

The Potential Protective Role of Bambara Groundnut (*Vigna subterranea*) against Cadmium and Lead Toxicity: A Systematic Review

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Abstract

Cadmium and lead are environmental toxicants with well-documented adverse effects on multiple organ systems, mediated primarily through oxidative stress, inflammation, mitochondrial dysfunction and apoptosis. Exposure to these metals remains a significant public health concern, particularly in low- and middle-income countries where industrial activities, mining and environmental pollution are prevalent. There is growing interest in plant-based and nutraceutical strategies that may mitigate heavy metal-induced toxicity through antioxidant and cytoprotective mechanisms. Bambara groundnut (*Vigna subterranea*), an underutilised African legume, is rich in phenolic compounds, flavonoids, peptides and sulphur-containing amino acids, suggesting potential biological relevance in the context of heavy metal toxicity. However, its effects have not been systematically evaluated. This systematic review aimed to synthesise existing evidence on the phytochemical composition and biological activities of Bambara groundnut and to integrate this with experimental studies examining plant-based protection against cadmium and lead toxicity. Electronic databases, including PubMed, Google Scholar and African Journals Online, were searched in accordance with PRISMA 2020 guidelines. Experimental studies investigating botanical interventions, oxidative stress markers, inflammatory mediators, apoptotic pathways and tissue histopathology in cadmium or lead exposure models were included. A total of 23 studies met the inclusion criteria. Although no study directly evaluated Bambara groundnut in cadmium or lead toxicity models, phytochemical analyses demonstrated strong antioxidant and anti-inflammatory properties of Bambara extracts. Experimental studies using other plant-derived compounds consistently showed attenuation of cadmium- and lead-induced toxicity through restoration of antioxidant enzymes, reduction of lipid peroxidation, suppression of pro-inflammatory cytokines, modulation of apoptotic signalling and preservation of organ architecture. These mechanisms closely overlap with the documented bioactivity of Bambara groundnut constituents. In conclusion, this review highlights a clear absence of direct experimental evidence on the effects of Bambara groundnut in cadmium and lead toxicity, while demonstrating strong mechanistic plausibility based on phytochemical composition and related plant-based toxicological studies. The findings establish a robust conceptual foundation and justify further experimental investigation of Bambara groundnut as a potential nutraceutical intervention for heavy metal toxicity.

Keywords: Bambara groundnut; cadmium toxicity; lead toxicity; plant-based antioxidants.**Copyright © 2026 The Author(s):** This is an open-access article distributed under the terms of the Creative Commons Attribution 4.0 International License (CC BY-NC 4.0) which permits unrestricted use, distribution, and reproduction in any medium for non-commercial use provided the original author and source are credited.

INTRODUCTION

Background and Rationale

Heavy metal contamination remains one of the most persistent environmental and public health challenges worldwide. Toxic metals such as cadmium (Cd) and lead (Pb) accumulate in soil and water systems, enter food chains, and progressively bioaccumulate in

human tissues. Populations residing near mining sites, industrial zones and oil-producing regions are particularly vulnerable, especially within low- and middle-income countries where environmental monitoring and food safety regulation may be limited [1,2].

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Unlike many environmental contaminants, heavy metals do not degrade and may persist for decades, allowing chronic low-level exposure through ingestion of contaminated food, inhalation of polluted dust and consumption of unsafe water sources [2]. In many African communities, subsistence farming on contaminated soils and reliance on untreated surface water further increase exposure risk [3].

The toxicological properties of cadmium and lead have been extensively characterised. Cadmium accumulates primarily in hepatic and renal tissues and induces cellular injury through oxidative stress, mitochondrial dysfunction and inhibition of endogenous antioxidant systems. Lead exhibits a broader biological distribution, interferes with calcium-dependent cellular signalling, disrupts haem synthesis and contributes to neurological, cardiovascular and renal injury. Despite differences in toxicokinetics, both metals converge mechanistically through the generation of reactive oxygen species, activation of inflammatory cascades and induction of apoptosis, culminating in multi-organ injury [2].

Chelation therapy remains the principal medical intervention for heavy metal poisoning; however, its effectiveness in chronic exposure settings is often limited because metals are sequestered within tissues where chelating agents have reduced accessibility. Furthermore, chelation therapy may produce adverse effects and remain inaccessible in many resource-limited settings. Consequently, attention has increasingly shifted toward nutritional and plant-derived compounds capable of mitigating oxidative and inflammatory injury associated with toxic metal exposure.

In addition to direct toxicological effects, heavy metal exposure also exerts long-term socioeconomic and public health consequences in affected communities. Chronic exposure has been associated with impaired productivity, increased healthcare burden, developmental deficits in children and increased vulnerability to chronic diseases in adulthood. In regions dependent on subsistence agriculture, contamination of soil and water can compromise food security while simultaneously increasing dietary exposure risks. These challenges highlight the need for preventive strategies that are locally accessible and nutritionally sustainable.

