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Review

An Assessment of Trace Element Accumulation in Palm Oil Production

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Abstract: African oil palm (*Elaeis guineensis*) is grown on 17,000,000 hectares in Southeast Asia, producing oil and the by-product, palm kernel expeller (PKE), for export. Elaeis guineensis is typically produced on weathered acidic soils, with fertilisers and fungicides used to increase production. These amendments can contain elevated concentrations of trace elements (TEs), either as the active ingredient (e.g., Cu-based fungicides) or as contaminants, including F, Zn, As, Cd, Pb and U. TEs may accumulate in soil over time, and be taken up by plants, posing a food-chain transfer risk if allowed to exceed soil guideline values. We reviewed available literature on trace elements in soil, plant material, oil and PKE to evaluate the risk of TE accumulation due to phosphate fertiliser and Cu-fungicide use. TE concentrations of Cu, Zn, and Cd were reported to be up to 69, 107 and 5.2 mg kg^{-1}, respectively, in *E. guineensis* plantation soils, while Cu and As were reported to be up to 28.9 and 3.05 mg kg^{-1}, respectively, in PKE (>50% their permissible limits). Iron, a TE, has also been reported in PKE up to 6130 mg kg^{-1} (>10-fold the permissible limit). TE accumulation is an emerging issue for the palm oil industry, which, if unaddressed, will negatively affect the industry's economic and environmental sustainability. There are critical knowledge gaps concerning TEs in palm oil systems, including a general lack of research from Southeast Asian environments and information concerning key contaminants (Fe, Cu, As and Cd) in soils, plants and PKE.

Keywords: copper; *Elaeis guineensis*; fertiliser contaminants; heavy metals; palm kernel expeller

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1. Introduction

The African oil palm (*Elaeis guineensis* Jacq.) is the highest yielding oil crop, with a maximum potential yield of 8 t ha^{-1} [1]. From 2012–2020, *E. guineensis* represented 36–37% of vegetable oil production worldwide [2,3]. Indonesia and Malaysia supply ca. 85% of the world's palm oil, with a combined harvestable area of more than 17,000,000 ha [4,5]. Thailand, Colombia and Nigeria are the third-, fourth- and fifth-highest producing countries of palm oil, respectively [6]. Palm oil is used in products for health care, home care and hygiene, as well as in many processed foods [7]. A dry matter by-product of palm oil production, palm kernel expeller (PKE), is sold as a supplementary stockfeed. In 2020, worldwide PKE production reached 10,214,000 t [8].

Production of *E. guineensis* in Southeast Asia occurs on tropical soils, which are typically weathered and acidic, and, as such, require significant fertiliser inputs to meet nutrient demands. Fungicides are applied to control plant disease [9–11]. Without fertiliser applications of Nitrogen (N), Phosphorus (P), Potassium (K), Magnesium (Mg) and Boron (B), *E. guineensis* trees will become nutrient deficient, yields will decline, and production may become uneconomic, particularly for smallholders in Southeast Asian environments [11,12]. Applications of Copper (Cu) and Zinc (Zn) are also critical when growing *E. guineensis* on Histosol soils [11]. Fertiliser trials have shown that yields may reach 8 t oil ha^{-1} yr^{-1} with appropriate fertiliser management; however, the average yield is 4 t ha^{-1} yr^{-1} [1,13,14]. Fungicidal treatments using Cu as an active ingredient are commonly applied to prevent plant diseases, including *Ganoderma* spp. [15]. Fertilizers and fungicides can contain significant concentrations of trace elements (TEs), either as part of the active ingredient [16] or as a contaminant [17]. TE contaminants in agrichemicals can accumulate in soil [18], which can result in reduced soil fertility [19] and/or uptake into the (human) food chain [20,21].

