate and compare their phytochemical profiles (total phenolics, flavonoids, and carotenoids); (iii) assess antioxidant capacity using FRAP and DPPH assays; and (iv) determine antimicrobial activity against selected foodborne bacteria and fungi.

Materials and methods

Sample collection and preparation

Fresh Nsukka yellow peppers were procured from the farm unit of the University of Nigeria, Nsukka. The fruits were washed, sorted, and manually separated into three fractions: whole fruit, seeds (including placenta), and pericarp. Each fraction was oven-dried at 40 °C to constant weight, milled to pass through a 0.5 mm sieve, and stored in airtight containers at 4 °C until Oleoresin extraction.

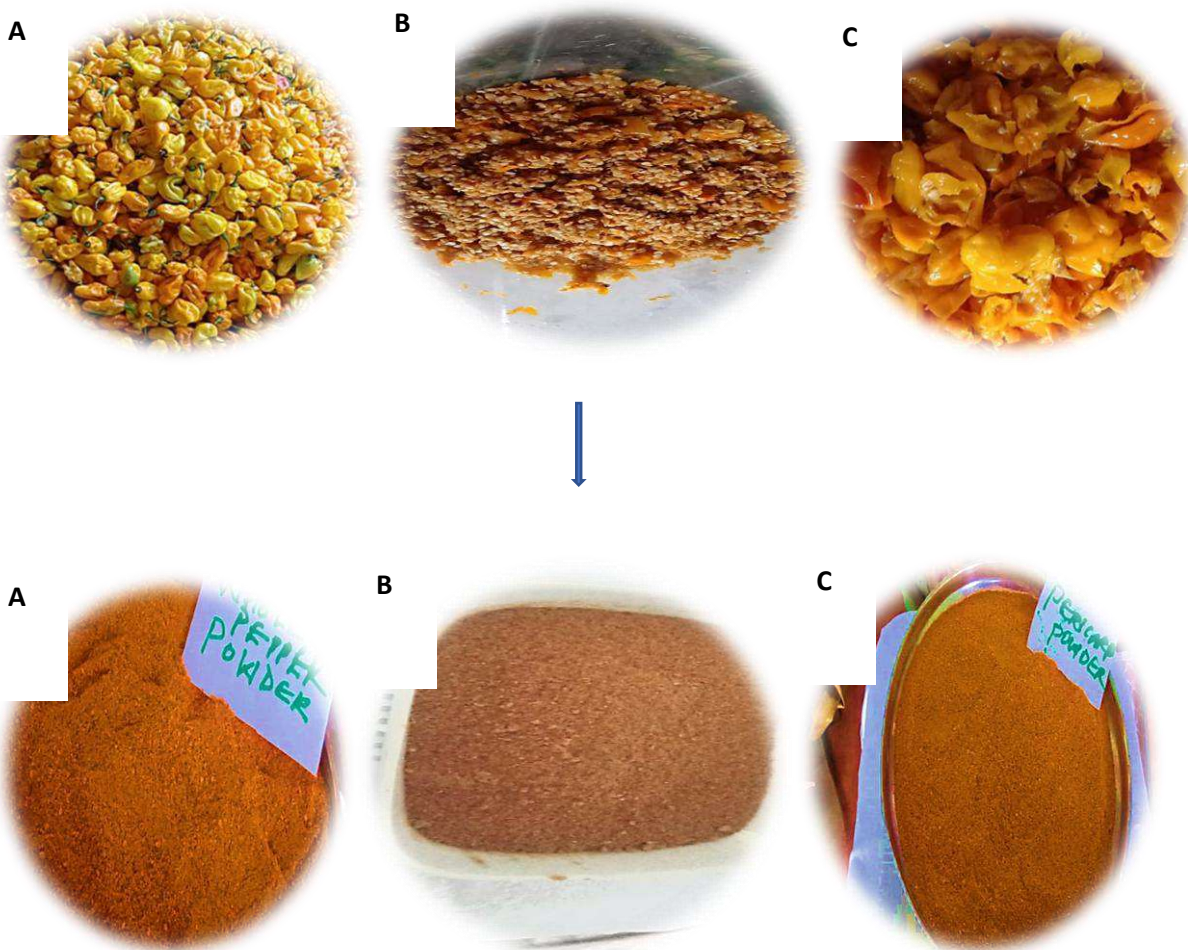


Plate 1: Fresh and powdered forms of whole Nsukka pepper, seeds/placenta, and pericarp
 Keywords: A = fresh and dry milled whole Nsukka yellow pepper B = fresh and dry-milled pepper seeds/placenta, and C = Fresh and dry-milled pepper pericarp

Extraction of essential oils and oleoresins

Essential oils were extracted by steam distillation using a Clevenger-type apparatus according to Gupta and Guha (2024). Briefly, 100 g of dried, milled sample was hydrodistilled in 1000 mL distilled water for 3 h. The collected essential oil was dried over anhydrous sodium sulfate and stored in amber vials at 4 °C until analysis. Oleoresins were obtained by maceration. Dried, milled samples (100 g) were extracted with 1000 mL of hexane-ethanol (1:1, v/v) at room temperature (25 ± 2 °C) for 96 h with intermittent agitation. The extract was filtered and concentrated under reduced pressure at 40 °C using a rotary evaporator. Residual solvent was removed under a stream of nitrogen, and the oleoresin was stored at -20 °C.