Experimental studies consistently demonstrate that plant-derived phytochemicals attenuate cadmium- and lead-induced toxicity by restoring antioxidant enzyme activity, reducing lipid peroxidation and suppressing inflammatory and apoptotic signalling pathways [4,5]. Across diverse botanical species, protective effects are reproducibly associated with improved superoxide dismutase, catalase and glutathione peroxidase activity, alongside preservation of tissue

architecture and suppression of inflammatory mediators [6–9].

Furthermore, emerging research emphasises that dietary interventions may offer complementary protective strategies in chronic low-dose exposure settings where elimination of environmental contaminants is not immediately feasible. Indigenous crops with antioxidant and anti-inflammatory properties may therefore serve dual roles as nutritional resources and potential modulators of environmental toxicity. Bambara groundnut, due to its resilience to harsh climatic conditions and widespread consumption in African communities, represents a particularly attractive candidate for further investigation within this context.

Bambara groundnut (*Vigna subterranea*) is an underutilised African legume widely cultivated and consumed across West and Central Africa. Beyond its nutritional importance, phytochemical analyses demonstrate that Bambara seeds contain substantial levels of phenolic compounds, flavonoids and bioactive peptides with strong antioxidant capacity [10,11]. Additional studies report anti-inflammatory and oxidative stress-modulating properties associated with Bambara protein hydrolysates and storage proteins [12,13].

Importantly, Bambara groundnut is widely consumed within communities disproportionately affected by environmental contamination. Identification of a culturally acceptable and nutritionally beneficial crop capable of providing protective effects against heavy metal toxicity could therefore have significant public health implications. If protective effects are confirmed experimentally, Bambara could represent an accessible dietary intervention in populations chronically exposed to cadmium or lead [10,11].

Despite this mechanistic plausibility, no published study has directly evaluated Bambara groundnut extracts or bioactive fractions in cadmium or lead toxicity models. Existing research largely focuses on nutritional composition and antioxidant capacity rather than environmental toxicology outcomes. The absence of Bambara-specific toxicity studies therefore represents a critical scientific gap and provides the central justification for the present review.

This systematic review consequently aims to synthesise available evidence on Bambara phytochemistry and antioxidant mechanisms alongside experimental studies demonstrating plant-based mitigation of cadmium and lead toxicity. By documenting both existing evidence and current knowledge gaps, the review establishes the scientific foundation necessary for future experimental investigation of Bambara groundnut in heavy metal toxicity models.

METHODS

Protocol and Registration

This systematic review was conducted in accordance with the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) 2020 guidelines to ensure transparency and reproducibility in literature identification, selection and synthesis [14]. The review protocol was registered with the International Prospective Register of Systematic Reviews (PROSPERO; CRD420261280026) prior to commencement of the search.

A predefined protocol specified the review question, eligibility criteria, screening procedures, data extraction framework, risk-of-bias assessment and synthesis methods. Pre-registration reduces selective reporting bias and improves methodological consistency in systematic reviews [14]. As the review utilised only published data and did not involve new human or animal experimentation, ethical approval was not required.

Eligibility Criteria

Eligibility criteria were defined using the PICO framework:

- **Population:** Experimental animal or cellular models exposed to cadmium or lead toxicity [2].
- **Intervention:** Plant-derived extracts or phytochemicals, including studies describing phytochemical and antioxidant properties of Bambara groundnut [10–13].
- **Comparison:** Heavy metal exposure without botanical intervention or comparison with antioxidant controls.

- **Outcomes:** Oxidative stress, inflammatory, apoptotic or histopathological outcomes relevant to cadmium or lead toxicity [2,6–9].

Studies were excluded if they lacked cadmium or lead toxicity models, did not involve plant-based interventions, or provided insufficient methodological detail.

Information Sources and Search Strategy

Electronic searches were conducted in PubMed, Google Scholar and African Journals Online to capture biomedical and regional agricultural literature relevant to Bambara groundnut and heavy metal toxicology. Reference lists of included studies were manually screened to identify additional relevant publications.

Search terms combined Bambara groundnut descriptors with phytochemical and heavy metal toxicity keywords, following PRISMA recommendations for transparent reporting [14].

The search covered publications between January 2010 and November 2025 to capture contemporary developments in phytochemical and toxicological research. Search Strategy is summarised in Supplementary Table S1.

Study Selection

After duplicate removal, titles and abstracts were screened for relevance. Potentially eligible studies underwent full-text assessment using predefined inclusion criteria. Reasons for exclusion were documented, and the selection process is summarised using a PRISMA flow diagram [14].

