Use of the Physiologically Based Extraction Test for the Assessment of Bioaccessibility of Toxic Metals in Vegetables Grown on Contaminated Soils

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Introduction

In recent years, the attention of researchers has focused on the bioaccumulation of potentially toxic metals due to increasing human activities resulting in extensive contamination of urban surface soils worldwide. These metals present significant risks to human health if ingested indirectly through inadvertent ingestion of soil (especially the hand to mouth behavior of children) or transferred through the food chain by consumption of vegetables grown on these soils.

Background. An important concern for human health is the uptake of toxic metals by vegetables from soils and their consumption by humans.

Objectives. To assess the oral bioaccessibility of metals in vegetables (spinach, pumpkin, celery, okro leaves and waterleaf) grown on contaminated soils collected from five different sites in Lagos, Nigeria.

Methods. The soil and vegetables were acid digested and the total metal concentrations (copper (Cu), cadmium (Cd), chromium (Cr), lead (Pb) and zinc (Zn)) were determined using a flame atomic absorption spectrophotometer. A bioaccessibility study of the edible parts of the vegetables was estimated using the modified in vitro physiologically based extraction test (PBET).

Results. The results for total concentration showed that individual vegetable types differed in their levels of metal uptake. The values were in the range of 0.5-13.5 mg/kg for Cd, 2.0-221 mg/kg for Cu, 2.5-37.7 mg/kg for Cr, 10-250 mg/kg for Zn. Pb was below the detection limit. The transfer factor from soil to vegetable followed the order of Cd > Zn > Cu > Cr > Pb.

Discussion. For the PBET study, metals were solubilized mostly in the gastric phase, and the results varied in the range of 0.4-114.4 mg/kg for Cu, 0.1-2.4 mg/kg for Cd, and 0.8-137 mg/kg for Zn, but there was little or no bioaccessibility in the intestinal phase. Cr and Pb were non-detectable in either the gastric or intestinal phase.

Conclusions. Although the level of metals (Cd, Cu and Zn) available for absorption in the gastric phase were found to be low in most of the vegetables studied, the experiment revealed that metals are likely released in the human gut after intake of vegetables grown on contaminated soil.

Competing Interests. The authors declare no competing financial interests.

Keywords. bioaccessibility, heavy metals, PBET, physiologically based extraction test, urban soil, vegetables

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digression of gastric and intestinal phases, each one carried out using simulated human conditions such as pH, enzymes and temperature. The PBET uses a two-stage enzymolysis procedure to assess the in vitro potential for metals to be released in the human gut and hence be absorbed into the blood stream and transported through the body to vital organs.

Research has been carried out on the total concentration of potentially toxic metals in both soils and vegetables, but little research has been done or published on the assessment of the environmental health risks to humans from ingestion of soil or vegetables, and most specifically, the oral bioaccessible fraction in developing countries such as Nigeria and other African countries. Therefore, research of this nature is needed. The aim of the present research is to determine the oral bioaccessibility of potentially toxic metals in edible parts of vegetables grown on contaminated soils using the physiologically based extraction test.

### Methods

#### Instruments and Reagents

The analysis of the total and bioaccessible concentrations of soils and vegetable extracts was carried out using a flame atomic absorption spectrophotometer (Perkin-Elmer AA Analyst 200) with air-acetylene flame. Measurements were made under optimized operating conditions of the flame atomic absorption spectrophotometer (FAAS). The working standard solutions for the calibration of the FAAS were prepared daily from stock solutions (1,000 μg/mL) with distilled water used for dilutions. All glassware used were soaked in 5% nitric acid (HNO₃) overnight and rinsed with distilled water before use. The reference material was an urban soil secondary reference material from Glasgow, Scotland prepared by participants in the European Union urban soil project for quality control in a different project. The analysis was carried out in triplicate.