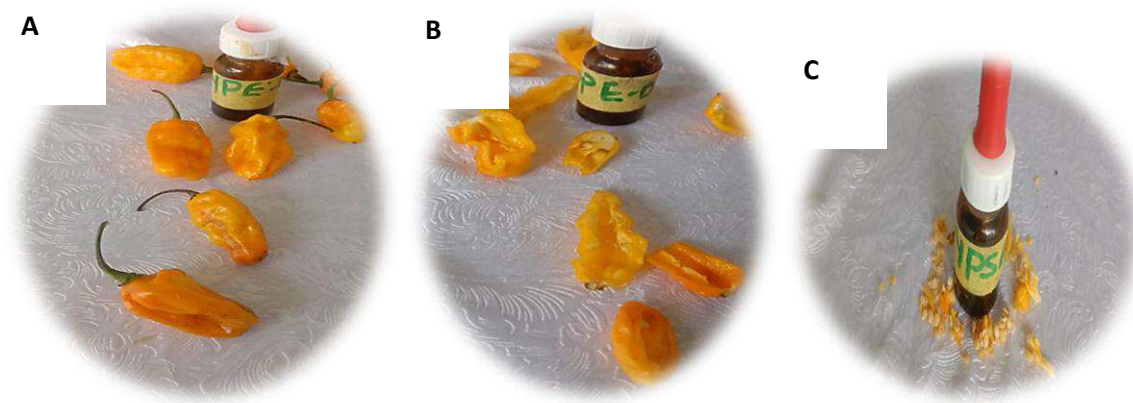


Plate 2: Nsukka yellow pepper seed, pericarp, and whole Essential oil extracts

Keywords: A = Essential oil extracted from whole pepper, B = essential oil extract from the pericarp, C = essential oil extract from the pepper seed/placenta

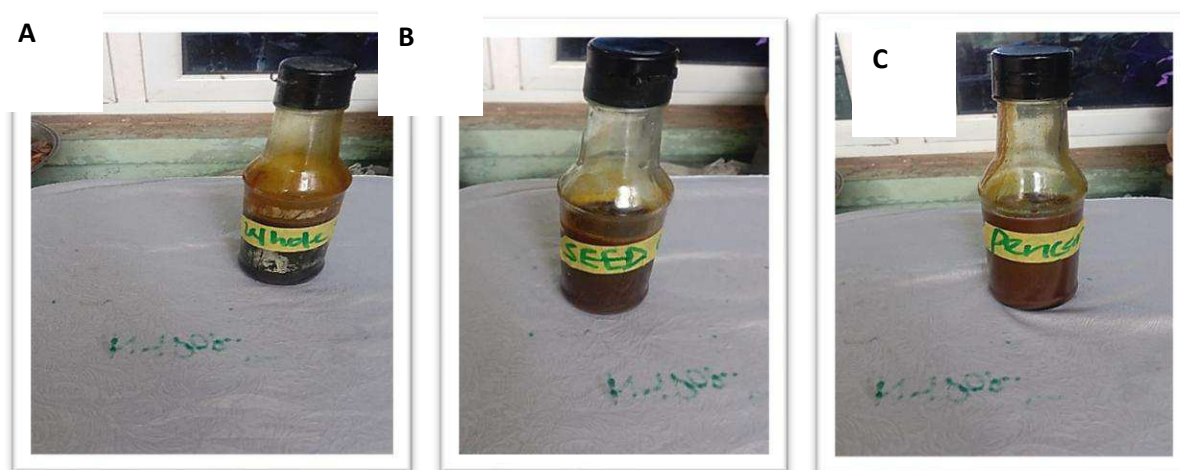


Plate 3: Nsukka yellow whole pepper, seeds/placenta, and Pericarp, oleoresin Extracts

Keywords A = Oleoresin extract from the whole pepper sample, B = Oleoresin extract from pepper seeds/placenta, and C = Oleoresin extract from the pepper pericarp

Extract yield

The yield of extract (extractable component) expressed on the dry weight basis of the sample was calculated using equation 1:

$$Yield \left(\frac{g}{100g} \right) = \frac{W_1 \times 1000}{W_2} \text{----- (1)}$$

Where; W_1 is the weight of the extract residue obtained after solvent removal; W_2 is the weight of the sample

Phytochemical analysis

The essential oil and oleoresin extracts were dissolved in methanol (1 mg/mL) for phytochemical quantification. Results were expressed per 100 g of extract.

Total Phenolic Content (TPC): TPC was determined using the Folin-Ciocalteu method as described by Eberhardt et al. (2005), with slight modifications. An aliquot (0.5 mL) of extract was mixed with 2.5 mL of Folin-Ciocalteu reagent (diluted 1:10) and 2 mL of sodium carbonate solution (7.5 %, w/v). After incubation in the dark for 30 min at room temperature, absorbance was measured at 765 nm. A gallic acid calibration curve (0–500 mg/L) was used for quantification, and results are expressed as mg gallic acid equivalents (GAE) per 100 g extract.

Total Flavonoid Content (TFC): TFC was determined by the aluminum chloride colorimetric method described by Zou et al. (2004). Extract (0.5 mL) was mixed with 1.5 mL of 95 % ethanol, 0.1 mL of 10 % aluminum chloride, 0.1 mL of 1 M potassium acetate, and 2.8 mL distilled water. After incubation at room temperature for 30 min, absorbance was read at 415 nm. Quercetin was used as the reference standard, and results are expressed as mg quercetin equivalents (QE) per 100 g extract.

Total Carotenoid Content (TCC): TCC was determined according to Ohizua et al. (2017) with minor modifications. Extract (2 g) was saponified with ethanolic potassium hydroxide (10 %, w/v) at room temperature for 16 h. Carotenoids were partitioned into diethyl ether, washed with distilled water, and re-extracted into light petroleum ether. The solvent was evaporated to dryness under nitrogen, and the residue was dissolved in acetone for spectrophotometric quantification at 450 nm. Results are expressed as mg carotenoids per 100 g extract.

Antioxidant assays

DPPH Radical Scavenging Assay: The free radical scavenging activity was determined using a modified method of Chang et al. (2007). Various concentrations of each extract (0.78–500 µg/mL) in methanol were mixed with 0.1 mM DPPH solution in methanol. The mixture was incubated in the dark for 30 min at room temperature, and absorbance was measured at 517 nm. Ascorbic acid served as the positive control. The percentage radical scavenging activity (% RSA) was calculated using Equation (2):

$$\% RSA = \frac{A_0 - A_s}{A_0} \times 100 \text{----- (2)}$$

Where: A_0 = absorbance of blank, A_s = absorbance of the sample at 517 nm

Ferric Reducing-Antioxidant Power (FRAP) Assay

FRAP Assay: The ferric-reducing antioxidant power was assessed according to Benzie and Strain (1999). The FRAP reagent was prepared by mixing 300 mM acetate buffer (pH 3.6), 10 mM TPTZ in 40 mM HCl, and 20 mM $\text{FeCl}_3 \cdot 6\text{H}_2\text{O}$ in a 10:1:1 ratio. Extract (100 μL) was mixed with 3 mL of freshly prepared FRAP reagent and incubated at 37 °C for 30 min. Absorbance was measured at 593 nm. A standard curve of $\text{FeSO}_4 \cdot 7\text{H}_2\text{O}$ (100–1000 μM) was used, and results are expressed as $\mu\text{mol Fe}^{2+}$ equivalents per gram of extract ($\mu\text{mol Fe}^{2+}/\text{g}$).

