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Variability in microplastic abundance, bisphenol A contamination, antioxidant properties, and health risks associated with vegetable consumption

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Abstract

Background Plastic pollution, particularly microplastics (MPs) and toxic additives such as bisphenol A (BPA), endangers human health. Therefore, their routes in the environment need to be investigated. This study investigated microplastic (MPs) abundance, bisphenol A (BPA) levels, and antioxidant activity (AA) in three commonly consumed vegetables—green amaranth, jute mallow, and spinach sourced from two markets in Osogbo, southwestern Nigeria. Microscopic technique was used to determine MP abundance, shapes, and colours. High-performance Liquid Chromatography (HPLC) was used to analyse BPA contents while 2,2-diphenyl-1-picrylhydrazyl (DPPH) assay was used to measure AA. A hazard index (HI) and estimated dietary intakes (EDIs) were used to estimate the associated risks and food safety concerns with MP and BPA in vegetables.

Results In this study, MP abundance in shoots ranged from 4.00 ± 0.50 to 7.67 ± 1.04 particles/g and in roots from 5.33 ± 1.53 to 18.00 ± 6.93 particles/g in spinach and green amaranth, respectively, indicating subsoil contamination. Three shapes (fragment, fibre, and irregular) and five colours (transparent, white, yellow, black, and brown) were detected, with fragment shape and transparent colour dominating. Fourier Transform Infrared spectroscopic (FTIR) analysis revealed a predominance of polyethylene, polypropylene, polyethylene terephthalate, polyvinyl chloride, and polyamide microplastics. The BPA ranged from 5.55 ± 0.56 to 6.65 ± 0.00 $\mu\text{g/g}$ while AA ranged from 40.67 ± 6.79 to $72.55 \pm 4.03\%$. A regression analysis and principal component analysis (PCA) were used to identify the relationship among the factors (MPs, BPA, and AA). It is suggested that high levels of MPs and BPA negatively impacted vegetable quality as they are associated with environmental contamination. Contrastingly, AA had a significant positive correlation with vegetable quality. Both EDIs and HI of MPs and BPA were < 1 , indicating no significant risk associated with BPA exposure from their consumption.

Conclusion This study highlights the potential health risks of MPs and associated BPA contamination in vegetables. The estimated dietary intake and hazard index suggest no immediate health risks, but long-term exposure remains a concern. MPs and BPA in commonly consumed vegetables warrant stricter monitoring of agricultural soil and irrigation water sources. Microplastic exposure in food crops can be reduced with policies that regulate plastic waste disposal and promote sustainable farming practices.

Keywords Bisphenol A, Microplastics, Principal component analysis, Regression analysis, Vegetable quality

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1 Introduction

Over the past seven decades, plastics have found extensive applications in virtually everything that has strong bearings on human lives—food, pharmaceuticals, cosmetics, detergents, chemicals, medical devices, etc. This has made them an indispensable part of our lives and quite ubiquitous in the global economy [1–3]. At the beginning, plastics were valued for their durability and resistance to natural degradation, making them perfect for packaging, medical devices, and construction materials. Due to their widespread use, particularly in disposable products, rapid waste generation, and population growth, global plastic pollution has been rising for some time now [4, 5]. At present, about 140 million tonnes/year of plastic polymers are produced worldwide [6].

About 30% of such production are utilized for packaging application, with significant portion for food packaging [7]. Their high production volume, coupled with their non-susceptibility to natural degradation, makes them accumulate fast in the environment as waste [8]. Thus, plastic pollution is pervasive across all environmental spheres—hydrosphere, lithosphere, atmosphere, and biosphere—contributing to biodiversity loss and ecosystem disruption [9, 10].

The widespread use of thermoplastics, such as low-density and high-density polyethylene (LDPE and HDPE), polyethylene terephthalate (PET), polyvinyl chloride (PVC), and polypropylene, raises concerns about the migration of microplastics and harmful plastic additives into food [5, 11, 12].

Approximately 40% of plastic waste pollution in the environment comes from packaging made of single-use plastics [13, 14], many of which are not recyclable primarily due to their polymeric chain complexity [15, 16]. Small packaging often escapes waste collection, while multi-layer plastic materials complicate recycling processes, increasing litter and incineration [17]. Despite increasing efforts to reduce plastic waste by disposing them off through segregated collection and recycling, a sizeable amount (about 60% of yearly production) is being left in the environment, with 95% of this in landfills/dump sites and 5% in the oceans and other terrestrial areas [18, 19]. However, with the passage of time, plastics debris in the environment is degraded in nature by photo-, bio-, and thermo-oxidative depolymerization, and friction to produce micro and nano plastics [20]. The threat of microplastics (MPs) to the environment and human health has grown significantly. Recent findings indicate that MPs are particularly prevalent in bottled water, aquatic organisms, salt, sugar, and vegetables [8, 19, 21].

In the ecological spheres, MPs are emerging pollutants that plant roots absorb and translocate to shoots with eventual bioaccumulation affecting different plant parts [8, 20]. Plant structures are known to be compromised by MPs that result in the decline of their integrity [19, 22]. The previous studies have documented MP abundance in some vegetables and fruits including onions, lettuce, apples, tomatoes, broccoli, and cucumbers [3, 5, 19]. Agricultural soils and products are significant repositories for various pollutants, including MPs [22] with plastic mulching materials such as polyethylene and polypropylene being the substantial sources of MP in agricultural soil environments [23]. Due to MPs'ability to penetrate plant tissues and potentially affect growth and nutritional composition, understanding their impact on food safety and human health is essential [3]. However, studies on the accumulation of MPs and their effects on edible plants remain largely limited, and this is crucial to assessing their impacts on the food safety [5]. The previous studies have demonstrated that MPs alter soil properties and microbial activities, disrupt nutrient balance, and reduce soil organic carbon, significantly affecting crop growth and quality [12, 24].

Exposure to MPs in food, mainly from contaminated fish, crustaceans, vegetables, tea bags, chicken, salt, sugar, and fruits, poses a huge and potentially severe health risk to man [16, 17]. Trace levels of MPs have been found in human blood, breast milk, and other human biological tissues and fluids. There have been reports of respiratory and digestive issues, hormonal imbalances [3, 21]. As MPs pollution becomes increasingly recognized as a threat to human safety and environmental health in general, this underscores the need to establish the nexus between MP abundance on health-promoting attributes of vegetables [25, 26]. Furthermore, the consequences on human health can be profound when edible vegetables and foods containing these MPs alongside other chemical additives are consumed [8, 27, 28].

Numerous chemical additives used in plastic production, particularly those meant for food packaging, interfere with the hormonal systems of humans and animals [28, 29]. These oestrogen-like additives such as phthalates and bisphenols have been found to widely accessible and leach gratuitously from plastics into food items [20, 30, 31].