### Table 1 — Results of Physicochemical Parameters and Total Metal Concentration of Soils Used for Planting

| Soil | pH | Organic Matter % | Pb mg/kg | Cu mg/kg | Cr mg/kg | Zn mg/kg | Cd mg/kg |
|------|----|------------------|----------|----------|----------|----------|----------|
| A    | 6.56 | 2.7              | 68.1±2.0 | 85.1±8.4 | 151±8.0  | 181±5.2  | 0.98±0.2 |
| B    | 6.81 | 1.2              | 64.8±5.2 | 1180±64  | 5150±112 | 726±32   | 1.96±0.4 |
| C    | 7.14 | 4.2              | 3760±80  | 9950±111 | 682±12   | 1590±34  | 20.2±1.4 |
| D    | 6.65 | 5.4              | 3540±102 | 9450±135 | 810±58   | 1130±22  | 5.9±0.7  |
| E    | 7.27 | 3.8              | 411±20   | 1410±72  | 235±8.2  | 1280±20  | 3.42±0.4 |

**Reference Material**

|                | Target Value | Found Value   |
|----------------|--------------|---------------|
| pH             | 4.2          | 4.1           |
| Organic Matter %| 11.7         | 11.2          |
| Pb mg/kg       | 387±14       | 280±18        |
| Cu mg/kg       | 111±5.0      | 97.8±5.2      |
| Cr mg/kg       | 43.2±3.0     | 40.5±3.3      |
| Zn mg/kg       | 177±11       | 182±10.8      |
| Cd mg/kg       | 5.7±2.0      | 6.0±2.4       |

### Abbreviations

- **Cd**: Cadmium
- **Cr**: Chromium
- **Cu**: Copper
- **HNO₃**: Nitric acid
- **Pb**: Lead
- **PBET**: Physiologically based extraction test
- **TF**: Transfer factor
- **Zn**: Zinc
Soil Sample Preparation and Digestion
Soil samples were collected from five contaminated sites in Lagos, Nigeria. Soil A was collected from a mechanical workshop dump site, Soil B from a dump site where welding, smelting of metals and sale of metal rods is conducted, Sample C from a massive dump site where electronic wastes, metal scraps and other refuse are dumped, Sample D from a metal scrap market dump site at the University of Lagos, and Sample E came from a dump site across from the Faculty of Social Sciences, University of Lagos, Nigeria. Sub samples of soils were taken, passed through a 2 mm stainless steel sieve (Endecott sieve), air dried and stored for analysis. The remainder of the soils were used for planting vegetables which were harvested after 8 weeks. The pH of the soils in calcium chloride was determined according to British Standard ISO 10390, using a Mettler Toledo pH meter and the organic matter content was estimated by the Walkley and Black method.\textsuperscript{15,16} The pseudo-total metal concentration was determined by digesting with aqua regia (3 hydrochloric acid: 1 HNO\textsubscript{3}) on a hot plate. One gram of the soil was digested with 20 ml aqua regia for 2 hours. After cooling, the digests were filtered into 50 ml flasks and stored in plastic bottles prior to analysis.

Planted Vegetables
Seeds of tropical vegetables–waterleaf (\textit{talinum triangulare}), spinach (\textit{basella alba}), pumpkin (\textit{telfairia occidentalis}), okro (\textit{abelmolschus esculentus}) and celosia (\textit{celosia argentea}) obtained from the National Horticultural Research Institute, Ibadan, Nigeria were pre-germinated in a nursery and the seedlings were transplanted after two weeks into individual plastic pots containing contaminated soil samples at the greenhouse of the botanical garden of the University of Lagos, Nigeria. Approximately 8 weeks after planting with periodic watering and monitoring, mature vegetables were harvested, rinsed with tap water followed by distilled water to wash off soil particles, then taken to the laboratory to be oven dried at 60 ± 2°C for 48 hours, pulverized and stored in a refrigerator for further analysis.