Antimicrobial activity

Test Microorganisms: The antimicrobial activity was evaluated against two bacteria (*Escherichia coli* ATCC 25922 and *Staphylococcus aureus* ATCC 25923), one yeast (*Candida albicans* ATCC 10231), and one mould (*Aspergillus flavus*). Cultures were maintained on appropriate agar slants and sub-cultured prior to testing. Agar Well Diffusion Assay: The assay was performed according to CLSI guidelines (Hussain et al., 2011). Molten Mueller-Hinton agar (MHA) was seeded with 100 μL of standardized inoculum (1.5×10^8 CFU/mL for bacteria; 1×10^6 CFU/mL for fungi) and poured into sterile Petri dishes. Wells (6 mm diameter) were punched and filled with 50 μL of extract at concentrations of 50 %, 25 %, 12.5 %, 6.25 %, and 3.125 % (v/v in dimethyl sulfoxide). Plates were incubated at 37 °C for 24 h (bacteria) or 48–72 h (fungi). The diameter of the zone of inhibition (IZD) was measured in millimetres. DMSO served as the negative control.

Determination of MIC, MBC, and MFC: Broth macrodilution was performed in Mueller-Hinton broth (MHB) according to CLSI protocols. Serial two-fold dilutions of each extract (50 % to 0.78 %) were prepared in MHB. Tubes were inoculated with standardized microbial suspensions and incubated at 37 °C for 18–24 h (bacteria) or 48 h (fungi). The MIC was defined as the lowest concentration showing no visible growth. To determine minimum bactericidal concentration (MBC) and minimum fungicidal concentration (MFC), aliquots from clear MIC tubes were sub-cultured on MHA. The MBC/MFC was defined as the lowest concentration yielding no microbial growth on solid medium.

Statistical analysis

All experiments were conducted in triplicate. Data were analyzed using 3×2 factorial arrangements in a Completely Randomized Design (CRD). One-way analysis of variance (ANOVA) was performed using SPSS version 23, and mean separation was conducted using Duncan's multiple range test at $p < 0.05$. Results were expressed as mean $\pm$ standard deviation.

Results

The yield of essential oil and oleoresin varied significantly ($p < 0.05$) among the pepper fractions (Figure 1). Among essential oils, the seed fraction yielded the highest amount, followed by whole pepper and pericarp. For oleoresins, whole pepper produced the highest yield, attributable to the combined contribution of pericarp and seed constituents. The pericarp yielded the lowest oleoresin, reflecting its lower lipid and volatile oil content relative to the other fractions.

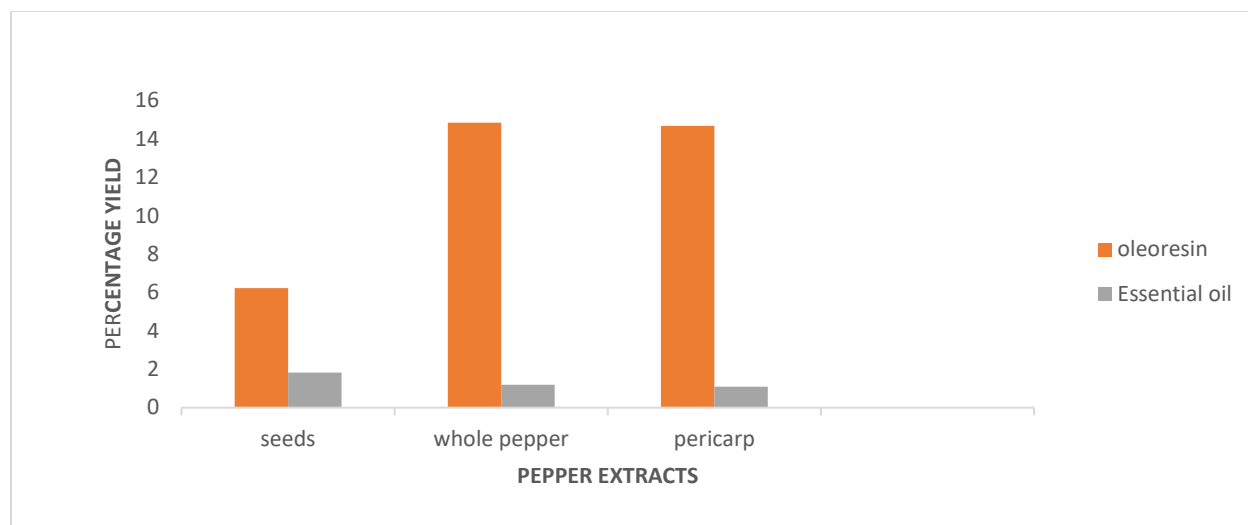


Fig 1: Extract yield of Essential oil and Oleoresin from whole seeds/placenta, Pericarpial tissues (endocarp, mesocarp, and exocarp) for a Nsukka yellow pepper

Ferric-reducing ability of the Oleoresin and Essential Oil Extracts from Seeds/Placenta, Pericarpial Tissues, and Whole Nsukka Yellow Pepper Variety

FRAP Assay: Oleoresins exhibited significantly higher ferric-reducing power than essential oils ($p < 0.05$) (Table 1). Seed oleoresin displayed the highest activity ($45.07 \mu\text{mol Fe}^{2+}/\text{g}$), followed by pericarp oleoresin ($41.17 \mu\text{mol Fe}^{2+}/\text{g}$) and whole pepper oleoresin ($38.74 \mu\text{mol Fe}^{2+}/\text{g}$). Among essential oils, the values were comparable and significantly lower than their oleoresin counterparts, ranging from 39.16 to $39.61 \mu\text{mol Fe}^{2+}/\text{g}$. The FRAP assay measures an antioxidant's ability to break free radical formation by donating hydrogen ions when reacting with ferric tripyridyltriazine (Fe^{3+} -TPTZ) complex, resulting in a colored ferrous tripyridyltriazine (Singh *et al.*, 2013).