Among the notable bisphenols is bisphenol A (–4,4'–(propane-2,2-diyl) diphenol)), commonly abbreviated as BPA. It is a synthetic compound commonly used as a structural component of polycarbonate plastics, epoxy resins, and other food storage containers [26, 32, 33]. Food and water can be contaminated by BPA when it leaches from can linings and bottles. Globally, BPA has been found in low levels

in environmental samples, posing a risk to marine life and humans who consume contaminated seafood [31, 34]. Consequently, BPA has been listed as a substance of very high concern, because of its endocrine-disrupting properties and several possible exposure pathways for humans [29, 33].

Green vegetables such as spinach, green amaranth, and jute mallow are cultivated for their nutritional value, bioactive compounds, affordability, widespread consumption, and culinary versatility. They possess anti-inflammatory and anti-cancer properties due to their high antioxidant activity [37]. Vegetables like these are traditional staples of everyday meals, particularly among the general population. According to some studies, Nigerians consume affordable green vegetables daily [36]. The three vegetables selected represent the most commonly consumed vegetable varieties sold in local markets across Nigeria. Nonetheless, their cultivation on contaminated soil, fragile shoots, and susceptibility to biotic and abiotic stressors can severely limit their availability and quality.

From all the foregoing, there is a growing concern regarding MPs and BPA contamination of agricultural soils and its implications for human health and ecological integrity has led this research to attempt to bridge an existing knowledge gap by combining these parameters in a single study. There have been several studies independently reporting MP levels, BPA content, and antioxidant activity in leafy vegetables, but few have analysed these factors collectively [33, 35, 37, 41]. Hence, this study offers a more comprehensive understanding of how environmental contamination, vegetable quality, and potential health risks interact by evaluating the nexus between them in three commonly consumed vegetables: green amaranth, jute mallow, and spinach. The study is also unique in comparing vegetable samples from two major market sources (Shasha and Oja-Oba) in Osogbo metropolis, Osun State's Capital. These markets were chosen because of their high consumer traffic and accessibility to residents and tourists particularly during Osun-Osogbo festival; a world heritage event where tourists/Osun adherents from all over the globe gather annually. The Shasha market caters primarily for local traders and farmers, while the Oja-Oba Market is a hub for various buyers, tourists, travellers, and sellers. The markets selected were chosen to capture variation in contamination levels influenced by sourcing patterns, handling practices, and environmental factors. This strategic choice enhances the relevance of the study for assessing vegetable consumption-related health risks. The impact of regional agricultural practices and environmental conditions on the scavenging capacity of vegetables against free radicals as a result

of MP abundance and associated chemical additives on vegetables' potency would be demonstrated using regression and principal components analysis.

Thus, this study examined the relationship between microplastic (MP) levels, bisphenol A content, and antioxidant activities in relation to vegetable quality and the health risks associated with their consumption.

2 Materials and methods

2.1 Collection of samples

Eighteen vegetable samples belonging to three species were purchased from two major markets—Shasha and Oja-Oba markets, Osogbo, Osun State. They were *Corchorus olitorius* (jute mallow), *Amaranthus viridis* (green amaranth), and *Spinacia oleracea* (spinach). These markets were chosen because of their high consumer traffic and accessibility to residents and tourists particularly during Osun-Osogbo festival; a world heritage centre where tourists/adherents from all over gather annually. The Shasha market caters primarily for local traders and farmers, while the Oja-Oba Market is a hub for various buyers, tourists, travellers, and sellers. The markets selected were chosen to capture variation in contamination levels influenced by sourcing patterns, handling practices, and environmental factors. The samples were wrapped in aluminium foil paper to avoid contamination and kept frozen until further use. The samples were separated into roots and shoots, labelled, and divided into three portions: one for microplastics analysis, one for antioxidant activity determination, and the last for BPA analysis. Afterwards, the portions for MPs and BPA were oven-dried at 50 °C to complete dryness, while the portion for antioxidant activity assay was dried at 105 °C for 3 h.

2.2 Digestion of samples and quantification of MP abundance

Quantification of MPs in shoots and roots of the six vegetables was done by digesting 2 g of each sample with 10 mL of 30% hydrogen peroxide (H_2O_2) for the removal of organics fully covered with aluminium paper foil, followed by agitation on UNISCOPE shaker (SM101; Surgifriend Medicals, England) at 300 rpm and 27 °C for 4 days. This was subsequently vacuum filtered using 0.45 µm filter paper and thereafter dried at 50 °C. Afterwards, 10 mL each of 0.1 M $ZnCl_2$ and 5 M NaCl were used for the removal of inorganics and density separation, respectively. The solutions were agitated, left for 4 days, vacuum filtered, and placed in glass Petri dishes for drying at 50 °C. Microplastic abundance, colours, and shapes were analysed using a Biobase microscope DM-125 + MD101 microscope (China) equipped with a digital camera and a 40 × magnification. The polymeric chains of MPs in the samples were analysed using a

Fourier Transform Infrared spectrometer (SHIMADZU, FTIR 8400S) for functional groups identification and characteristics by scanning from 400 to 4000 cm^{-1} .

2.3 Extraction and HPLC analysis of BPA

Exactly 2 g of each sample (shoots and roots) was extracted with 20 mL of 60% ethanol with vigorous stirring for 10 min. The extraction was further enhanced by placing the mixture in an ultrasonic bath at 50 °C for 30 min. This was allowed to cool after which it was dried using anhydrous sodium sulphate, evaporated to dryness under a nitrogen gas stream, and then reconstituted to 1 mL with methanol. Each extract was further filtered with a 0.22 μm filter paper. This filtration procedure after reconstitution was necessary to remove all insoluble components which may constitutes impurities for HPLC analysis.

The samples were later analysed with an Agilent HPLC 1100 Series (Agilent, Germany) equipped with a UV/VIS detector, and a Water Scientific XBridge C_{18} column (length, 150 mm; inner diameter, 4.6 mm; particle size 3.5 μm ; Waters Scientific). An isocratic eluent 40/60 v/v ultra-pure water/methanol solution was applied at a flow rate of 1.0 mL min^{-1} —The UV detection was obtained at 230 nm. Quantification was based on extrapolation of a seven-point calibration curve covering a concentration range of 5–100 $\mu\text{g/mL}$, with a coefficient of determination (R^2) 0.999 and a limit of detection of 0.0012 mg/L . The values obtained in $\mu\text{g/L}$ were then converted to $\mu\text{g/g}$ using Eq. 1.

$$BPA(\mu\text{g/g}) = \frac{BPA(\mu\text{g/mL}) \times \text{volume of extract (1 mL)}}{\text{weight of sample (2g)}} \quad (1)$$

2.4 Extraction and determination of antioxidant activity

As previously described by Azeez et al. [35], 2 g of dried samples was extracted twice with 70% methanol. The extracts were then combined, filtered, and concentrated. The ability of the extract to scavenge free radicals by bleaching 2,2-diphenyl-1-picrylhydrazyl (DPPH) was measured at 517 nm and reported as the antioxidant activity of the samples.