A combination of poor environmental controls (in the form of poor monitoring and enforcement of fertiliser-use recommendations) and a lack of knowledge about soil nutrient status and plant requirements often leads to inappropriate fertiliser applications, particularly in Southeast Asian smallholder plantations [22]. As well as having demonstrable negative effects on fruit-bunch yield [12], inefficient nutrient management can lead to the contamination of soils and surface and groundwaters due to N leaching or the run-off of P and TEs [23]. Similarly, TE-containing fungicides may be overapplied, accelerating TE accumulation in soil. Cadmium (Cd) from fertilisers and Cu from fungicides are two of the most likely TE contaminants to accumulate in horticultural soils [24,25]; however, other fertiliser-borne contaminants include Fluorine (F), Chromium (Cr), Zn, Arsenic (As) and Lead (Pb) [17].

While there are disparate reports on TE concentrations in some components of *E. guineensis* production, there is no information available on fluxes throughout the whole system. This review aims to identify key TEs of concern, elemental fluxes, potential risks to ecosystems and human health, and knowledge gaps concerning this production system.

2. Trace Elements in Soils of *Elaeis guineensis* Production

2.1. Sources of Trace Elements in Elaeis guineensis Plantation Soils

2.1.1. Geogenic Trace Elements

Soils naturally contain TEs, with concentrations varying geographically due to biogeochemical processes [26]. In tropical regions, weathering and climate are key factors influencing background TE concentrations of soils [27,28]. Food-chain transfer risk may occur when naturally high TE soils with low pH and organic matter content are used to produce food crops, as these conditions favour TE mobility and subsequent plant uptake [29,30]. *Elaeis guineensis* in Southeast Asia is typically cultivated on acidic, weathered soils, including Ultisols, Inceptisols, and Oxisols, as well as Histosols [11] according to the USDA Soil Classification [31]. Ultisols and Oxisols are generally highly leached and contain TEs, including Cobalt (Co), Nickel (Ni), Cu, Zn, Cd, Mercury (Hg) and Pb [32]. General background concentrations of these TEs in soils are 8, 40, 20, 50, 0.06, 0.03 and 10 mg kg^{-1}, respectively [26]. Histosols contain TEs (Titanium (Ti), Manganese (Mn), F and Barium (Ba) at background concentrations of 5000, 850, 200 and 500 mg kg^{-1}, respectively [26,33], which are released as the soil degrades under drainage and cultivation processes [34].

2.1.2. Anthropogenic Sources of Trace Elements in Soils

Most TEs that enter soils via agrichemical use are rapidly immobilised through the processes of specific absorption, occlusion and precipitation [35]. Therefore, most TEs will accumulate in soil following repeated applications of agrichemicals. TEs may be lost from the soil via surface erosion or run-off, while leaching of TEs is usually negligible [36].

Tropical soils in Southeast Asia typically contain deficient levels of P to support *E. guineensis* production, thus requiring fertiliser inputs to provide plants with the required nutrients [11,37]. A study of smallholder plantations in Indonesia by Woittiez et al. [22] identified that Indonesian farmers relied heavily on subsidised fertilisers, which did not supply soils with appropriate nutrients for *E. guineensis* production. More than 99% of smallholders surveyed used mineral fertilisers, including several phosphatic fertilisers. These fertilisers can contain contaminants including F, Cu, Zn, As, Cd, Pb and Uranium (U), which can result in soil contamination and human exposure risk if inappropriately or excessively applied [17,38]. Rare earth elements (REEs) are also present in phosphate fertilisers and may enter the soil-plant system through regular use of these [39,40]. The rate of use and application of the most commonly used fertilisers reported by Woittiez et al.

are presented in Table 1, as well as the average mass of key elements added as fertiliser contaminants through such applications.

Table 1. Fertiliser use and application rates in smallholder plantations in Indonesia, reported by Woittiez et al. [22] with associated contaminant inputs of F, Cu, Zn, Cd, Pb and U.