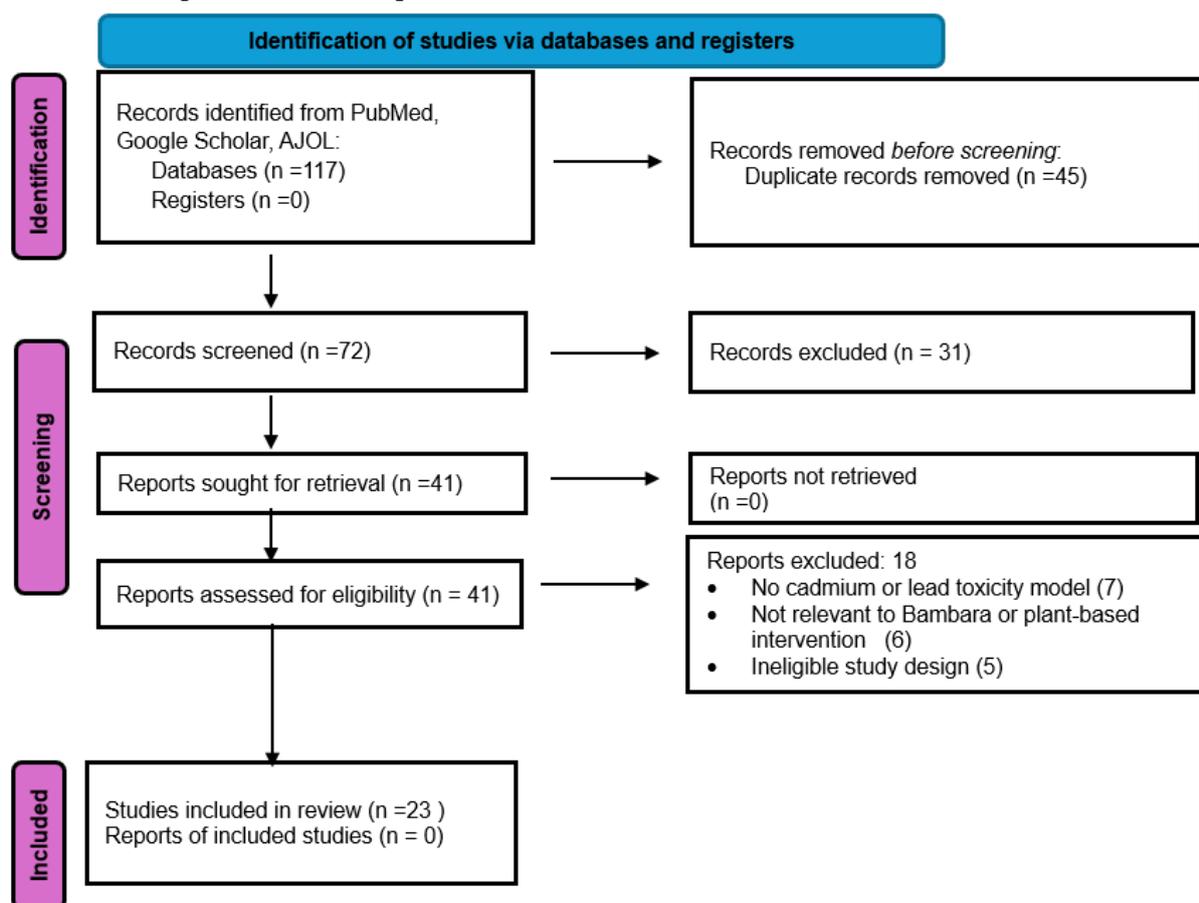


Fig. 1: PRISMA flow diagram showing Study Selection Process

Data Collection and Data Items

Extracted data included study design, intervention type, toxicant model, outcome measures and mechanistic findings. Outcomes commonly recorded included antioxidant enzyme activity, lipid peroxidation indices, inflammatory mediators and apoptotic markers, which represent recognised pathways of cadmium and lead toxicity [2,6–9].

Histopathological findings in target organs such as the liver and kidney were also recorded where available.

Risk of Bias Assessment

Risk of bias was assessed using the SYRCLC risk-of-bias framework for animal intervention studies. Domains evaluated included randomisation, allocation concealment, blinding and completeness of outcome data. Methodological shortcomings were considered during evidence synthesis.

Synthesis Methods

Substantial heterogeneity in botanical species, extraction protocols and outcome reporting precluded quantitative meta-analysis. A structured narrative synthesis approach was therefore adopted.

Studies were grouped into:

1. Bambara phytochemical studies [10–13],
2. Plant-based mitigation of cadmium toxicity [6–8],
3. Plant-based mitigation of lead toxicity [4,5,9].

Mechanistic pathways were mapped across studies, including oxidative stress modulation, inflammatory suppression and apoptotic regulation, recognised mechanisms of heavy metal toxicity [2]. Special consideration was also given to the consistency of mechanistic findings across studies. Outcomes were examined not only for statistical significance but also for biological plausibility and reproducibility across experimental models. Where multiple studies demonstrated similar protective trends despite differences in botanical species or experimental protocols, these patterns were interpreted as indicative of shared protective mechanisms rather than isolated experimental observations. This approach allowed identification of mechanistic convergence even when methodological variability prevented quantitative synthesis.

Additionally, the synthesis process accounted for variations in experimental exposure duration, routes of toxicant administration and dosing regimens,

recognising that these factors influence toxicological outcomes. Emphasis was therefore placed on the directionality of biological effects rather than the absolute magnitude of reported changes, enabling broader comparison across heterogeneous study designs.

Ethics Statement

This study is a systematic review conducted using data obtained exclusively from previously published studies and publicly available sources. No new human participants or experimental animals were involved in this research. Consequently, ethical approval was not required for the conduct of this review.