2.5 Risk assessment of MPs and BPA in vegetables

The estimated dietary intakes (EDI) of MPs and BPA in vegetables were calculated using Eq. 2a and b as reported by [19] while their hazard risk indices (HI) were calculated using Eqs. 3 and 4, respectively, with a higher HI than 1 indicating greater threats [19, 31].

$$EDI(\text{mgkg}^{-1}\text{BWday}^{-1}) = \frac{C_M \times CR}{BW} \quad (2a)$$

$$EDI(\text{mgkg}^{-1}\text{BWday}^{-1}) = \frac{C_{BPA} \times CR}{BW} \quad (2b)$$

$$HI_{MPs} = \sum S_n \times P_n \quad (3)$$

$$HI(\text{mgkg}^{-1}\text{kg}^{-1}\text{BWday}^{-1}) = \frac{EDI}{R_f D} \quad (4)$$

where C_M represents the mean MP abundance/g in each vegetable, C_{BPA} represents BPA concentration in each vegetable, CR indicates the average daily consumption rate of each vegetable (0.17 $\text{kg person}^{-1} \text{day}^{-1}$ as reported by Chibuke et al. [36] and Adeyi and Babalola [25]), BW is the average body weight of Nigerians (60 kg, Azeez et al. [37]), and $R_f D$ of BPA is 4 $\mu\text{gkg}^{-1}\text{day}^{-1}$ [25, 32]. In each polymer comprising the MP, S_n represents the hazard score, and P_n represents the proportion of polymeric chains in the vegetables. As reported by Xu et al. [38] and Venkatesh et al. [17], the hazard scores of monomers of each polymer type are 11, 1, 10,551, 47, 30, and 1177 for ethylene, propylene, vinyl chloride, adipic acid, styrene, and bisphenol A in PE, PP, PVC, PA, PS, and PC, respectively.

2.6 Quality control

A random sampling was conducted at two markets in different locations, with three replications every market day. All containers used in the study were made of glass, and deionized distilled water was obtained from a glass distiller. For HPLC analysis, internal standards were run, and calibration curves were obtained.

2.7 Statistical analysis

Results are presented as the mean $\pm$ standard error of the mean (SEM) of five replicates. The variances among the various experimental groups were analysed using a Shapiro–Wilk normality test to verify the normal distribution of the data obtained from the experiment. An analysis of variance (one-way ANOVA) was conducted, followed by a Tukey's honest significance test (HSD) post hoc test at $p < 0.05$ to compare the means of different treatments using the IBM Statistical Package for the Social Sciences (SPSS) version 26. Using the same statistical tool, linear regression analysis and principal component analysis (PCA) were carried out to establish the relationship and/or inter-correlations among various factors (microplastic abundance, bisphenol A, and antioxidant activity) on vegetable quality.

3 Results and discussion

3.1 Microplastic abundance, shape, and colour in different vegetables

As shown in Fig. 1, the abundance of MPs with size $\leq 0.45 \mu\text{m}$ in the shoots of the three vegetable samples ranged from 4.00 ± 0.50 particles/g (spinach from Shasha) to 7.67 ± 1.04 particles/g (green amaranth from Shasha). For the roots, the MPs abundance ranged from 5.33 ± 1.53 particles/g (spinach from Shasha) to 18.00 ± 6.93 particles/g (green amaranth from Oja-Oba). These results show significant variations in the levels of MPs in samples across the two markets with green amaranth from both markets showing significantly higher total MPs abundance than other vegetables, although green amaranth from Shasha had slightly higher MPs. Jute mallow from both markets had significantly higher MPs compared to spinach. Jute mallow from Shasha contained significantly higher MPs than Oja-Oba's, while spinach from Oja-Oba had a considerably higher MP abundance compared to the one from Shasha. Generally, the roots of the vegetables have significantly higher MPs than the shoots, with the shoots and roots of green amaranth containing the highest MPs while shoots and roots of spinach contained the lowest MPs.

The vegetable samples considered in this study contained lower MPs than what Conti et al. [19] reported for carrots, broccoli, apples, and pears from Italy while they have comparable MP abundance with fruits and vegetables such as onion, pears, tomatoes, apples, potatoes, and cucumber reported by Aydin et al. [5] from Turkey, though with slightly higher values in this study. Moreover, Canha et al. [23] found similar MP levels in lettuce from Portugal compared to those reported in this study. Based on the results of this study, vegetables can be prone to MP accumulation and can become potential sources of MP to humans when consumed [5]. In addition, market sources can provide information on the agricultural practices employed by local farmers with respect to MP pollution and the level of pollution in the region [13, 24]. A higher MP abundance in the roots than in the shoots indicates soil contamination by MP or from wastewater-containing used for irrigation, since the roots absorb MP from the soil, which plants then translocate to the shoots [16, 22]. The previous studies have shown that roots in the subsoil would absorb more MP than soil roots [23]. This study reveals vegetable type, and market/soil sources can influence MP abundance in vegetables.

Three shapes of MPs were detected, namely fibre, fragment, and irregular (Figs. 2 and 3). Fragment dominated (62.38%) the shapes of MPs in the vegetables, while

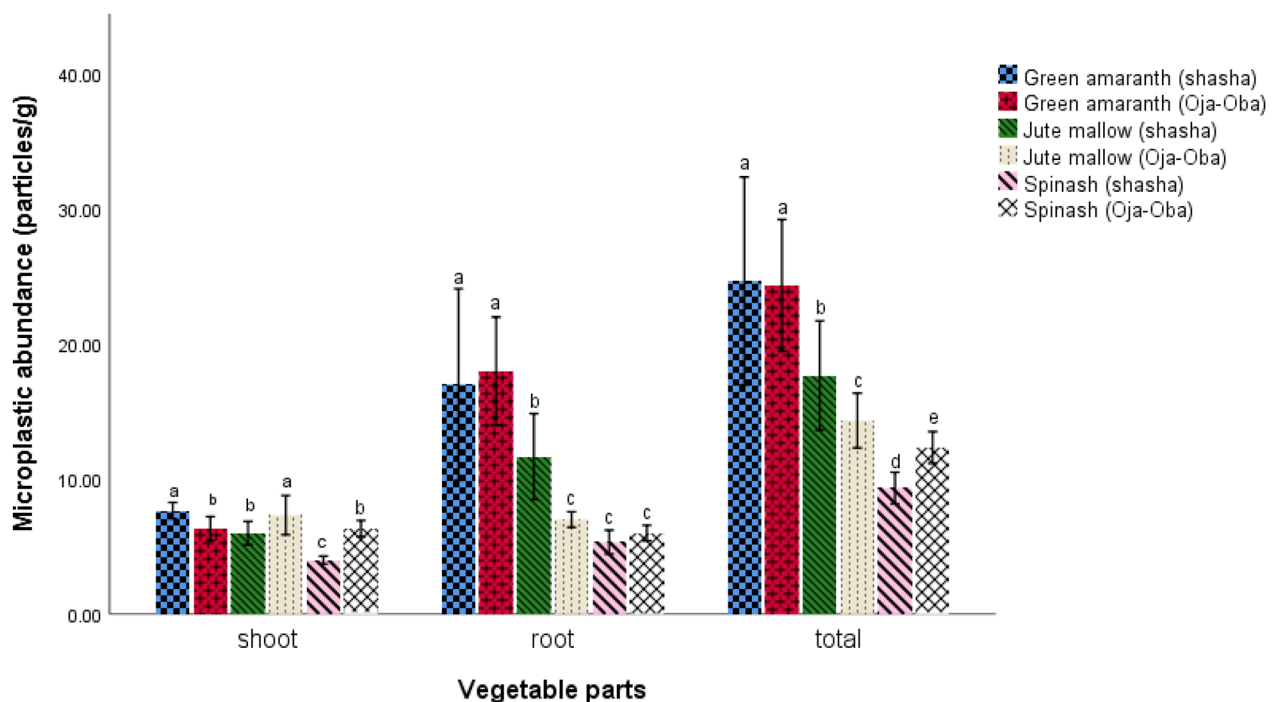


Fig. 1 Microplastic abundance in vegetable samples. Bars are presented as the mean $\pm$ standard error of the mean (SEM) of MP abundance in each vegetable. Bars with different superscripts for different plant parts are significantly different at $p < 0.05$