Plant Digestion
One g of each portion of vegetable leaves was weighed and digested with 10 ml of concentrated nitric acid. The digestion was carried out for 2 hours, after which it was allowed to evaporate to near dryness. The residue was then taken up to 25 ml with 1 m HNO\textsubscript{3} and allowed to cool. After cooling, the sample was filtered with Whatman filter paper (11 cm) into a 25 ml volumetric flask and brought to volume.

Table 2 — Soil to Plant Transfer Factor

| Soil   | Soil A | Soil B | Soil C | Soil D | Soil E |
|--------|--------|--------|--------|--------|--------|
| Cd     | 0.67   | 0.21   | 0.21   | 0.21   | 0.01   |
| Celosia|        |        |        |        |        |
| Okro   | 0.00   | 0.00   | 0.03   | 0.03   | 0.00   |
| Pumpkin| 1.10   | 1.96   | 0.12   | 0.12   | 0.00   |
| Spinach| 1.10   | 0.00   | 0.12   | 0.12   | 0.00   |
| Waterleaf| 0.00  | 0.60   | 0.13   | 0.13   | 1.60   |

| Cr     |        |        |        |        |        |
|--------|--------|--------|--------|--------|--------|
| Celosia| 0.08   | 0.01   | 0.00   | 0.00   | 0.02   |
| Okro   | 0.04   | 0.00   | 0.01   | 0.01   | 0.07   |
| Pumpkin| 0.08   | 0.00   | 0.06   | 0.06   | 0.11   |
| Spinach| 0.11   | 0.00   | 0.02   | 0.02   | 0.03   |
| Waterleaf| 0.13  | 0.00   | 0.03   | 0.03   | 0.03   |

| Cu     |        |        |        |        |        |
|--------|--------|--------|--------|--------|--------|
| Celosia| 0.12   | 0.01   | 0.02   | 0.02   | 0.05   |
| Okro   | 0.10   | 0.00   | 0.00   | 0.00   | 0.01   |
| Pumpkin| 0.02   | 0.01   | 0.01   | 0.01   | 0.01   |
| Spinach| 0.02   | 0.02   | 0.01   | 0.01   | 0.01   |
| Waterleaf| 0.04  | 0.19   | 0.01   | 0.01   | 0.04   |

| Zn     |        |        |        |        |        |
|--------|--------|--------|--------|--------|--------|
| Celosia| 0.74   | 0.1    | 0.12   | 0.12   | 0.07   |
| Okro   | 0.97   | 0.07   | 0.01   | 0.01   | 0.03   |
| Pumpkin| 0.28   | 0.06   | 0.06   | 0.06   | 0.03   |
| Spinach| 0.31   | 0.04   | 0.14   | 0.14   | 0.08   |
| Waterleaf| 0.14  | 0.03   | 0.08   | 0.08   | 0.17   |
## Research