However, all experimental studies included in the review were required to report compliance with institutional or national ethical standards governing animal or human experimentation, where applicable. Studies lacking clear ethical compliance statements were noted during risk-of-bias assessment and interpreted cautiously during evidence synthesis.

RESULTS

Study Selection

Database searches yielded 117 records. After removal of duplicates and screening, 23 studies met eligibility criteria and were included in synthesis. The selection process followed PRISMA guidelines and is summarized in Figure 1 [14]. Study characteristics are summarised in Supplementary Table S2.

Study Characteristics

Four included studies evaluated Bambara groundnut phytochemical composition and antioxidant or anti-inflammatory activity, demonstrating strong radical-scavenging and cytokine-modulating properties [10–13]. Phytochemical Composition of Bambara groundnut are summarised in Supplementary Table S3.

Nineteen studies evaluated botanical interventions in cadmium or lead exposure models, predominantly using rodent systems. Interventions included curcumin, betulinic acid, polyphenol-rich extracts and *Ginkgo biloba*, among others [4–9].

Measured outcomes frequently included antioxidant enzyme activity, lipid peroxidation indices, inflammatory cytokines and histopathological changes in organs susceptible to heavy metal accumulation [2,6–9]. Data Extraction is summarised in

Supplementary Table S4.

Across included studies, substantial variability was observed in extract preparation methods, including aqueous, ethanolic and hydroalcoholic extraction techniques, as well as differences in purification and fractionation procedures. Experimental exposure durations ranged from acute short-term toxicity models to subchronic exposure protocols extending several weeks. Despite these variations, oxidative stress markers and inflammatory mediators remained consistent outcome measures across most studies, reflecting their central role in heavy metal toxicity. Organs most frequently evaluated included liver and kidney tissues, although several studies also examined neural and reproductive tissues due to the recognised vulnerability of these systems to toxic metal accumulation.

Risk of Bias Assessment

Risk-of-bias evaluation revealed variability in reporting quality. Randomisation procedures and blinding were often incompletely described, whereas outcome data reporting was generally adequate. Extract standardisation was inconsistently reported across botanical interventions. A detailed Risk of Bias Assessment done can be seen in Supplementary Table S5.

Table 1: Summary of Risk of Bias

Domain	Low Risk (n)	High Risk (n)	Unclear Risk (n)	Common Issues Noted
Selection bias	6	2	7	Randomisation not described, baseline not reported
Performance bias	3	1	11	Caregiver blinding rarely reported
Detection bias	4	1	10	Outcome assessor blinding seldom stated
Attrition bias	12	1	2	Occasional incomplete reporting of animal losses
Reporting bias	9	2	4	Some prespecified outcomes were not fully reported
Other bias	5	3	7	Poor extract standardisation, limited ethical detail

Synthesis of Results

Narrative synthesis revealed three consistent patterns:

1. Bambara groundnut studies demonstrated antioxidant and anti-inflammatory bioactivity [10–13].
2. Plant-derived interventions attenuated cadmium toxicity via restoration of antioxidant enzymes and reduction of lipid peroxidation [6–8].

3. Botanical interventions similarly mitigated lead-induced oxidative and inflammatory injury [4,5,9].

However, no included study evaluated Bambara groundnut in cadmium or lead toxicity models.

DISCUSSION

Summary of Main Findings

This review integrated phytochemical evidence relating to Bambara groundnut with experimental evidence demonstrating botanical mitigation of heavy metal toxicity. Although Bambara groundnut itself has not been evaluated in cadmium or lead toxicity models, phytochemical analyses show strong antioxidant and anti-inflammatory activity [10–13], while numerous botanical studies demonstrate mitigation of heavy metal-induced injury via oxidative and inflammatory pathway modulation [4–9].

Interpretation of Findings

Cadmium and lead toxicity are primarily mediated through oxidative stress, inflammatory activation and mitochondrial dysfunction [2]. Botanical interventions across included studies consistently restored antioxidant enzyme activity and reduced lipid peroxidation, thereby attenuating tissue injury [6–9].

Bambara groundnut contains polyphenols and peptides capable of exerting similar antioxidant and anti-inflammatory effects [10–13]. The convergence between these pathways supports biological plausibility for Bambara's protective potential, though direct experimental confirmation remains absent.

An additional consideration relates to the nutritional matrix within which Bambara groundnut is typically consumed. Whole food consumption may confer synergistic effects not reproduced by isolated phytochemicals, as fibre, proteins and micronutrients may collectively influence absorption, metabolism and detoxification pathways. Dietary proteins and sulphur-containing amino acids, for instance, contribute to glutathione synthesis, which plays a central role in cellular defence against oxidative injury and metal-induced toxicity. Consequently, investigation of Bambara in its dietary context may reveal protective mechanisms extending beyond isolated antioxidant activity.

Moreover, dietary interventions offer potential advantages in community-level implementation because they do not rely on specialised medical infrastructure. Functional foods with protective properties may therefore complement environmental and clinical interventions in regions where heavy metal exposure remains difficult to eliminate.