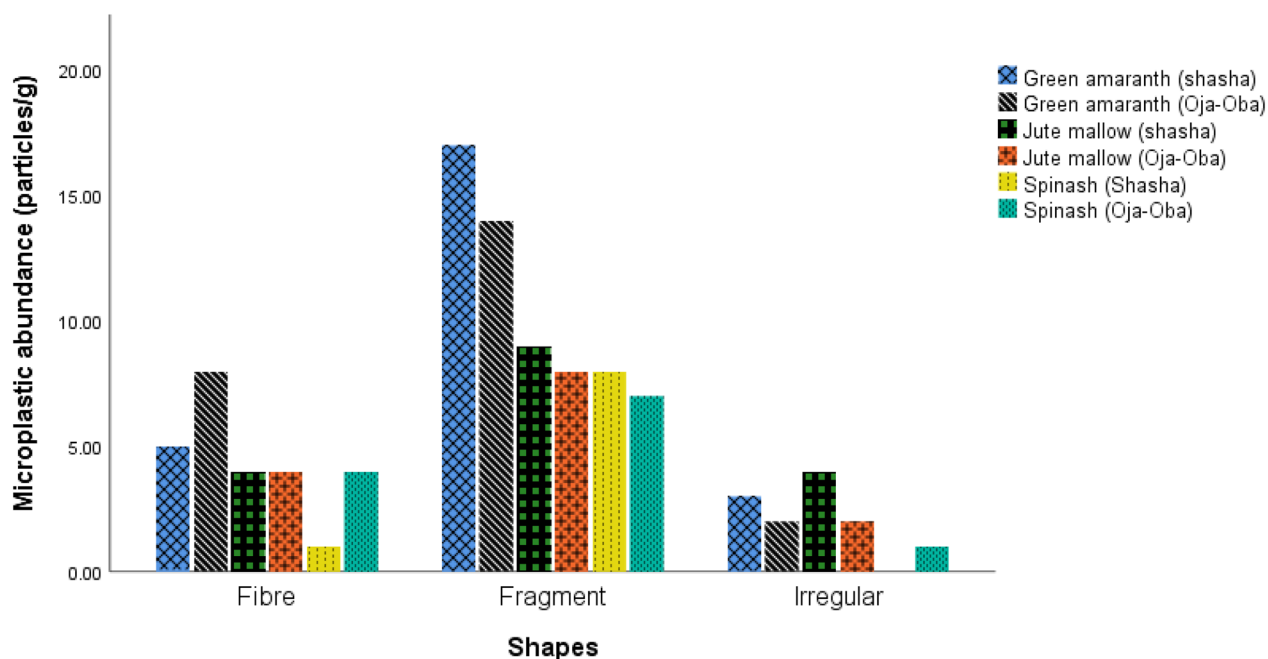


Fig. 2 Microplastic shape distribution in vegetable samples

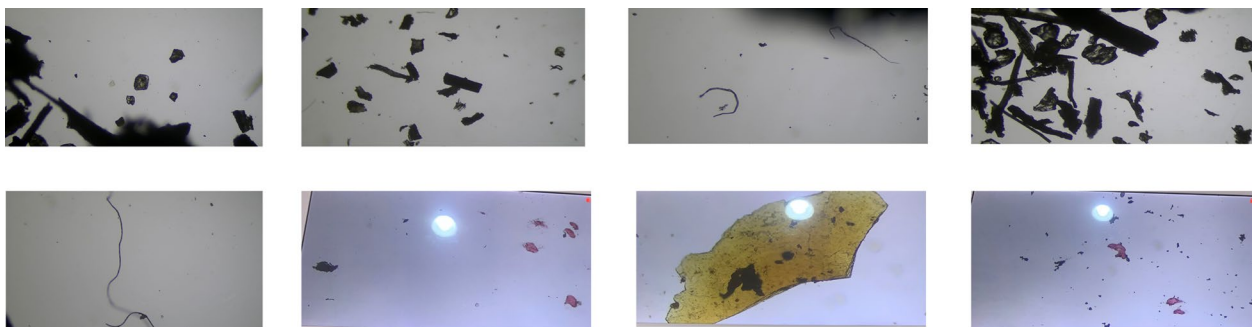


Fig. 3 Micrographs of shapes and colours observed in vegetable samples

fibres constituted 25.74% and irregular shapes constitute 11.88%. Green amaranth from Shasha had the highest fragment abundance, while green amaranth from Oja-Oba had the highest fibre abundance. Spinach from Shasha did not have any irregularly shaped MPs. In these vegetables, MPs appear in a variety of colours, from transparent to white, yellow, black, and brown, as well as varying in sizes. In Fig. 4, transparent MPs accounted for 46.53% of the abundance, while yellow (18.81%), white (11.88%), black (14.85%), and brown (7.92%) accounted for the least amount. The predominance of fragment shape and transparent colour highlights the type of plastic waste these vegetables were exposed to in the soil [17, 40] as the distribution patterns of shape and colour of MPs can be a useful indicator of their probable plastic

sources and the health risks associated with them [10, 14]. Typically, fragments are associated with degradation products of larger plastic wastes and can be harmful to humans when consumed due to their irregular shapes, which can cause lacerations in the digestive system [6, 14]. As a result of their ability to easily transport contaminants, fragments and irregular-shaped MPs can further increase the toxicity of MPs [2].