Fertiliser (NPK Ratio)	Use (% of Farmers Surveyed)	Application Rate (kg ha^{-1} yr^{-1})	Approximate Mass Added (g ha^{-1} yr^{-1})					
			F [a]	Cu [a]	Zn [a]	Cd [b]	Pb [a]	U [a]
NPK Phonska (15–15–15)	66	692	15,916	64	261	4.8–48	3.5	25
NPK Pelangi (15–15–15)	9	756	17,388	70	285	5.2–52	3.8	27
Single super-phosphate (0–36–0)	21	452	6396	26	94	7.5–75	9.04	24
Triple super-phosphate (0–46–0)	7	400	8400	17	146	8.4–84	6.8	47
Rock phosphate (0–20–0)	1	1000	29,856	22	245	9.2–92	12	92

[a] Calculated using average total contaminant concentrations in phosphate fertilisers from Taylor et al. [38]. [b] Possible range given due to the differing contaminant concentrations of Cd in phosphate rock dependent on geographical origin (20–200 mg Cd kg $P_2O_5{}^{-1}$ in sedimentary rock [41]).

The majority of smallholders surveyed by Woittiez et al. [22] applied excessive amounts of fertilisers compared with the nutritional requirements of the crop and employed practices likely to lead to nutrient run-off and leaching. Such practices included weed-clearing in plantations using glyphosate and paraquat, which left soil bare and vulnerable to erosion and transfer to kernels. Farmers also manually (un-uniformly) mixed straight fertilisers, applied fertilisers in bulk once per year, and applied fertilisers in a narrow ring around the base of the palm, rather than uniformly to the soil area colonised by palm roots or on top of decomposing palm fronds, as is recommended as good practice [42–44]. Conversely, some farmers applied insufficient fertilisers for *E. guineensis* production (18% applied no K, 20% no P, and 15% no N), leading to decreased yield and soil nutrient deficiencies. Smallholders manage more than 40% of *E. guineensis* plantations in Indonesia (4,700,000 ha) [45], and inefficient nutrient management over this area is both a significant risk to the economic sustainability of this industry as well as a driver of deforestation, as more land area is needed to produce economically viable yields [22].

Elaeis guineensis production can be reduced by diseases; in particular, the fungal pathogen *Ganoderma* spp., which causes trunk rot, is especially problematic in Southeast Asian plantations [9,10,46]. Copper-based fungicides are commonly employed to control this disease, with available products having varying active ingredient (Cu) concentrations from 7.6–75% [10,15,47]. Bivi et al. [15] found that continuous Cu applications totalling 21.45 g Cu ha^{-1} yr^{-1} (combined with Calcium (Ca) and salicylic acid) were effective in controlling basal stem rot in *E. guineensis* plants (This application rate was calculated using data from Bivi et al. [15] with a tree density of 143 trees ha^{-1}, described as optimal by FAO [48]). However, the actual application rates used by farmers may be in excess of this due to the uncontrolled nature of fungicide use in Indonesia [49]. There is a lack of data available on actual Cu application rates utilised in *E. guineensis* plantations. In Europe, past fungicide application rates have been as high as 80 kg Cu ha^{-1} on agricultural soils and have led to soil contamination [50]. Current European Union guidelines allow for applications of 6 kg Cu ha^{-1} on agricultural soils [51]. Only one Indonesian study on fungicide use could be found for comparison [49]. Here, fungicide application rates used in hot pepper cultivation in Indonesia are reported as a mean of 14.3 kg active ingredient ha^{-1} and a maximum of 33.8 kg active ingredient ha^{-1}. Copper was an active ingredient in the fungicides used in this study [52]. The variation in application rates observed in this study fits with that observed throughout other systems: for example, Morgan and Taylor [53] reported median Cu application rates of 2 kg ha^{-1} yr^{-1}, with the highest application rate being 16 kg ha^{-1} yr^{-1} in New Zealand vineyards. Repeated applications of Cu-containing products to horticultural crops can result in Cu accumulation in soils [54,55] through the return of fungicide-applied plant material to the soil surface and through spray drift landing on the soil surface during application. In excessive quantities, Cu in soils can inhibit plant growth and pose risks to human health [56,57].

2.2. Measured Trace Element Concentrations in Soil

Available data on trace element concentrations in *E. guineensis* plantation soils are presented in Table 2. Two soils from Papua New Guinean *E. guineensis* plantations have Cd concentrations <1 mg kg^{-1} [58]. Aini Azura et al. [59] reported Zn and Cd concentrations up to 99 and 5.2 mg kg^{-1}, respectively, in Malaysian *E. guineensis* production soils. These are the only two studies to be identified which were conducted in Southeast Asia, and thus there is a lack of relevant research looking at critical TEs, including F, Cu and Pb, in a Southeast Asian environment.