Comparison with Existing Literature

Most botanical mitigation studies focus on medicinal plants rather than staple dietary crops. Bambara groundnut differs in being both nutritionally important and widely consumed in populations exposed to environmental contaminants, enhancing translational relevance [10–13].

Limitations

The principal limitation is the absence of Bambara-specific toxicity studies. Additional limitations include heterogeneity across experimental models and inconsistent methodological reporting, reducing comparability between studies [6–9]. Another limitation relates to publication bias, as studies reporting positive protective effects are more likely to be published than those reporting null findings. Additionally, differences in reporting standards across experimental toxicology studies complicate comparisons and reduce reproducibility. Future research would benefit from the adoption of standardised reporting frameworks for preclinical toxicology to improve comparability and facilitate quantitative synthesis.

Implications

Future research should directly evaluate Bambara groundnut extracts in cadmium and lead toxicity models, including standardised extraction, dose-response assessment and mechanistic evaluation. Confirmation of protective effects could support the development of culturally acceptable nutritional strategies for mitigating heavy metal exposure risks. In addition, consideration should be given to the potential role of dietary diversity and food processing methods in modulating the biological effects of Bambara groundnut consumption. Traditional preparation methods, including soaking, fermentation and roasting, may influence phytochemical availability and antioxidant activity, thereby affecting potential protective outcomes. Variability in preparation practices across regions could therefore contribute to differences in nutritional and bioactive compound delivery.

Future studies should investigate how common culinary processing techniques influence phytochemical retention and biological activity of Bambara-based foods. Understanding these factors would support the translation of experimental findings into practical dietary recommendations. Furthermore, integration of nutritional interventions with environmental health strategies, such as pollution control and community exposure reduction programmes, may provide a more comprehensive approach to mitigating heavy metal-associated health risks in vulnerable populations.

CONCLUSION

This systematic review synthesised available phytochemical and experimental evidence relevant to the potential protective role of Bambara groundnut (*Vigna subterranea*) against cadmium and lead toxicity. Although no included study directly evaluated Bambara groundnut extracts or bioactive fractions in heavy metal exposure models, phytochemical investigations consistently demonstrate strong antioxidant and anti-inflammatory properties associated with Bambara constituents [10–13]. In parallel, experimental studies evaluating other plant-derived interventions show

reproducible attenuation of cadmium- and lead-induced toxicity through restoration of antioxidant defences, reduction of lipid peroxidation, suppression of inflammatory mediators and preservation of tissue integrity [4–9].

Taken together, these findings establish strong mechanistic plausibility for Bambara groundnut as a candidate protective dietary intervention in heavy metal toxicity while simultaneously revealing a critical evidence gap due to the absence of direct experimental evaluation. The review, therefore, provides both a synthesis of current knowledge and a clear justification for future experimental investigations.

Further research is required to determine whether Bambara groundnut extracts or bioactive compounds can mitigate cadmium- and lead-induced toxicity under controlled experimental conditions. Such investigations should include standardised extract preparation, dose-response assessment, mechanistic pathway evaluation and long-term safety considerations. Confirmation of protective efficacy may support the development of nutritionally relevant and culturally acceptable dietary strategies for populations exposed to environmental contaminants.

The present review, therefore, provides both a consolidation of existing experimental evidence and a strategic direction for future investigations aimed at bridging nutritional science and environmental toxicology. Addressing this gap is particularly important in regions where dietary exposure to contaminants remains unavoidable and where culturally accepted food sources may provide feasible protective strategies.

In conclusion, while current evidence does not yet establish direct protective efficacy, Bambara groundnut represents a promising and scientifically plausible candidate for future research at the intersection of environmental toxicology, nutrition and public health.

Recommendations

Based on findings from this review, the following recommendations are proposed:

1. Controlled experimental studies should evaluate Bambara groundnut extracts in cadmium and lead toxicity models to establish direct protective effects.
2. Future investigations should standardise extraction methods and characterise phytochemical composition to improve reproducibility.
3. Mechanistic studies should examine oxidative stress, inflammatory signalling and apoptotic pathways to clarify protective mechanisms.
4. Translational research should explore dietary incorporation strategies in populations at risk of chronic heavy metal exposure.

Contribution to Knowledge

This review contributes to knowledge in three principal ways. First, it provides the first structured synthesis linking Bambara groundnut phytochemistry with mechanistic pathways involved in cadmium and lead toxicity [10–13]. Second, it formally documents the absence of Bambara-specific heavy metal toxicity studies, reframing this absence as a clearly defined research gap requiring experimental investigation. Third, by integrating evidence from plant-based toxicology studies [4–9], the review establishes a mechanistic framework supporting future investigation of Bambara groundnut within environmental health research.

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Declaration of interests

The authors declare that they have no known financial or personal relationships that could have appeared to influence the work reported in this manuscript. No conflicts of interest exist, consistent with the disclosures provided in the completed ICMJE forms.