3.2 Identification of plastic monomers using functional groups

The FTIR spectra (Fig. 5) and peaks (Table 1) show the functional groups characteristic of polymeric chains corresponding to different polymers of plastics degraded to MPs, as previously documented by Parvin et al. [9],

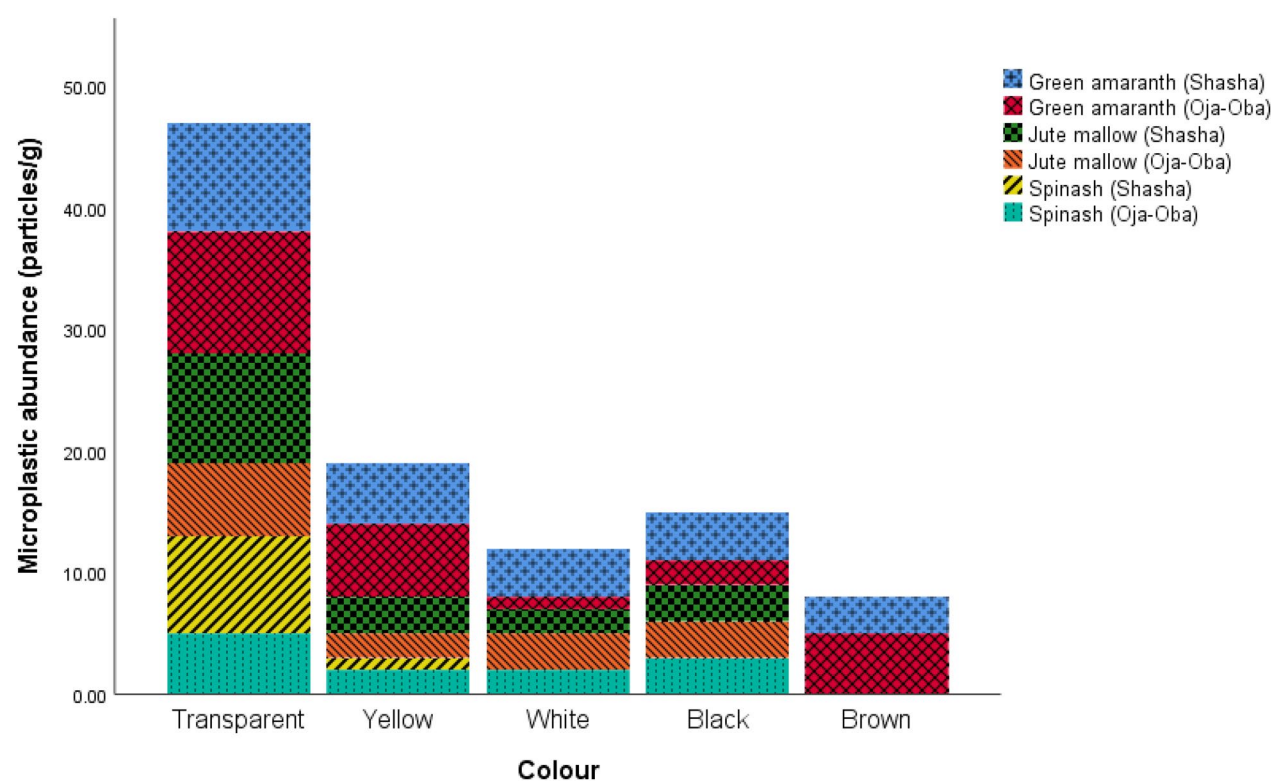


Fig. 4 Microplastic colour distribution in vegetable samples

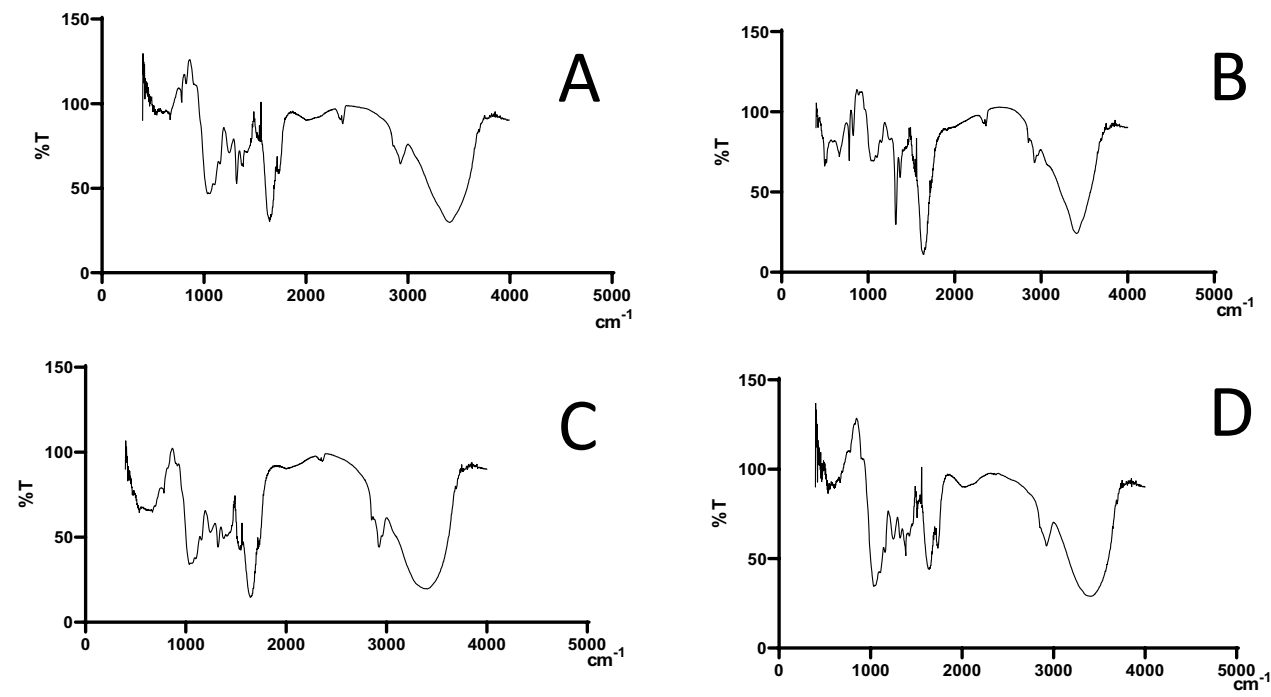


Fig. 5 FTIR spectra of microplastic particles found in vegetable samples

Table 1 Microplastic polymeric chain obtained in the vegetable samples and their characteristic FTIR peaks

S/N	Polymer type	FTIR peaks (cm ⁻¹)	Assignment	Vegetable sources
1	Polyethylene terephthalates (PET)	2920 1736 1107–1250 779–898	Aliphatic C–H stretch (CH ₃) C=O stretch C–O stretch Aromatic C–H bend	Spinach from both markets, green amaranth and jute mallow from Shasha
2	Polyethylene (PE—LDPE and HDPE)	2924 2851 1412 1377	Aliphatic C–H stretch (CH ₃) Aliphatic C–H stretch (CH ₂) Aliphatic C–H bend (CH ₂) Aliphatic C–H bend (CH ₃)	All vegetable samples
3	Polyvinyl chloride (PVC)	2928 613–898 1161–1323	Aliphatic C–H stretch (CH ₃) C–Cl stretch C–H (CH ₂) of halide	All vegetable samples
4	Polyamide (PA)—nylon	3410 2928 2850 1636 1037–1099 1246–1319	N–H stretch Aliphatic C–H stretch (CH ₃) Aliphatic C–H stretch (CH ₂) C=O stretch of amide C–N bend C–N bend	Spinach and green amaranth from both markets
5	Polypropylene (PP)	2920 1377–1427	Aliphatic C–H stretch (CH ₃) Aliphatic C–H stretch (CH ₂)	All vegetable samples
6	Polystyrene (PS)	3066 2920 1370 783	Aromatic C–H stretch Aliphatic C–H stretch (CH ₃) C–H bend C–H bend of phenyl	Spinach from both markets and green amaranth from Oja-Oba
7	Polycarbonate (PC)	3403 1736 1624 1107–1250 2920	OH stretch C=O stretch C=C stretch C–O stretch Aliphatic C–H stretch (CH ₃)	Jute mallow from Shasha