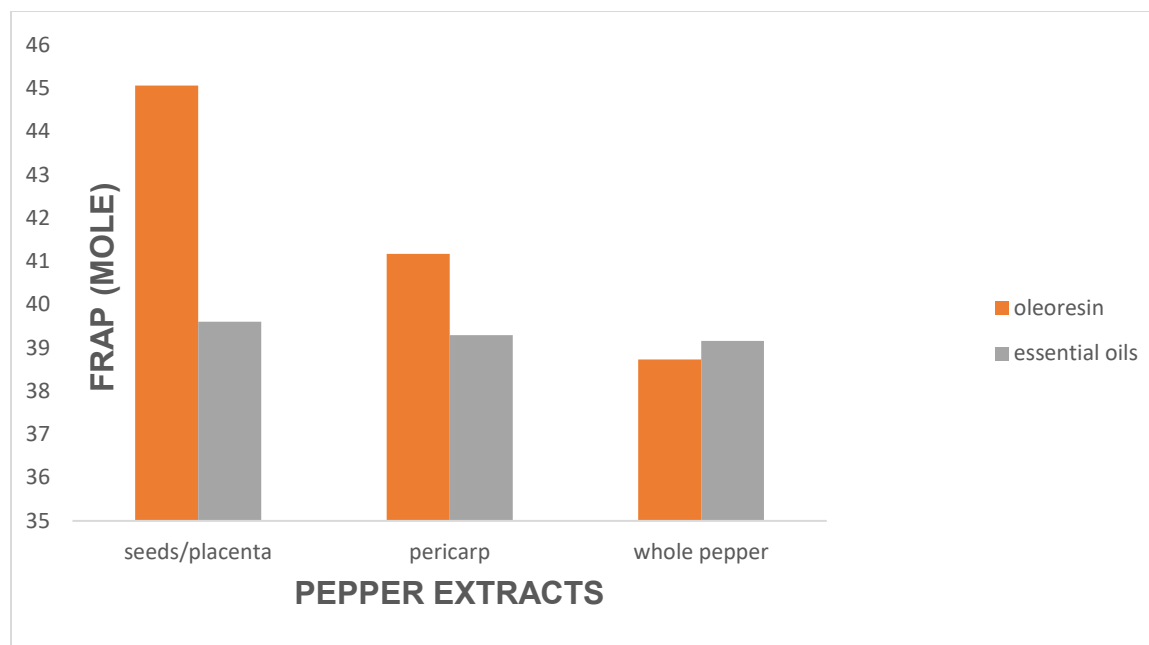


Fig.2: The Ferric Reducing Ability (FRAP) of Parts Pepper Essential Oil and Oleoresin

The DPPH assay of oleoreson and essential oil from whole and specific pepper parts of Nsukka yellow pepper

Table 1 shows that pepper oleoresin and essential oil extracts exhibit increased radical scavenging ability with higher concentrations. The study found that oleoresins exhibited significantly higher radical scavenging capacity than essential oils.

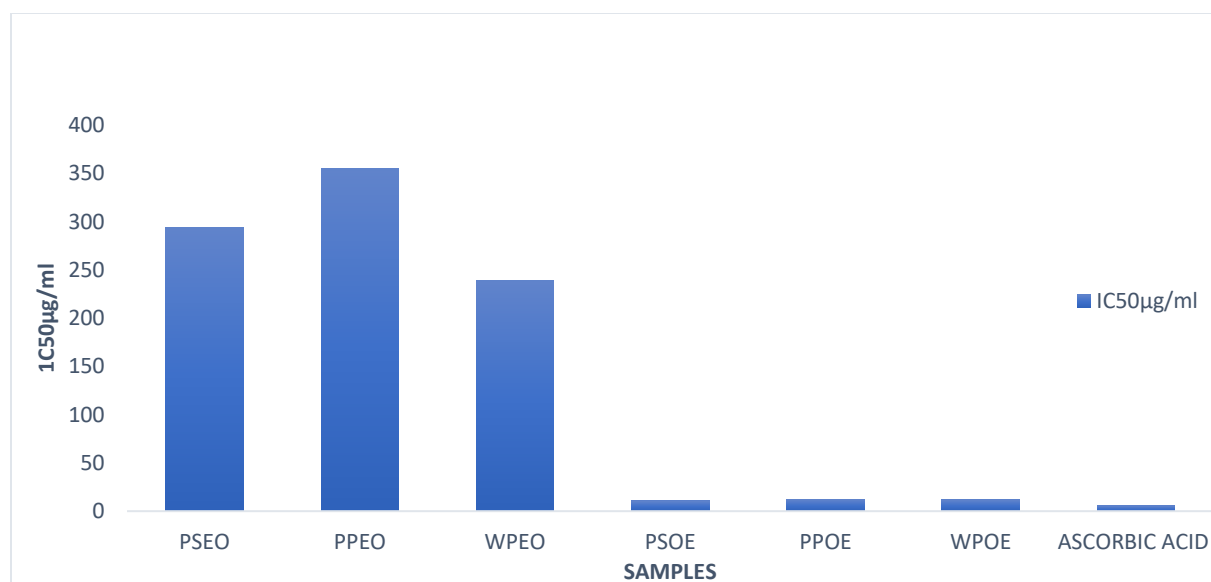


Fig 3: The DPPH assay of oleoresin and essential oil from whole and specific pepper parts of Nsukka yellow pepper

Keywords: PSEO = pepper seed/placenta essential oil extracts, PPEO = pepper pericarp essential oil extract, WPEO = whole pepper essential oil extract, PSOE = pepper seed/placenta oleoresin extract, PPOE = pepper pericarp oleoresin extract, WPOE = whole pepper oleoresin extract, and Ascorbic

Phytochemical properties of the Oleoresin and Essential oil extracts from seeds/placenta, Pericarpal tissues, and whole Nsukka yellow pepper variety

The phytochemical composition of essential oil and oleoresin extracts from whole pepper, seeds/placenta, and pericarp tissues of Nsukka yellow pepper showed significant ($p < 0.05$) differences among parts. Seed oleoresin and pericarp showed higher phenolic content than essential oils, with seed oleoresin having the highest value at 320.00 mg GAE/100 g. The phenolic content in essential oils varied from 80.90 mg GAE/100 g in seeds to 138.20 mg GAE/100 g in whole pepper.