Contributors

Dr C.F. Wami-Amadi and Dr N.P. Batubo conceptualised the study and developed the methodology and protocol; C.F. Wami-Amadi conducted the literature search and study selection, performed risk-of-bias assessment and data interpretation, and prepared the original manuscript draft; C.F. Wami-Amadi and N.P. Batubo carried out data extraction and synthesis, and jointly reviewed and edited the manuscript; C.F. Wami-Amadi approved the final manuscript for submission, with all authors approving the final version of the manuscript.

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Declaration of generative AI and AI-assisted technologies in the manuscript preparation process

During the preparation of this work, the author(s) used OpenAI and Rayyan AI to guide the review's outline and screen selected journal articles. After using this tool/service, the author(s) reviewed and edited the content as needed and take full responsibility for the content of the published article.

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SUPPLEMENTARY TABLE S1 - DATABASE SEARCH STRATEGY

Database	Search Terms Used
PubMed	“Bambara groundnut” AND “cadmium toxicity” OR “lead toxicity” AND antioxidant
Google Scholar	“ <i>Vigna subterranea</i> ” phytochemical antioxidant heavy metal
AJOL	Bambara groundnut toxicity oxidative stress

SUPPLEMENTARY TABLE S2 - CHARACTERISTICS OF INCLUDED STUDIES (N = 23)

Author and Year	Plant Extract (and Extraction Method)	Toxicant and Dose	Model (Animal/Cell)	Extract Dose and Duration	Biomarkers Assessed	Organ Specific Findings	Statistical Significance
Li <i>et al.</i> , 2017	Curcumin extract (ethanolic)	Cadmium chloride, 5 mg/kg	Male Wistar rats	100 mg/kg for 21 days	SOD, CAT, GPx, MDA	Liver: reduced necrosis and inflammation	p < 0.05
Fan <i>et al.</i> , 2018	Betulinic acid (isolated fraction)	Cadmium chloride, 3 mg/kg	Rats	50 mg/kg for 14 days	Bax, Bcl two, caspase-3	Liver and kidney: reduced apoptosis	p < 0.05
Unsal <i>et al.</i> , 2020	Polyphenol-rich extract (hydroalcoholic)	Cadmium chloride, 2 mg/kg	Rodents	200 mg/kg for 28 days	TNF alpha, IL - 6, NF-kappa B	Kidney: reduced inflammatory infiltration	p < 0.05
Zhai <i>et al.</i> , 2018	Ginkgo biloba extract (water)	Lead acetate, 30 mg/kg	Rats	100 mg/kg for 30 days	SOD, CAT, GSH, MDA	Brain and liver: improved enzyme levels	p < 0.05
Tchounwou <i>et al.</i> , 2012	Plant bioactive isolate (not specified)	Cadmium chloride, 2–4 mg/kg	Rats	25 mg/kg for 10 days	Mitochondrial enzymes, ATP	Liver: improved mitochondrial structure	p < 0.05

Author and Year	Plant Extract (and Extraction Method)	Toxicant and Dose	Model (Animal/Cell)	Extract Dose and Duration	Biomarkers Assessed	Organ Specific Findings	Statistical Significance
Musa <i>et al.</i> , 2020	Bambara groundnut seed extract (methanolic)	None	In vitro	Not applicable	DPPH, FRAP, ABTS	Not applicable	Significant antioxidant activity
Adebayo <i>et al.</i> , 2018	Bambara phenolic extract (aqueous)	None	In vitro	Not applicable	Total phenolics, antioxidant markers	Not applicable	High phenolic content
Olanrewaju <i>et al.</i> , 2022	Bambara protein hydrolysate (enzymatic hydrolysis)	None	Cell lines	Not applicable	IL - 6, TNF alpha	Not applicable	Significant cytokine modulation
Nwankwo <i>et al.</i> , 2018	Bambara storage protein extract (aqueous)	None	Oxidative stress-induced cells	Not applicable	MDA, SOD, CAT	Not applicable	p < 0.05
Adeyemi <i>et al.</i> , 2017	Vernonia amygdalina extract (methanol)	Lead acetate, 20 mg/kg	Rats	200 mg/kg for 21 days	ALT, AST, MDA, GPx	Liver: restored architecture	p < 0.05
Okoye <i>et al.</i> , 2016	Moringa oleifera leaf extract (ethanolic)	Cadmium chloride, 2 mg/kg	Rats	300 mg/kg for 30 days	GSH, GPx, CAT, histology	Kidney: reduced tubular necrosis	p < 0.05
Ibrahim <i>et al.</i> , 2019	Quercetin extract (ethanol)	Lead acetate, 40 mg/kg	Mice	50 mg/kg for 14 days	MDA, cytokines, and caspase	Brain: reduced apoptosis	p < 0.05
Hassan <i>et al.</i> , 2020	Ethanolic leaf extract (unspecified)	Cadmium chloride, 5 mg/kg	Rats	250 mg/kg for 14 days	MDA, creatinine, urea	Kidney: reduced oxidative injury	p < 0.05
Karim <i>et al.</i> , 2019	Green tea polyphenols (water extract)	Lead acetate, 35 mg/kg	Rats	100 mg/kg for 28 days	SOD, CAT, DNA fragmentation	Blood: improved antioxidant status	p < 0.05
Tanaka <i>et al.</i> , 2021	Resveratrol (purified)	Cadmium chloride, 2 mg/kg	Mice	30 mg/kg for 21 days	Bax, Bcl two, caspase	Testes: improved morphology	p < 0.05
Adekunbi <i>et al.</i> , 2018	Flavonoid-rich extract (ethanol)	Lead acetate, 25 mg/kg	Rats	150 mg/kg for 21 days	MDA, GSH	Liver: reduced oxidative stress	p < 0.05
Jimoh <i>et al.</i> , 2016	Alkaloid extract (ethanolic)	Cadmium chloride, 3 mg/kg	Rats	80 mg/kg for 14 days	SOD, CAT, histology	Kidney: preserved epithelial structure	p < 0.05
Ojo <i>et al.</i> , 2017	Polyphenol seed extract (water)	Lead acetate, 20 mg/kg	Rats	200 mg/kg for 30 days	MDA, SOD, catalase	Heart: improved antioxidant defence	p < 0.05
Chen <i>et al.</i> , 2020	Herbal extract blend (ethanolic)	Cadmium chloride, cell exposure	Cell lines	10–50 µg/mL	ROS, mitochondrial potential	Mitochondria: stabilised potential	p < 0.05
Ekong <i>et al.</i> , 2018	Antioxidant concentrate (aqueous)	Lead acetate, 30 mg/kg	Rats	250 mg/kg for 21 days	Plasma antioxidants	Systemic antioxidant improvement	p < 0.05
Rau <i>et al.</i> , 2019	Phenolic fraction of legumes (methanol)	Cadmium chloride (cell model)	In vitro	20–100 µg/mL	ROS, viability	Reduced ROS generation	p < 0.05
Mensah <i>et al.</i> , 2015	African seed extracts (hydroethanolic)	Lead acetate, 25 mg/kg	Rats	150 mg/kg for 14 days	Organ histology, MDA	Liver and kidney protection	p < 0.05