Moura et al. [20], Idowu et al. [14], and Venkatesh et al. [17]. Notably, polyethylene (PE that includes LDPE and HDPE), polyvinyl chloride (PVC), polypropylene (PP), polyethylene terephthalate (PET), polyamide (PA—nylon), polycarbonate, and polystyrene (PS) are the polymers extracted from the FTIR results. Generally, PE, PET, PP, and PVC are the most common MP polymers found in the vegetables (Table 1). The green amaranth from Shasha contained PE, PET, PVC, PA, and PP, while the green amaranth from Oja-Oba contained PS alongside all the above except PET. Spinach from both markets contained MP polymers similar to green amaranth from Oja-Oba. Jute mallow from Shasha contained PVC, PP, PE, PC, and PET, while the one from Oja-Oba contained all except PC and PET. For MP analysis, FTIR characterization is one of the mostly used techniques to reveal the functional groups that constitute the MP polymeric chains [17, 34]. This spectroscopic technique has previously been used to

identify MPs in sediments, water, air, and food samples [12, 14, 20]. A number of functional groups were identified, including those associated with polyethylene (PE), polyvinyl chloride (PVC), polypropylene (PP), polyethylene terephthalate (PET), polyamide (PA), and polystyrene (PS) polymeric chains which align with the previous studies on the prevalence of these plastic wastes in soil, water, sediment, and air [11, 15, 38, 40]. Since PET, PP, PE, and PVC are used for various purposes such as food packaging, wrappers, sachets, and bottles, they account for more than half of plastic pollution worldwide [14, 27, 30]. Additionally, this study agrees with earlier reports, emphasizing human exposure to MP through food items planted on MP-contaminated soil [3, 16].

3.3 Bisphenol A contents of vegetables

In terms of BPA levels, green amaranth from Shasha had the highest concentration at 6.65 ± 0.00 µg/g, while

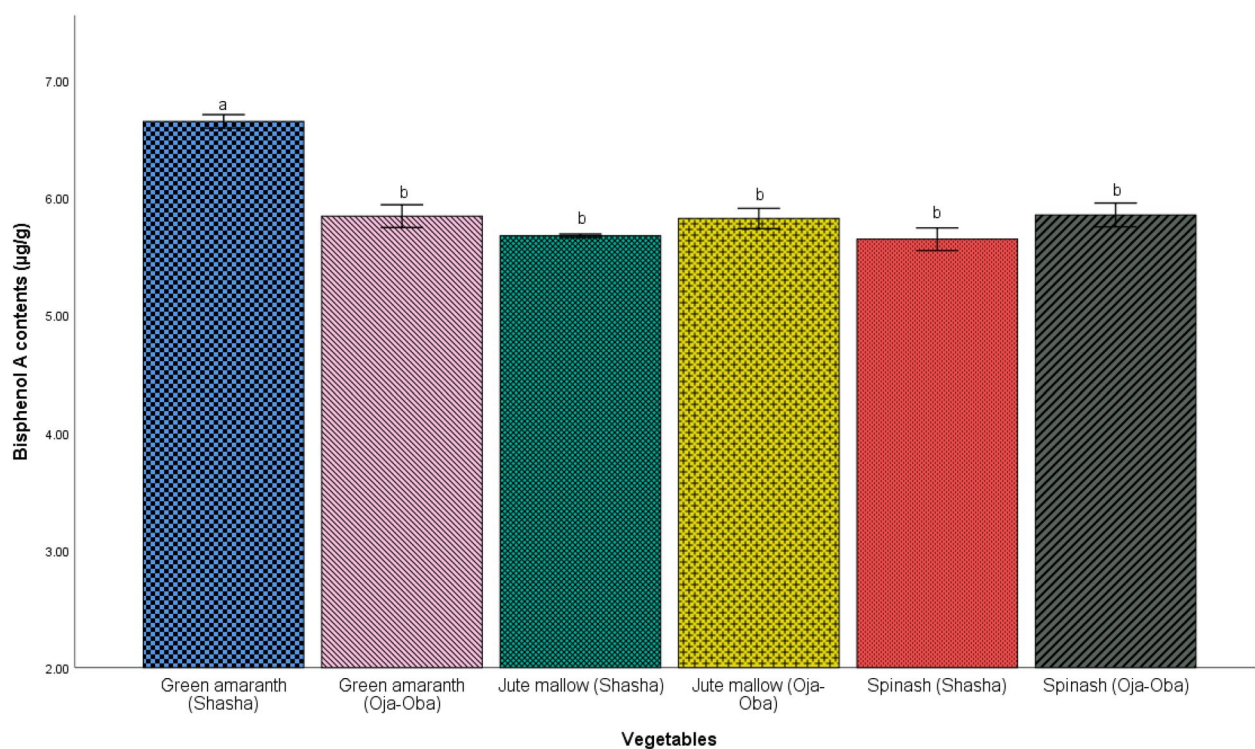


Fig. 6 Bisphenol A contents in vegetable samples. Bars are presented as the mean $\pm$ standard error of the mean (SEM) of BPA contents in each vegetable. Bars with different superscripts for different plant parts are significantly different at $p < 0.05$

spinach from Oja-Oba had the lowest at 5.55 ± 0.56 $\mu\text{g/g}$ (Fig. 6). These vegetables contained significantly higher BPA than the tolerable limit of 4 $\mu\text{g/g}$ [39] and were higher than some previous studies on apples, cucumber, tomatoes, and pears consumed by Nigerians [5, 19, 23]. Essentially, this indicates the pollution status of the soil on which the vegetables were grown [32, 34, 38]. The presence of BPA in edible vegetables may predispose consumers to non-carcinogenic illnesses due to its effects as an endocrine disruptor [25, 30, 41].

3.4 Antioxidant activities in vegetables

The antioxidant activities of the vegetable samples analysed (Fig. 7) differed significantly ($p < 0.05$) in terms of their ability to scavenge free radicals, with both types of green amaranth having the lowest activities, while spinach from Oja-Oba had the highest antioxidant activity, followed by jute mallow from Shasha. The values of antioxidant activities range from $40.67 \pm 6.79\%$ in green amaranth from Shasha to $72.55 \pm 4.03\%$ in spinach from Oja-Oba.

It appears that a higher content of BPA and MPs is associated with lower antioxidant activity in the selected vegetables, particularly green amaranth, since higher levels of these contaminants significantly ($p < 0.05$) decreased its antioxidant activity. It has been shown that

these contaminants can interfere with the vegetables natural antioxidant compounds, decreasing their capacity to combat free radicals, and ultimately diminishing their health benefits [35, 41]. Moreover, studies have confirmed that BPA and MPs accumulate in plant tissues, causing alteration of physiological processes involved in antioxidant compounds production, thereby further reducing their health-promoting benefits [31].