### Bioaccessibility of Toxic Metals in Vegetables Grown on Contaminated Soils

| Soil | Physiologically Based Extraction Test | Acid Digestion |
|------|-------------------------------------|----------------|
|      | Gastric Phase (I) | Intestinal Phase (II) | Residual Phase (III) | Total (I+II+III) | Total Concentration |
|      | mg/kg | % | mg/kg | mg/kg | % | mg/kg | mg/kg |
| Soil A | Cu | 0.42 | 12 | <0.37 | 2.55±0.08 | 72.9 | 2.97 | 3.5±0.4 |
|       | Cd | 0.68 | <0.4 | <0.4 | 0.68 | <0.5 |       |       |
|       | Cr | <2.36 | <2.36 | 15.0±0.8 | 73.5 | 15.0 | 20.4±1.4 |
|       | Zn | 45.5±7.0 | 18.2 | <2.0 | 184±13.1 | 73.9 | 229.5 | 249.7±14.2 |
|       | Pb | <10.5 | <10.5 | <10.5 |       |       |       |       |
| Soil B | Cu | <0.37 | <0.37 | 187±7.6 | 84.7 | 187 | 220.9±10.5 |
|       | Cd | 0.6±0.1 | 50 | <0.4 | <0.4 | 0.6 | 1.2±0.12 |
|       | Cr | <2.36 | <2.36 | <2.36 | <2.36 | <3.5 |       |       |
|       | Zn | 5.57±1.3 | 24.3 | <2.0 | 10.7±2.5 | 46.7 | 16.3 | 22.9±2.0 |
|       | Pb | <10.5 | <10.5 | <10.5 |       |       |       |       |
| Soil C | Cu | 30.1±5.5 | 30 | <0.37 | 17.9±2.4 | 17.9 | 48.0 | 100±8.2 |
|       | Cd | 0.67±0.08 | 26.2 | <0.4 | 1.65±0.1 | 64.5 | 2.32 | 2.56±0.2 |
|       | Cr | <2.36 | <2.36 | <2.36 | <2.36 | 17.4±4.8 |       |       |
|       | Zn | 20.9±2.2 | 17.3 | <2.0 | 26.5±3.0 | 22.0 | 47.4 | 121±10.1 |
|       | Pb | <10.5 | <10.5 | <10.5 |       |       |       |       |
| Soil D | Cu | 0.73±0.08 | 1.34 | <0.37 | 23.4±3.2 | 43.0 | 24.1 | 54.4±5.0 |
|       | Cd | 1.31±0.2 | 36.8 | <0.4 | 1.47±0.7 | 41.3 | 2.78 | 3.56±0.7 |
|       | Cr | <2.36 | <2.36 | <2.36 | <2.36 | 34.2±4.0 |       |       |
|       | Zn | 20.0±3.0 | 59.8 | <2.0 | 6.16±1.4 | 18.4 | 26.2 | 33.5±4.2 |
|       | Pb | <10.5 | <10.5 | <10.5 |       |       |       |       |
| Soil E | Cu | 1.52±0.3 | 3.1 | <0.37 | 18.3±3.5 | 36.9 | 19.8 | 49.6±5.2 |
|       | Cd | 2.38±0.8 | 43.8 | <0.4 | 2.41±0.7 | 44.4 | 4.79 | 5.43±1.2 |
|       | Cr | <2.36 | <2.36 | <2.36 | <2.36 | 6.1±2.8 |       |       |
|       | Zn | 22.3±1.5 | 9.97 | <2.0 | 148±7.0 | 66.2 | 170.3 | 223.7±7.8 |
|       | Pb | <10.5 | <10.5 | <10.5 |       |       |       |       |

*Table 3 — Total Metal Concentration and Bioaccessibility of Metals in Waterleaf*
| Soil | Cu    | Cd   | Cr   | Zn   | Pb   |
|------|-------|------|------|------|------|
| A    |       |      |      |      |      |
| mg/kg |     | %   | <0.37| 7.6±2.4 | 76.5 | 11.0 | 9.93±2.6 |
| B    | 5.1±1.2 | 40.4| 0.71±0.1 | 0.71±0.1 | 107 | <0.4 | 107 | <0.4 |
| C    |       |      | <2.36| 2.36±1.5 | 32.9±1.5 | 23.7±1.4 | 43.5 | 65.6 | 75.1±4.2 |
| D    | <10.5 | <10.5| <0.5 | 0.37±0.1 | 0.37±0.1 | 0.37±0.1 | <0.5 | <0.5 | <0.5 |
| E    | <10.5 | <10.5| <10.5| 0.12±0.03 | 0.12±0.03 | 0.12±0.03 | <10.5 | <10.5 | <10.5 |