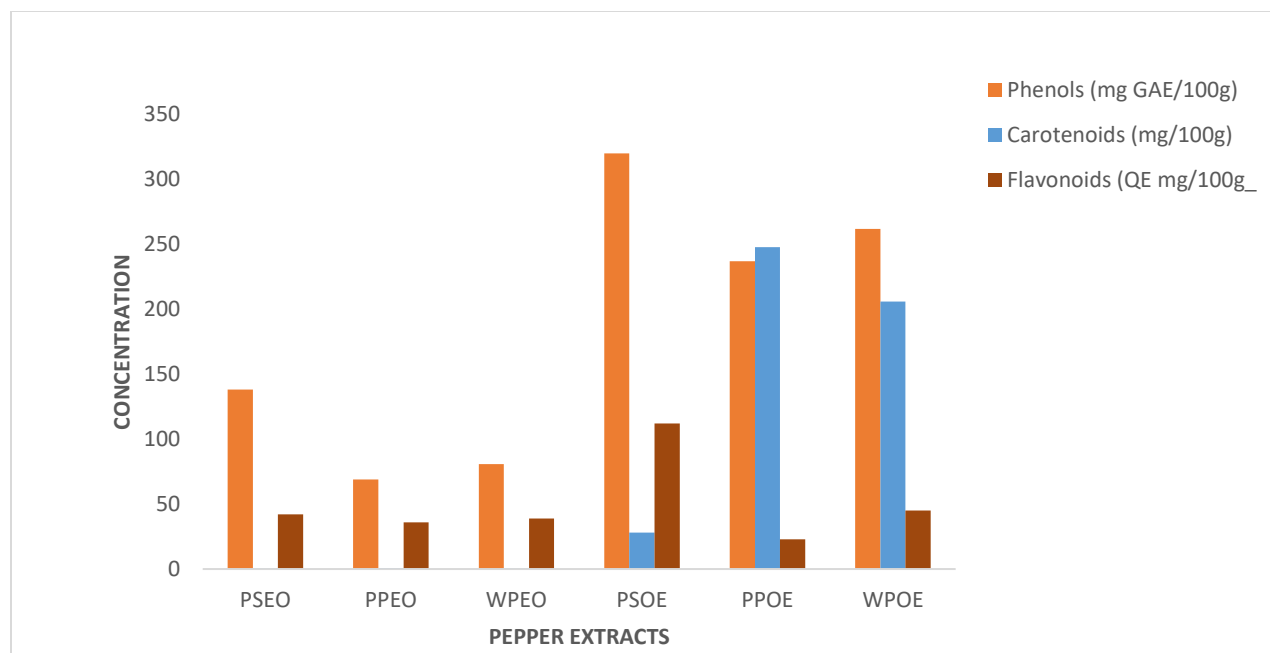


Figure 4: The phytochemical properties of pepper seeds/placenta. Pericarp and whole Nsukka yellow pepper variety.

Keywords: GAE = Garlic acid equivalent QE = Quercetin equivalent

The antimicrobial properties of Oleoresin and Essential extracts from seeds/placenta, pericarp and whole Nsukka yellow pepper variety

The antimicrobial activities of the respective samples as presented in Table 1 showed the inhibition zone diameter which indicated that most extracts exhibited measurable antimicrobial effects at 50% concentration, with very limited activity at lower concentrations (25% or below). Seed essential oil (PSEO) showed strong activity against *S. aureus* (17.5 ± 2.5 mm) and *C. albicans* (13.5 ± 1.5 mm), but no inhibition of *A. flavus*. Whole pepper essential oil (WPEO) had moderate inhibitory effects against all organisms, notably *C. albicans* (13 ± 0 mm) and *E. coli* (12.5 ± 2.5 mm), and displayed some activity at 25% for *A. flavus*. Pericarp oleoresin (PPOE) was most effective against *E. coli*, showing inhibition at both 50 % (13.5 ± 3.5 mm) and 25% (12.5 ± 1.5 mm). It also showed moderate zones for *S. aureus* (9.5 ± 0.5 mm) and *C. albicans* (11 ± 1 mm). The MIC values revealed that whole pepper oleoresin extracts (WPOE) had the strongest antimicrobial activity with the lowest MIC of 6.25% against all test microorganisms (*A. flavus*, *C. albicans*, *S. aureus*, and *E. coli*). Pericarp oleoresin (PPOE) also showed good activity with MICs ranging from 6.25% to 25%, while seed essential oil extracts (PSEO) were less effective, with MICs of 25% for *A. flavus* and *S. aureus*, and 12.5% for *C. albicans* and *E. coli*. The MBC and MFC values further confirmed the bactericidal and fungicidal effects of the extracts. Whole pepper extracts (WPOE) showed MBC/MFC values of 6.25% for *A. flavus* and 12.5% for *E. coli*, indicating strong cidal activity at low concentrations.

Table 1: Minimum inhibition zone diameter (IZD) of Oleoresin and Essential extracts from seeds/placenta, pericarp and whole Nsukka yellow pepper variety