3.5 Influence of MP, BPA, and antioxidant activity on vegetable quality

An analysis of regression revealed the nexus between contaminants (MP and BPA) and health-promoting ability (antioxidant activity) on the quality of vegetables used in this study. There is a strong correlation between the dependent variable (vegetables: green amaranth, jute mallow, and spinach) and independent variable (MPs, BPA, and antioxidant activity) (Table 2b: supplementary document). This model provides a statistically significant explanation of substantial portions of the data of dependent variables based on independent variables by accounting for 77.1% variability (Table 2).

A statistically significant negative correlation was found between vegetable quality and MP abundance ($r = -0.647$, $p = 0.02$) and bisphenol A ($r = -0.604$, $p = 0.04$) (Table 3). This suggests that an increase in either or both

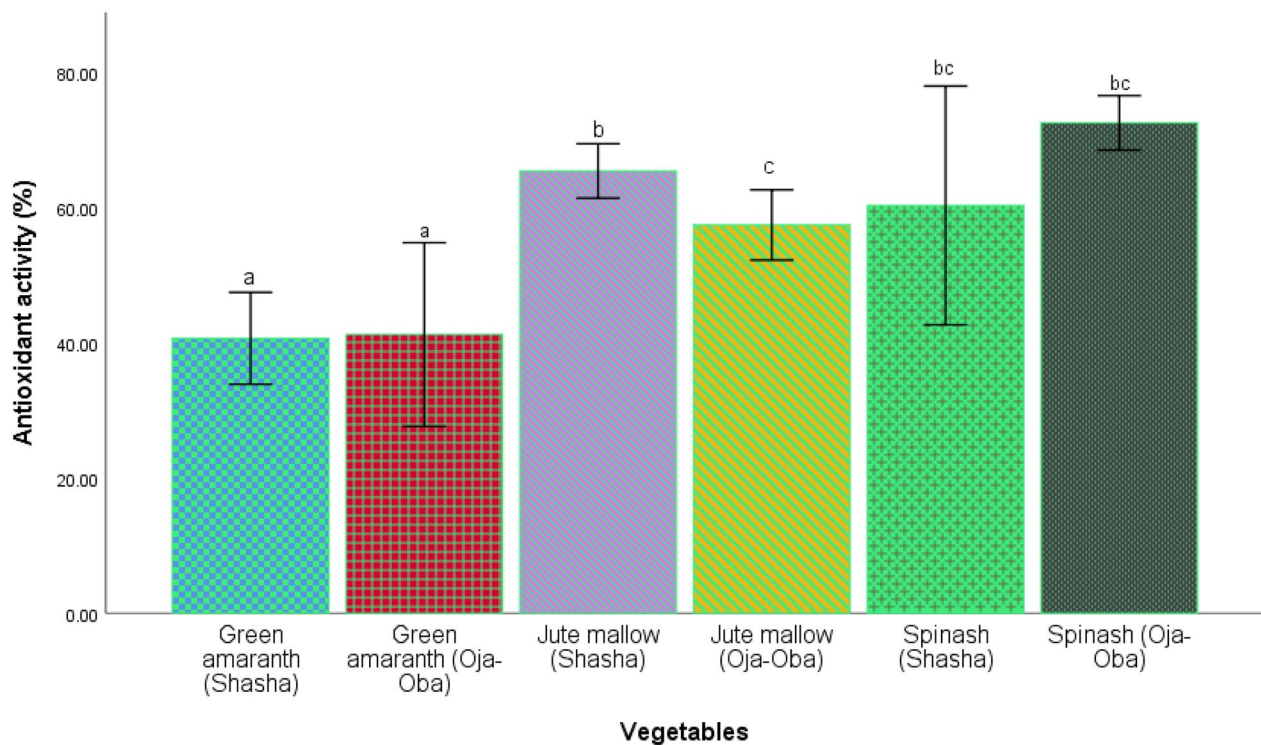


Fig. 7 Antioxidant activities of different vegetable samples. Bars are presented as the mean $\pm$ standard error of the mean (SEM) of antioxidant activity of each vegetable. Bars with different superscripts for different plant parts are significantly different at $p < 0.05$

Table 2 Regression analysis Model Summary^b

Model	R	R square	Adjusted R square	Std. error of the estimate	Durbin-Watson
1	0.878 ^a	0.771	0.722	0.926	1.237

a. Predictors: (Constant), antioxidant, microplastics and bisphenol A

b. Dependent variable: vegetables

indicates a decrease in vegetable quality. Additionally, in Table 2d (supplementary document), every increase in MP and BPA will result in decrease in vegetable quality by 0.109 and 1.164 units, respectively, with a beta (β)

value of -0.528 , indicating that MP negatively impacts vegetable quality.

An increase in antioxidant activity favours vegetable quality, as indicated by the positive statistically significant correlation between vegetable quality and antioxidant activity ($r = 0.552$, $p = 0.09$). Furthermore, vegetable quality will improve for every increase in antioxidant activity by 0.047 units with a beta (β) of 0.512, suggesting a strong positive effect on vegetable quality (Table@ 2d: supplementary document).

Microplastic abundance and bisphenol A levels ($r = 0.505$, $p = 0.16$) display a moderate statistically positive

Table 3 Correlation matrix for different factors on selected vegetables

		Vegetables	Microplastics	Bisphenol A	Antioxidant activity
Pearson correlation	Vegetables	1.000	-0.647	-0.604	0.552
	Microplastics	-0.647	1.000	0.505	0.008
	Bisphenol A	-0.604	0.505	1.000	-0.184
	Antioxidant activity	0.552	0.008	-0.184	1.000
Sig. (one-tailed)	Vegetables		0.002	0.004	0.009
	Microplastics	0.002		0.016	0.487
	Bisphenol A	0.004	0.016		0.233
	Antioxidant activity	0.009	0.487	0.233	

correlation, suggesting a nexus between them with an increase in MPs possibly resulting in a rise in BPA contents along with reduced vegetable quality (Table 3). In the selected vegetables, MP abundance may not have a significant impact on antioxidant activity, but the negative correlation between BPA and antioxidant activity ($r = -0.184$, $p = 0.233$) indicates that a higher BPA content will decrease antioxidant activity (Table 3).

Based on the regression analysis of data in this study, it was found that MP negatively affected vegetable quality statistically, suggesting health concerns associated with MP exposure [17]. Furthermore, given the moderate correlation between MPs and BPA, environmental processes that increase one may also increase the other, which may have implications for human health and food safety [28]. Conversely, antioxidant activity appears to increase vegetable quality, demonstrating the importance of antioxidants in diets.