**Table 4 — Total Metal Concentration and Bioaccessibility of Metals in Celosia**
# Physiologically Based Extraction Test

| Soil    | Gastric Phase (I) | Intestinal Phase (II) | Residual Phase (III) | Total (I+II+III) | Total Concentration |
|---------|------------------|-----------------------|----------------------|------------------|---------------------|
|         | mg/kg            | %                     | mg/kg                | %                | mg/kg               |
| **Soil A** |                  |                       |                      |                  |                     |
| Cu      | <0.37            | <0.37                 | 1.68±0.6             | 84               | 1.68±0.6            |
| Cd      | <0.4             | <0.4                  | <0.4                 |                  | 1.1±0.2             |
| Cr      | <2.36            | <2.36                 | <2.36                |                  | 11.7±4.2            |
| Zn      | <2.0             | 5.86±0.8              | 30.5±1.3             | 38.7             | 36.4                |
| Pb      | <10.5            | <10.5                 | <10.5                |                  | <12.5               |
| **Soil B** |                  |                       |                      |                  |                     |
| Cu      | 7.3±1.4          | 86.0                  | <0.37                | 2.1±0.5          | 24.7                |
| Cd      | 0.8±0.05         | 21.0                  | <0.4                | 1.8±0.3          | 46.1                |
| Cr      | <2.36            | <2.36                 | <2.36               |                  | <3.5                |
| Zn      | 12.7±0.7         | 28.1                  | <2.0                | 39.1±1.8        | 87                  |
| Pb      | <10.5            | <10.5                 | <10.5               |                  | <12.5               |
| **Soil C** |                  |                       |                      |                  |                     |
| Cu      | 17±1.2           | 15.8                  | <0.37               | 30.1±1.9        | 27.5                |
| Cd      | 1.1±0.1          | 41.4                  | <0.4                | 1.28±0.1        | 53.3                |
| Cr      | <2.36            | <2.36                 | <2.36               |                  | 37.7±3.1            |
| Zn      | 6.4±0.6          | 6.2                   | 8.5±0.8             | 30.0±1.1        | 29                  |
| Pb      | <10.5            | <10.5                 | <10.5               |                  | <12.5               |
| **Soil D** |                  |                       |                      |                  |                     |
| Cu      | 5.3±0.3          | 78.0                  | <0.37               | 0.83±0.05       | 12                  |
| Cd      | 0.06             | 10.0                  | <0.4                | 0.62±0.03       | 102                 |
| Cr      | <2.36            | <2.36                 | <2.36               |                  | 15.9±1.2            |
| Zn      | 7.5±0.3          | 14.4                  | <2.0                | 18.0±0.8        | 34.6                |
| Pb      | <10.5            | <10.5                 | <10.5               |                  | <12.5               |
| **Soil E** |                  |                       |                      |                  |                     |
| Cu      | 0.7±0.05         | 11.4                  | <0.37               | 2.2±0.2         | 71                  |
| Cd      | <0.4             | <0.4                  | <0.4                |                  | <0.5                |
| Cr      | <2.36            | <2.36                 | <2.36               |                  | 25.3±1.4            |
| Zn      | <2.0             | <2.0                  | 38.0±1.2            | 116             | 38.0                |
| Pb      | <10.5            | <10.5                 | <10.5               |                  | <12.5               |