Test Samples	Test Microorganism	Mean Inhibition zone diameter (IZD), measured (in mm), at the test concentration gradients (%)				
		50	25	12.5	6.25	3.125
PSEO	<i>Aspergillus flavus</i>	ND	ND	ND	ND	ND
	<i>Candida albicans</i>	13.5 ± 1.5	ND	ND	ND	ND
	<i>Staphylococcus aureus</i>	17.5 ± 2.5	ND	ND	ND	ND
	<i>Escherichia coli</i>	12 ± 0	ND	ND	ND	ND
WPEO	<i>A. flavus</i>	11 ± 1	10 ± 0	ND	ND	ND
	<i>C. albicans</i>	13 ± 0	ND	ND	ND	ND
	<i>S. aureus</i>	8 ± 0	ND	ND	ND	ND
	<i>E. coli</i>	12.5 ± 2.5	ND	ND	ND	ND
PPEO	<i>A. flavus</i>	ND	ND	ND	ND	ND
	<i>C. albicans</i>	11 ± 1	ND	ND	ND	ND
	<i>S. aureus</i>	13 ± 0	ND	ND	ND	ND
	<i>E. coli</i>		ND	ND	ND	ND
PSOE	<i>A. flavus</i>	13.5 ± 1.5	ND	ND	ND	ND
	<i>C. albicans</i>	9 ± 1	ND	ND	ND	ND
	<i>S. aureus</i>	ND	ND	ND	ND	ND
	<i>E. coli</i>	10 ± 0	ND	ND	ND	ND
WPOE	<i>A. flavus</i>	10 ± 0		ND	ND	ND
	<i>C. albicans</i>	9.5 ± 0.5	9.5 ± 1.5	ND	ND	ND
	<i>S. aureus</i>	11 ± 1		ND	ND	ND
	<i>E. coli</i>	10.5 ± 0.5	10.5 ± 1.5	ND	ND	ND
PPOE	<i>A. flavus</i>	9 ± 0	ND	ND	ND	ND
	<i>C. albicans</i>	11 ± 1	ND	ND	ND	ND
	<i>S. aureus</i>	9.5 ± 0.5	ND	ND	ND	ND
	<i>E. coli</i>	13.5 ± 3.5	12.5 ± 1.5	ND	ND	ND

Key: (ND) = Not Detected or Absence of inhibition zone at the given concentrations, PSEO = Pepper seed/placenta essential oil, WPEO = whole pepper essential oil, PPEO = pepper pericarp essential oil, PSOE = pepper seed/placenta oleoresin extract, WPOE = whole pepper oleoresin extract, and PPOE = pepper pericarp oleoresin extract

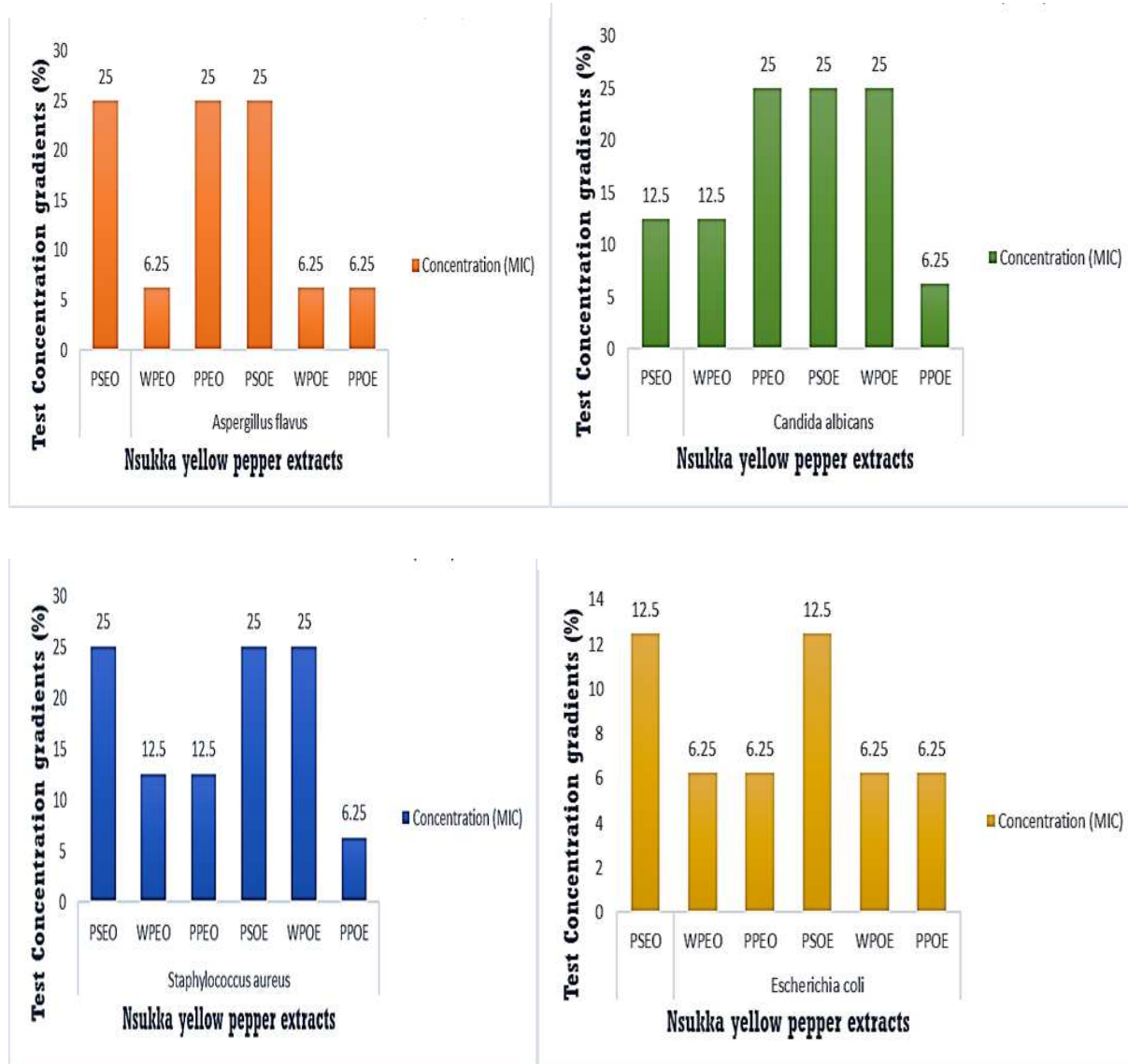
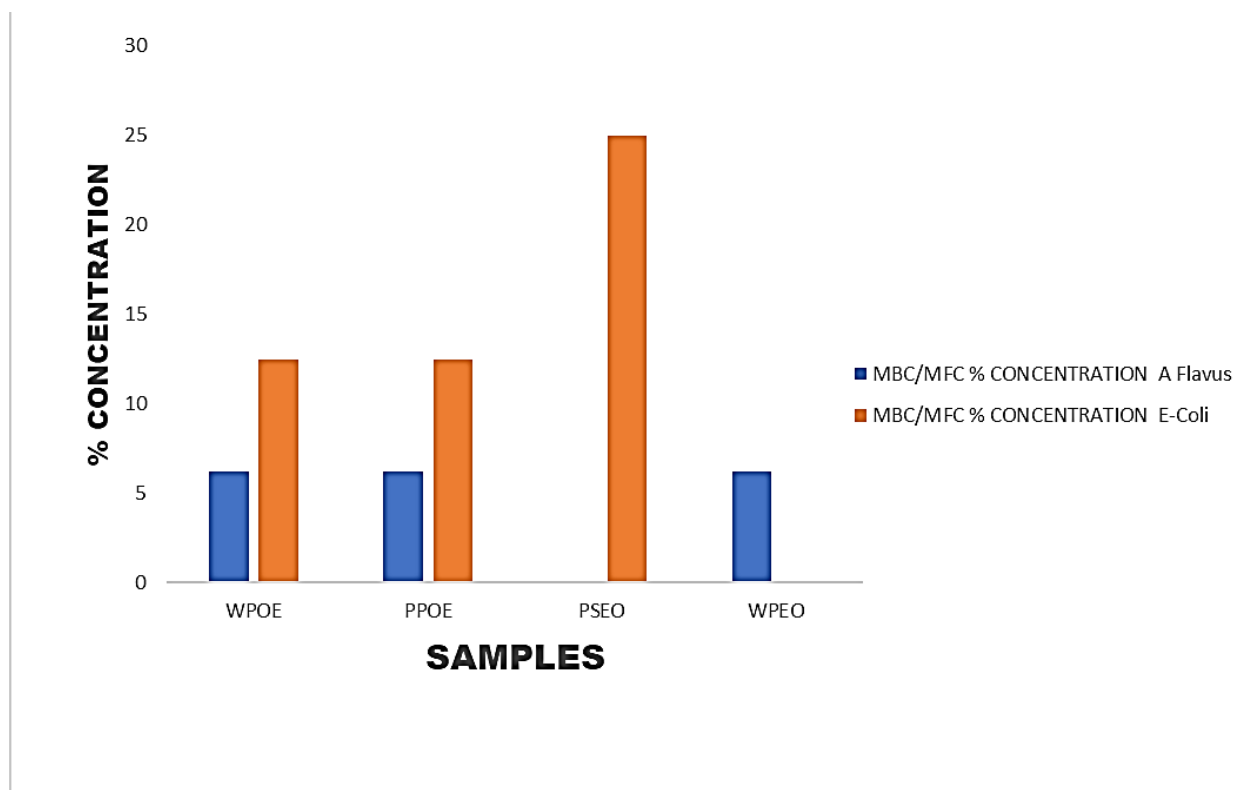