In Nigeria, TEs have been reported present in concentrations that both exceed and fall short of optimal concentrations for *E. guineensis* cultivation. Orobator et al. [60] reported significant differences in Mn, Iron (Fe), and Cd concentrations across three plantation sites, with Cu and Zn found to be deficient at one site and no excessive TE concentrations observed. In a separate study, *E. guineensis* plantation soil reportedly contained lower concentrations of Cu and Zn than secondary forest soils [61]. Soil Cr and Pb concentrations have been reported at background levels by Uwumarongie-Ilori et al. [62]. In contrast to these studies, Olafisoye et al. [63] reported Cd concentrations exceeding background concentrations (0.5 mg kg^{-1}) in 15 plantation soils, with the highest soil containing 4.3 mg kg^{-1} Cd. This was attributed to the repeated use of phosphate fertilisers. Additionally, the authors reported that total Cr, Co, Ni and Pb concentrations exceeded maximum permissible levels for soils (100, 8, 40, and 10 mg kg^{-1}, respectively). The maximum reported soil copper concentration was 61 mg kg^{-1} and was concluded to pose a toxicity risk to plants and animals. *Elaeis guineensis* production soils in Ghana were reported as Molybdenum (Mo) deficient by Golow et al. [64]. In all studies mentioned here, soil TE levels were found to be either deficient (Cu, Zn, Mo) or excessive (Cr, Co, Ni, Cu, Cd, Pb) relative to the requirement and tolerance of *E. guineensis*. This underlines the need to match on-farm management with soil status, especially in systems with high nutrient demands, such as palm cultivation on weathered tropical soils. Notably, no data could be found on F, As, or U concentrations in soil under *E. guineensis* production.

Table 2. Trace element concentrations in *E. guineensis* plantation soils (0–30 cm depth unless otherwise stated) with average concentrations for soil, rocks and Earth's crust.

Element	Concentration Range (mg kg^{-1})	Average Concentrations of Earth Materials [a]				
		Soil (mg kg^{-1})	Earth's Crust (mg kg^{-1})	Granite (mg kg^{-1})	Sandstones (mg kg^{-1})	Igneous Rocks (mg kg^{-1})
V	0.56–4.9 [b]	100	135	17	20	135
Cr	26–132 [c]	100	100	20	35	100
Mn	2.4–20.5 [b] 0.12–29 [c] 20.6–81 [d]	850	950	195	X0 [h]	950
Co	0.80–9.4 [c] 0.03–2.9 [d]	8	25	2.4	0.3	25
Ni	1.5–13 [b] 30.3–59 [c]	40	75	1	2	75

Table 2. *Cont.*

Element	Concentration Range (mg kg^{-1})	Average Concentrations of Earth Materials [a]				
		Soil (mg kg^{-1})	Earth's Crust (mg kg^{-1})	Granite (mg kg^{-1})	Sandstones (mg kg^{-1})	Igneous Rocks (mg kg^{-1})
Cu	1.1–9.8 [b] 3.9–6.5 [e] 13–69 [c] 3.06–18 [d]	20	55	13	X [h]	55
Zn	2.09–25 [b] 4.8–6.2 [e] 12–107 [c] 0.85–6.8 [d] 11–99 [f]	50	70	45	16	70
Mo	<0.01–1.05 [d]	2	1.5	6.5	0.2	1.5
Cd	0.22–2.0 [b] 0.32–4.3 [c] 0.45–5.2 [f] <1 [g]	0.06	0.2	0.03	0.0X [h]	0.08
Pb	6.8–14 [c]	10	13	48	7	13

[a] [26]. [b] Nigeria [60]. [c] Nigeria, range of means [63]. [d] Ghana, 0–40 cm depth [64]. [e] Nigeria [61]. [f] Malaysia [59]. [g] Papua New Guinea [58]. [h] X denotes an order of magnitude estimate.