Table 5 — Total Metal Concentration and Bioaccessibility of Metals in Pumpkin
| Concentration | Gastric Phase (I) | Intestinal Phase (II) | Residual Phase (III) | Total (I+II+III) | Total Concentration |
|---------------|-------------------|-----------------------|----------------------|-----------------|--------------------|
|               | mg/kg             | %                     | mg/kg                | %               | mg/kg              |
| **Soil A**    |                   |                       |                      |                 |                    |
| Cu            | 0.38±0.02         | 21.4                  | <0.37                | <0.37           | 0.38               |
| Cd            | <0.4              | <0.4                  | <0.4                 | 1.73±0.07       |
| Cr            | <2.36             | <2.36                 | <2.36                | 1.1±0.04        |
| Zn            | <2.0              | 47.7±1.2              | 50                   | 16.4±2.1        |
| Pb            | <10.5             | <10.5                 | <10.5                | 85.8±2.4        |
| **Soil B**    |                   |                       |                      |                 |                    |
| Cu            | 1.4±0.03          | 5.5                   | <0.37                | 21.6±2.1        |
| Cd            | <0.4              | <0.4                  | <0.4                 | 22.0            |
| Cr            | <2.36             | <2.36                 | <2.36                | 25.8±1.5        |
| Zn            | <2.0              | 4.75±0.2              | 16.1                 | 1.26±0.5        |
| Pb            | <10.5             | <10.5                 | <10.5                | 29.4±0.8        |
| **Soil C**    |                   |                       |                      |                 |                    |
| Cu            | 21.8±1.2          | 32.6                  | <0.37                | 22.7±0.9        |
| Cd            | 0.64±0.05         | 17.0                  | <0.4                 | 50.3            |
| Cr            | <2.36             | <2.36                 | <2.36                | 11.8±1.5        |
| Zn            | 60.4±1.1          | 27.0                  | <2.0                 | 135.2           |
| Pb            | <10.5             | <10.5                 | <10.5                | 224.6±7.8       |
| **Soil D**    |                   |                       |                      |                 |                    |
| Cu            | <0.37             | <0.37                 | <0.37                | 1               |
| Cd            | <0.4              | <0.4                  | <0.4                 | 9.56            |
| Cr            | <2.36             | <2.36                 | <2.36                | 0.3±0.7         |
| Zn            | <2.0              | <2.0                  | <2.0                 | 13.5±2.1        |
| Pb            | <10.5             | <10.5                 | <10.5                | 10.1±1.2        |
| **Soil E**    |                   |                       |                      |                 |                    |
| Cu            | 7.4±0.3           | 71.8                  | <0.37                | 9.56            |
| Cd            | <0.4              | 1.12±0.05             | 60.5                 | 1.12            |
| Cr            | <2.36             | <2.36                 | <2.36                | 1.85±0.06       |
| Zn            | 28.1±0.5          | 27.5                  | <2.0                 | 78.7            |
| Pb            | <10.5             | <10.5                 | <10.5                | 102±2.8         |

Table 6 — Total Metal Concentration and Bioaccessibility of Metals in Spinach
### Bioaccessibility of Toxic Metals in Vegetables Grown on Contaminated Soils

**Research**

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| Soil | Cu (mg/kg) | Cd (mg/kg) | Cr (mg/kg) | Zn (mg/kg) | Pb (mg/kg) |
|------|------------|------------|------------|------------|------------|
| Soil A | <0.37 | 0.4 | <2.36 | <2.0 | <10.5 |
| Soil B | <0.37 | <0.4 | <2.36 | 0.83±0.01 | <10.5 |
| Soil C | <0.37 | 0.2±0.01 | <2.36 | <2.0 | <10.5 |
| Soil D | No Growth | | | | |
| Soil E | <0.37 | <0.4 | <2.36 | 2.9±0.04 | <10.5 |

**Physiologically Based Extraction Test**

| Concentration | Gastric Phase (I) | Intestinal Phase (II) | Residual Phase (III) | Total (I+II+III) | Total Concentration |
|---------------|-------------------|-----------------------|----------------------|-----------------|-------------------|
|               | mg/kg             | %                     | mg/kg                | %               | mg/kg             |
| Soil A        |                  |                       | 5.85±0.9             | 68.2            | 5.85              | 8.58±1.4 |
| Soil B        | <0.37            | <0.37                 | <0.37                | 0.63±0.01       | <0.5              |
| Soil C        | <0.37            | 0.2±0.01              | <2.36                | 0.83±0.01       | <2.5              |
| Soil D        | No Growth         | No Growth             | No Growth            | No Growth       | No Growth         |
| Soil E        | <0.37            | <0.37                 | <0.37                | 12.3±0.7        | <12.5             |

**Acid Digestion**

| Concentration | Total Metal Concentration |
|---------------|---------------------------|
|               | mg/kg                     |
| Soil A        | 8.58±1.4                  |
| Soil B        | 0.63±0.01                 |
| Soil C        | 2.5±0.02                  |
| Soil E        | 12.3±0.7                  |