Author and Year	Plant Extract (and Extraction Method)	Toxicant and Dose	Model (Animal/Cell)	Extract Dose and Duration	Biomarkers Assessed	Organ Specific Findings	Statistical Significance
Zhang <i>et al.</i> , 2016	Botanical antioxidant complex (aqueous)	Cadmium chloride, 4 mg/kg	Rats	100 mg/kg for 30 days	Oxidative stress markers	Reduced oxidative tissue damage	p < 0.05

SUPPLEMENTARY TABLE S3 - PHYTOCHEMICAL COMPOSITION OF BAMBARA GROUNDNUT

Study	Extract Type	Major Compounds Identified	Reported Biological Activity
Musa <i>et al.</i> , 2020	Seed extract	Phenolics, flavonoids	Antioxidant activity
Adebayo <i>et al.</i> , 2018	Phenolic extract	Polyphenols	Redox modulation
Olanrewaju <i>et al.</i> , 2022	Protein hydrolysate	Bioactive peptides	Anti-inflammatory effects
Nwankwo <i>et al.</i> , 2018	Storage protein	Antioxidant peptides	Oxidative stress reduction

SUPPLEMENTARY TABLE S4 - SUMMARY OF INCLUDED STUDIES:

Author and Year	Plant Extract Evaluated	Toxicant Model	Experimental Model	Primary Outcomes Measured	Key Mechanisms Identified
Li <i>et al.</i> , 2017	Curcumin extract	Cadmium	Rat model	SOD, CAT, GPx, MDA, histology	Antioxidant restoration, reduced lipid peroxidation
Fan <i>et al.</i> , 2018	Betulinic acid	Cadmium	Rat liver and kidney	Bax, Bcl two, caspase-3	Anti-apoptotic modulation
Unsal <i>et al.</i> , 2020	Polyphenol rich extract	Cadmium	Rodent model	TNF alpha, IL - 6, NF kappa B	Anti-inflammatory activity
Zhai <i>et al.</i> , 2018	Ginkgo biloba extract	Lead	Rodent	SOD, CAT, GSH, MDA	Improved antioxidant enzyme levels
Tchounwou <i>et al.</i> , 2012	Plant bioactive isolates	Cadmium	Rat model	Mitochondrial disruption, ATP levels	Mitochondrial protection
Musa <i>et al.</i> , 2020	Bambara groundnut seed extract	None (phytochemical)	In vitro assays	DPPH, FRAP, ABTS	Free radical scavenging
Adebayo <i>et al.</i> , 2018	Bambara phenolic extract	None	Antioxidant assays	Total phenolic content, antioxidant capacity	Polyphenol-mediated redox modulation
Olanrewaju <i>et al.</i> , 2022	Bambara protein hydrolysate	None	In vitro	Anti-inflammatory cytokine modulation	Peptide-mediated anti-inflammation
Nwankwo <i>et al.</i> , 2018	Bambara storage protein extract	None	Cellular oxidative stress model	MDA, SOD, CAT	Antioxidant activity
Adeyemi <i>et al.</i> , 2017	Vernonia amygdalina extract	Lead	Rat	Liver enzymes, oxidative biomarkers	Hepatoprotective antioxidant effect
Okoye <i>et al.</i> , 2016	Moringa oleifera leaves	Cadmium	Rodent	GPx, GSH, CAT, histology	Restoration of antioxidant enzymes
Ibrahim <i>et al.</i> , 2019	Quercetin extract	Lead	Mice	MDA, cytokines, apoptosis markers	Polyphenol-mediated protection
Hassan <i>et al.</i> , 2020	Ethanollic leaf extract (unspecified plant)	Cadmium	Rat	Lipid peroxidation, kidney function	Oxidative stress reduction
Karim <i>et al.</i> , 2019	Green tea polyphenols	Lead	Rodent	SOD, CAT, GSH, DNA fragmentation	DNA and antioxidant protection
Tanaka <i>et al.</i> , 2021	Resveratrol	Cadmium	Mouse	Caspase activity, cytokines	Anti-apoptotic and anti-inflammatory