Fig 10: Minimum Inhibition Concentration (Mic) of the Test Organisms (*A. Flavus*, *C. albicans*, *S. aureus* and *E. coli*) on Nsukka yellow pepper extracts. Keys: PSEO = Pepper seed/placenta essential oil, WPEO = whole pepper essential oil, PPEO = pepper pericarp essential oil, PSOE = pepper seed/placenta oleoresin extract, WPOE = whole pepper oleoresin extract, and PPOE = pepper pericarp oleoresin extract



Discussion

The study examined the essential oil and oleoresin extracts from various parts of the Nsukka yellow pepper variety, with the seed yielding the most. Seeds have higher concentrations of lipophilic compounds, which are easier to extract during processing due to their chemical composition and structure (Ebiringa, 2022). Pepper, containing seeds and pericarp, yields moderately, but its fibrous structure results in lower content and less favorable extraction properties. The distribution of oils and other compounds significantly ($p < 0.05$) varies among these components. The whole pepper yielded the highest oleoresin content due to its diverse chemical constituents, including the pericarp and seeds, which provide more oils (Zhang *et al.*, 2022). The pericarp, rich in compounds, yields less than the whole fruit due to the absence of seeds' contributions, which typically contain fewer volatile oils and flavor compounds (Cvetković *et al.*, 2022).

The antioxidant activities of Oleoresin and essential oil extracts from seeds/placenta, pericarp, and Nsukka yellow pepper showed no significant ($p > 0.05$), differences in FRAP concentration, as they were at similar levels. The study found that oleoresins, a type of extract, consistently showed higher ferric-reducing activity than essential oils, indicating their wider phytochemical composition. Seed oleoresin is most potent, followed by pericarp and whole pepper oleoresin. Essential oil extracts from seeds, pericarp, and fruit have modest FRAP values. The whole pepper variety, without separation of parts, had the lowest ferric-reducing power. The study shows that non-volatile compounds, particularly phenolics and flavonoids, significantly enhance the reducing capacity of extracts, indicating their potential as natural antioxidant agents (Singh *et al.*, 2013).

The study analyzed the DPPH free radical scavenging ability of pepper oleoresin and essential oil extracts, revealing that all extracts showed enhanced radical scavenging capacity with higher concentrations. The study found that oleoresins have a higher radical scavenging capacity than essential oils, likely due to the presence of both volatile and non-volatile phytochemicals (Zhang *et al.*, 2022). Seed oleoresin (PSOE) showed the strongest DPPH radical scavenging potential, with the lowest IC₅₀ value of 10.87 µg/ml among the samples. This was followed closely by pericarp oleoresin (12.47 µg/ml) and whole pepper oleoresin (12.10 µg/ml). In contrast, the essential oil extracts exhibited considerably weaker activity: PSEO (294.03 µg/ml), PPEO (354.73 µg/ml), and WPEO (239.20 µg/ml), respectively. The study substantiates the superiority of oleoresin extracts, particularly from seeds and pericarp, in neutralizing free radicals (Ana Flavia *et al.*, 2024). The difference in antioxidant effectiveness between oleoresins and essential oils is due to extraction method and chemical profile, with oleoresins retaining more high-molecular-weight antioxidants like polyphenols and capsaicinoids (Bellucci *et al.*, 2022). Gülçin (2005) pointed that black pepper seeds demonstrated their superior capacity to scavenge free radicals, which is consistent with the current research findings.