To further affirm the influence of these factors on vegetable quality, factor analysis using principal component analysis (PCA) was employed. The results revealed strong loadings of vegetable, antioxidant activity, and MP abundance in the PCA communalities (Table@ 3a: supplementary document), while moderate loading was recorded for BPA. Components 1 and 2 with eigenvalues of ≥ 1 describe the inter-associations between various factors and vegetable quality, explaining 51.05 and 33.26% of variances, respectively, with overall variance described by 84.30% (Table 4). These findings underscore the importance of these factors on vegetable quality. Moreover, the dominance of component 1 may describe the key factors affecting vegetable quality [11]. In component 1, MP abundance (0.906) and BPA (0.800) strongly correlate with a significant decrease in vegetable quality (-0.761) (Table 5). Based on these components, MP and BPA could share similar sources of contamination and indicate environmental pollution, affecting vegetable quality [38]. In component 2, vegetable quality (0.568) correlates positively and significantly with antioxidant activity (0.984), with a non-significant contribution from BPA (-0.172). This further explains that MP and BPA are associated with environmental contamination, causing

Table 5 Rotated component matrix^a

	Component	
	1	2
Microplastics	0.906	
Bisphenol A	0.800	–
		0.172
Vegetables	– 0.761	0.568
Antioxidant activity		0.984

Extraction method: principal component analysis. Rotation method: Varimax with Kaiser normalization

^a Rotation converged in three iterations

a decrease in vegetable quality. In contrast, antioxidant activity is associated with healthful dietary consideration when vegetable quality is needed. These key points provide a clear understanding of the factors affecting vegetable quality.

3.6 Risk assessment of MPs and BPA in vegetables

In the selected vegetables, the values of EDI of MPs range between $2.64\text{E-}02$ (particles/g.kg.BW) for spinach from Shasha and $6.99\text{E-}02$ (particles/g.kg.BW) for green amaranth from Shasha (Table 6). A similar assessment of BPA from Shasha shows that the EDI ranged between $1.60\text{E-}02$ ($\mu\text{g/g.kg.BW}$) for spinach and $1.88\text{E-}02$ ($\mu\text{g/g.kg.BW}$) for green amaranth (Table 4). The HI for MPs ranged from 10,610 in green amaranth from Oja-Oba to 11,740 in jute mallow from Shasha, while for BPA, it ranged from $4.00\text{E-}02$ in spinach from Shasha to $4.71\text{E-}02$ in green amaranth from Shasha (Table 6). From the findings, continued consumption of MP-containing vegetables, particularly jute mallow, may cause non-carcinogenic illnesses or induce allergic reactions as presented in the risk categories reported by Xu et al. [38], Yuan et al. [34], and Nyaga et al. [12]. The major threat to the consumption of vegetables comes from polycarbonate (PC)-containing BPA (monomer) content in jute mallow, since the higher the values of HI, the greater the non-carcinogenic threats [17]. In addition, HI for BPA in green amaranth from Shasha presents the highest value, suggesting

Table 4 Total variance explained

Component	Initial eigenvalues	Extraction sums of squared loadings					Rotation sums of squared loadings		
		Total	% of variance	Cumulative %	Total	% of variance	Cumulative %	Total	% of variance
1	2.321	58.029	58.029	2.321	58.029	58.029	2.042	51.049	51.049
2	1.051	26.275	84.304	1.051	26.275	84.304	1.330	33.255	84.304
3	0.493	12.322	96.626						
4	0.135	3.374	100.000						

Extraction method: principal component analysis

Table 6 EDI and HI of MPs and BPA in vegetables

S/N	Vegetable	EDI (mgkg ⁻¹ BWday ⁻¹)	HI		
		MPs	BPA	MPs	BPA (mgkg ⁻¹ kg ⁻¹ BWday ⁻¹)
1	Green amaranth (Shasha)	6.99E-02	1.88E-02	10,640	4.71E-03
2	Green amaranth (Oja-Oba)	6.89E-02	1.66E-02	10,610	4.14E-03
3	Jute mallow (Shasha)	5.01E-02	1.61E-02	11,740	4.02E-03
4	Jute mallow (Oja-Oba)	4.06E-02	1.65E-02	10,563	4.12E-03
5	Spinach (Shasha)	2.64E-02	1.60E-02	10,640	4.00E-03
6	Spinach (Oja-Oba)	3.49E-02	1.66E-02	10,640	4.15E-03

EDI: estimated dietary intake, HI: hazard index, MPs: microplastics, and BPA: bisphenol A

that it is the least health-promoting edible with respect to BPA. The values of BPA in vegetables in this study are higher than those reported for tomatoes by Adeyi and Babalola [25] and Parvin et al. [9].

4 Conclusion

This study highlights the implications of plastic pollution, particularly MPs and toxic plastic additives like bisphenol A (BPA), on vegetable quality. The results in this study show the abundance of MPs in shoots and roots, with roots having a greater abundance indicative of subsoil contamination with plastic particles. The predominance of fragments and transparent MPs provides insights into the probable sources of MPs which is the degradation of larger plastic particles that have undergone a series of reactions. The FTIR spectroscopic technique revealed the dominance of six types of plastics: polyethylene, polypropylene, polyethylene terephthalate, polyamide, and polyvinyl chloride. The study also illustrates a clear negative relationship between MP abundance, BPA content, and vegetable quality, as regression analysis indicates that environmental pollutants compromised the health benefits typically associated with these vegetables. In contrast, antioxidant activity positively correlated with vegetable quality, emphasizing its potential protective role against the adverse effects of these contaminants.

Despite the detectable levels of MPs and BPA, the estimated dietary intakes (EDIs) and hazard indices (HIs) were below 1, indicating no immediate health risks associated with their consumption. However, the long-term implications of chronic exposure to these pollutants due to their hormone-disrupting activities are cause for concern.

Abbreviations

- AA Antioxidant activity
- BPA Bisphenol A
- DPPH 2,2-Diphenyl-1-picrylhydrazyl
- EDI Estimated dietary intake
- FTIR Fourier transform infrared
- HDPE High-density polyethylene
- HI Hazard index
- HPLC High-performance liquid chromatography

- LDPE Low-density polyethylene
- MP Microplastics
- PA Polyamide
- PCA Principal component analysis
- PET Polyethylene terephthalate
- PP Polypropylene
- PS Polystyrene
- PVC Polyvinyl chloride

Supplementary Information

The online version contains supplementary material available at <https://doi.org/10.1186/s43088-025-00627-9>.

Additional file 1.

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Author contributions

Luqmon Azeez helped in conceptualization, methodology, supervision, and validation. Adetoro Rasheed helped in data curation. Babatunde K. Agbaogun helped in formal analysis, manuscript editing, and interpretation. Hassan K. Busari helped in data curation. Abdulrasaq O. Oyedepi helped in data analysis and manuscript editing. Abayomi A. Oladejo helped in data curation. Oyeyinka K. Oyelami helped in data curation and validation. Osilaja Deborah worked in investigation. Ruqoyyah D. Oladejil helped in data analysis and manuscript editing. Saheed Basiru helped in data curation. Shakirat Muhammad-Lawal helped in experimental analysis. Aisha Hammed helped in data curation and Abdulrahman O. Makanjuola helped in methodology.

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Declarations

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Consent for publication

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Competing interests

The authors declare no competing interests.

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