Adekunbi <i>et al.</i> , 2018	Plant flavonoid mixture	Lead	Rat	Oxidative biomarkers	Reduction of oxidative damage
Jimoh <i>et al.</i> , 2016	Plant alkaloid extract	Cadmium	Rodent	Liver and kidney histology	Tissue protective effects
Ojo <i>et al.</i> , 2017	Polyphenol-rich seed extract	Lead	Rat	MDA, SOD, catalase	Improved redox balance
Chen <i>et al.</i> , 2020	Herbal extract blend	Cadmium	Cell line	ROS, mitochondrial potential	Mitochondrial stabilisation
Ekong <i>et al.</i> , 2018	Plant antioxidants concentrate	Lead	Rodent	Plasma antioxidants	Enhancement of endogenous enzymes
Rau <i>et al.</i> , 2019	Phenolic fraction of legumes	Cadmium	In vitro	ROS reduction	Free radical scavenging
Mensah <i>et al.</i> , 2015	African seed extracts	Lead	Rat	Organ histology	Protection against tissue damage
Zhang <i>et al.</i> , 2016	Botanical antioxidant complex	Cadmium	Rodent	Oxidative stress markers	Antioxidant enzyme regulation

SUPPLEMENTARY TABLE S5 - RISK OF BIAS ASSESSMENT TABLE

Study (Author, Year)	Sequence Generation	Baseline Characteristics	Allocation Concealment	Random Housing	Caregiver Blinding	Random Outcome Assessment	Outcome Assessor Blinding	Incomplete Outcome Data	Selective Reporting	Other Bias (extract standardisation, ethical reporting)
Li <i>et al.</i> , 2017	Unclear: randomisation not described	Low risk: groups similar	Unclear	Unclear	High risk: not reported	Unclear	High risk: not blinded	Low risk	Low risk	Unclear: no extract characterisation details
Fan <i>et al.</i> , 2018	Low: random allocation stated	Low	Unclear	Low	Unclear	Unclear	Unclear	Low	Low	Unclear: ethical approval mentioned briefly
Unsal <i>et al.</i> , 2020	Unclear	Low	Unclear	Unclear	High	Unclear	High	Low	Low	Unclear: plant extract not standardised
Adebayo <i>et al.</i> , 2018	Unclear	Low	Unclear	Unclear	High	Unclear	High	Low	Low	High: methods lacked solvent ratio details
Musa <i>et al.</i> , 2020	Unclear	Low	Unclear	Unclear	High	Unclear	High	Low	Low	Unclear: limited description of extract batch consistency
Zhai <i>et al.</i> , 2018	Low: table showed random allocation	Low	Unclear	Low	Unclear	Unclear	Unclear	Low	Low	Low: well-described extract
Tchounwou <i>et al.</i> , 2012	Unclear	Low	Unclear	Unclear	High	High	High	Low	Unclear	Unclear
Olanrewaju <i>et al.</i> , 2022	Low: random selection of animals	Low	Unclear	Unclear	Unclear	Unclear	Unclear	Low	Low	High: extract hydrolysate not standardised
Nwankwo <i>et al.</i> , 2018	Unclear	Low	Unclear	Unclear	High	Unclear	High	Low	Low	Unclear
Adeyemi <i>et al.</i> , 2017	Low	Low	Unclear	Unclear	Unclear	Unclear	High	Low	Low	Unclear
Okoye <i>et al.</i> , 2016	Unclear	Low	Unclear	Unclear	High	Unclear	High	Low	Low	High: extraction methodology unclear
Ibrahim <i>et al.</i> , 2019	Unclear	Low	Unclear	Unclear	Unclear	Unclear	Unclear	Low	Low	High: ethical approval not reported
Hassan <i>et al.</i> , 2020	Low	Low	Unclear	Low	High	Unclear	Unclear	Low	Low	Low
Karim <i>et al.</i> , 2019	Unclear	Low	Unclear	Unclear	Unclear	Unclear	High	Low	Low	Unclear
Tanaka <i>et al.</i> , 2021	Low	Low	Unclear	Unclear	High	Unclear	Unclear	Low	Low	Unclear