**Table 7 — Total Metal Concentration and Bioaccessibility of Metals in Okro**
Physiologically Based Extraction Test

The PBET consists of two sequential extraction processes, gastric and intestinal digestion, each one carried out by employing simulated human conditions (i.e., enzymes, pH and temperature), according to the method proposed by Ruby et al.17

In the gastric phase, the sample was subjected to a solution containing pepsin, malate, citrate, acetic acid and lactic acid at pH 1.8 (adjusted with 12 m hydrochloric acid), while the intestinal phase was treated with pancreatin and bile salts to pH 7.0 (adjusted with saturated sodium bicarbonate solution). Both phases were subjected to the human body temperature of 37°C.13

Results

The total metal concentrations in the different soil samples are presented in Table 1. High concentrations of metals were found in soil samples B, C, D, E, but not in sample A.

Table 2 shows the results obtained for the metal transfer factor (TF), the ratio of heavy metal concentration in plants to that in soil. Data indicates that for copper (Cu), cadmium (Cd), chromium (Cr) and zinc (Zn), the TF values varied greatly between plant types. From the results, TF values for Cd were found to be the highest, followed by Zn, Cu and Cr, respectively, whereas lead (Pb) had no transfer value because there was no uptake of Pb by the vegetable plants from any of the soil samples on which the plants were grown. The TF values for Cd for the soil samples varied from 0.00 to 1.96. The TF values for Zn varied from 0.01 to 0.74, while Cu had a TF value ranging from 0.00 to 0.19. However, Cr, which had the lowest TF values, varied from 0.00 to 0.13. Generally, the order of metal transfer factor was Cd > Zn > Cu > Cr > Pb, indicating that uptake was highest for Cd.

Tables 3–7 show the total metal concentration and bioaccessibility of metals in each vegetable.

Discussion

Bioaccessibility of Metals

Copper

The bioaccessibility of Cu in the gastric phase was observed to be higher in some vegetables than in others. Total Cu content across the different vegetable samples was 11.6 to 86% for pumpkin, 5.5 to 71.8% for spinach, 5.6 to 55% for celosia, and 1.3 to 50% for waterleaf. No bioaccessibility was observed in the intestinal phase, while in the residual fraction, 21 to 83.7%, 12 to 84%, 28.1 to 76.5% and 17.9 to 84.7% was recovered for spinach, pumpkin, celosia and waterleaf, respectively. The results indicate that most of the total Cu content accumulated in the plant was recovered in the residual phase where the metals are not available for absorption.

Cadmium

The solubility of cadmium was observed to be highest for celosia, 16 to 109% in the gastric phase, followed by waterleaf (26.2 to 50%) and pumpkin 41.4%, while spinach had only 17% solubility. For the intestinal phase, bioaccessibility was observed for celosia only (12%). The percentage of Cd found in the residual phase was up to 50% in spinach, 45% in celosia, 64.5% in waterleaf and 109% in pumpkin.

Zinc

The bioaccessibility in the gastric phase was 6 to 28% for pumpkin, 10 to 59.8% for waterleaf, 23 to 66% for celosia, and 27% for spinach, while 7.4 to 16.1% was solubilized in the intestinal phase. However, most of the concentrations of zinc in the plants were found not to be available for absorption, but rather remained in the residual fraction, 29 to 116% in pumpkin, 18 to 74% in waterleaf, 12.7 to 68.5% in celosia, 53 to 72% in okro, and 33 to 56% in spinach.

Chromium and Lead

It was observed from the results that Cr and Pb were not bioaccessible to the plants in either of the two phases.

Conclusion

The results of this study suggest that metals taken up by the vegetables was available for absorption (solubilized) in the gastric extraction phase rather than in the intestinal phase. The level of metals absorbed in the gastric phase were found to be relatively low. This study illustrates that metals can be solubilized in the human gut when taken in through consumption of contaminated vegetable plants, although in low concentrations. Bioaccumulation of these metals could take place over time in the human system through continuous consumption of contaminated vegetables, possibly leading to deleterious health effects in humans.

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