The phytochemical composition of essential oil and oleoresin extracts from the whole pepper, seeds/placenta, and pericarp tissues of the Nsukka yellow pepper is depicted in Figure 2. Oleoresins consistently exhibited higher phenolic content than essential oils, with seed oleoresin recording the highest value (320.00 mg GAE/100 g), followed by pericarp (236.80 mg GAE/100 g). In contrast, phenolic content in essential oils ranged from 80.90 mg GAE/100 g in seeds to 138.20 mg GAE/100 g in whole pepper. These values greatly exceed those reported for black pepper essential oil (4–7%) by Kaliyaperumal *et al.* (2021). Oleoresins' enhanced phenolic profile is likely due to their retention of volatile and non-volatile compounds, making them a more potent source of bioactive compounds than essential oils (Chaohua *et al.* (2022). Nsukka yellow peppers contain primary carotenoids violaxanthin, lutein, and antheraxanthin, which vary based on fruit maturity and tissue type. The study found that the carotenoid content in Nsukka yellow pepper essential oil extracts was low, ranging from 0.43 mg/100 g in seed extracts to 0.47 mg/100 g in whole pepper extracts. The extracts of oleoresin showed significantly ($p < 0.05$) higher values, with pericarp oleoresin reaching 260.99 mg/100 g and seed oleoresin at 27.66 mg/100 g. The pericarp oleoresin's high carotenoid levels are due to the accumulation of β -carotene compounds, which intensify as the fruit ripens, causing yellow pigmentation. Pericarp tissue is a rich source of provitamin A, especially β -carotene, with oleoresins being effective in extracting both volatile and non-volatile components, enhancing color and nutritional value (Malinda *et al.*, 2023). Essential oils, primarily composed of volatile components, lack significant carotenoid content. Essential oils, primarily composed of volatile components, lack significant carotenoid content (Orav *et al.*, 2004).

The carotenoid levels in the pericarp oleoresin of Nsukka yellow pepper were found to surpass those reported by Gómez-García and Ochoa-Alejo (2013).

Pepper seeds contain a higher flavonoid content than other parts, possibly due to their protective role against oxidative stress and enhanced seed viability, as reported by Cho *et al.* (2020). Pepper seeds act as a nutrient reservoir for plants, requiring higher bioactive compounds like flavonoids to be present. Thuphairo *et al.* (2019) found that the total flavonoids content of five types of sweet peppers, including green, red, orange, and yellow, significantly contributes to their antioxidant activity and inhibitory properties. The study found that sweet peppers contain more bioactive compounds like flavonoids than capsicum peppers, with extracts containing higher levels of QE

mg/100 g. Oleoresin extract contains more flavonoids than essential oil extracts due to the structural composition of seeds, which facilitates the accumulation of these beneficial phytochemicals (Cortes-ferre *et al.*, 2022).

Seed oleoresin (PSOE) showed moderate activity against *A. flavus* and *E. coli*, but was ineffective against *S. aureus*. Whole pepper oleoresin (WPOE) demonstrated broad activity with inhibition across all organisms, especially against *E. coli* (10.5 ± 0.5 mm) and *C. albicans* (9.5 ± 0.5 mm), including measurable zones at 25%. The study indicates that whole pepper extracts and pericarp oleoresin show superior antimicrobial activity compared to seed-based extracts, likely due to their more complex bioactive compounds. Oleoresin, a compound with antimicrobial and antifungal properties, is attributed to its bioactive compounds like capsaicin, dihydrocapsaicin, piperidine, and C-spathulenol. These compounds disrupt microbial cell membranes, interfere with metabolic processes, and result in microbial inhibition (Romero-Luna 2022).

The MIC values revealed that whole pepper oleoresin extracts (WPOE) had the strongest antimicrobial activity with the lowest MIC of 6.25% against all test microorganisms (*A. flavus*, *C. albicans*, *S. aureus*, and *E. coli*). Pericarp oleoresin (PPOE) also showed good activity with MICs ranging from 6.25% to 25%, while seed essential oil extracts (PSEO) were less effective, with MICs of 25% for *A. flavus* and *S. aureus*, and 12.5% for *C. albicans* and *E. coli*. The study indicates that the whole pepper contains a potent combination of bioactive compounds, while the seed extract alone lacks sufficient potency. The MBC and MFC values confirmed the bactericidal and fungicidal effects of the extracts. The study found that whole pepper extracts (WPOE) demonstrated strong cidal activity at low concentrations, with MBC/MFC values of 6.25% for *A. flavus* and 12.5% for *E. coli*. Seed extracts showed no MBC/MFC values against *A. flavus*, *C. albicans*, or *S. aureus*, and required a 25% concentration for bactericidal effect against *E. coli*. Whole and pericarp-based extracts are more effective in inhibiting and killing microbial pathogens due to their diverse phytochemical content, particularly in oleoresin, and their better extraction and availability Baenas *et al.*, (2019). Careaga *et al.* (2003) found that a capsicum annum bell pepper extract, with a minimum inhibitory concentration of 1.5 mL100g⁻¹, effectively inhibited *S. typhimurium* growth in minced beef meat.

Conclusion

This study demonstrated that Nsukka yellow pepper (*Capsicum annum L.*) is a rich source of antioxidant and antimicrobial compounds, with significant variation based on the part of the pepper used (seeds/placenta, pericarp, or whole fruit) and the extraction method (oleoresin or essential oil). Oleoresin extracts, particularly from seeds/placenta and pericarp, consistently exhibited higher extract yield, antioxidant capacity (as evidenced by lower IC₅₀ values and higher FRAP scores) compared to essential oils. The phytochemical profile indicated that oleoresins contain greater concentrations of phenolics, flavonoids, and carotenoids, especially in the pericarp, making them good for nutraceutical and functional food applications. Antimicrobial activity varied across extracts, with whole pepper and pericarp oleoresins showing the strongest inhibition zones and lowest MIC/MBC values. The seed extracts demonstrated the weakest activity, particularly in essential oil form. These findings confirm that Nsukka yellow pepper, especially when processed into oleoresin from specific parts, holds great potential as a natural preservative and health-promoting ingredient in food formulations.

Competing Interests

The authors declare no conflicts of interest or competing interests.

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