The TE concentrations in the aforementioned reports will be a function of both the agrichemicals used and the time that the land has been under agricultural production, either as *E. guineensis* or a previous crop(s). Given that many *E. guineensis* plantations have recently been converted from virgin forests, TE concentrations may still be similar to background levels. Therefore we might hypothesise that TE concentrations in African soils, which were converted to *E. guineensis* some 100 years ago [13], will have higher TE concentrations than recently converted soils in Southeast Asia.

3. Trace Elements in *Elaeis guineensis* and Comparable Species

There are three varieties of *E. guineensis*: pisifera, dura, and the hybrid variety tenera [65]. Var. pisifera typically has no endocarp and a thick mesocarp, var. dura a thick mesocarp and endocarp, and var. tenera a moderately thick mesocarp and thin endocarp, with a moderately sized endosperm [13]. This hybrid variety was developed to produce higher oil-yielding crops and now dominates most plantations in Southeast Asia [66].

Monocotyledonous plants, including *E. guineensis,* uptake TEs from soil via exchange sites on root surfaces that are then transported to the above-ground portions, especially the leaves, via xylem transport, using the symplastic and apoplastic pathways. Leaf tissue, a water sink, is expected to have higher concentrations of TEs relative to other tissue. To reach the fruit, however, TEs must be transported in the phloem and maybe traverse the placenta, making fruit tissues (mesocarp and seed) likely to contain lower TE concentrations [67]. In *E. guineensis* production systems, leaves (fronds) are often returned to soil as organic matter inputs [68,69]. If high levels of TEs are contained within these leaves, or if TEs are sorbed to palm fronds after fungicide spray applications, this may result in accumulation of TEs on the soil surface following leaf abscission. The study mentioned in Section 2.2 by Aini Azura et al. [56] is the only study that could be identified which investigated TE concentrations in *E. guineensis* fronds, reporting concentrations of ca. 0.18–0.38 mg kg^{-1} for Cd and ca. 15–28 mg kg^{-1} for Zn.

Only three relevant studies could be identified which addressed TE concentrations in *E. guineensis* kernels. Nigerian kernels were generally reported to contain higher levels of Mn, Fe, Cu and Zn (up to 610, 220, 26 and 43 mg kg^{-1}, respectively) relative to Malaysian kernels (up to 145, 52, 18 and 36 mg kg^{-1}, respectively) [70,71]. Lead was reported below detection levels in Nigerian kernels, while Cd was reported up to ca. 0.31 mg kg^{-1} in Malaysian kernels [59,71]. Mean concentrations of TEs in *E. guineensis* kernels from these studies are compared with average TE concentrations of land plants in Table 3.

Table 3. Trace element concentrations in *E. guineensis* kernels from Malaysia and Nigeria.

Element	Mean Concentration Range in Malaysian Kernels (mg kg^{-1})	Mean Concentration Range in Nigerian Kernels (mg kg^{-1})	Mean Concentration in Land Plants (mg kg^{-1}) [a]
Mn	82–145 [b]	410–610 [c]	630
Fe	43–52 [b]	110–220 [c]	140
Cu	16–18 [b]	17–26 [c]	14
Zn	25–36 [b] 4–13 [d]	26–43 [c]	100
Cd	0.09–0.31 [d]	—	0.6
Pb	—	≤0.05 [b]	2.7

[a] [26]. [b] Endosperm of seed- and clonally-derived var. tenera [70]. [c] Defatted and undefatted var. tenera and var. dura [71]. [d] Estimated from graph [59].

While research on TEs in *E. guineensis* plant material is sparse, data have been collected on TEs in other Arecaceae species, including date palm (*Phoenix dactylifera* L.), acai (*Euterpe oleracea* Mart.), and jucara (*Euterpe edulis* Mart.) (Table 4). Due to their similar physiologies, TEs in these species may behave similarly to those in *E. guineensis*. As such, it is beneficial here to review the literature concerning TEs in these Arecaceae species to garner insights into whether a wider range of TEs may accumulate in *E. guineensis*.

Table 4. Trace element concentrations in materials of other Arecaceae species.

Element	Mesocarp Concentration *P. dactylifera* (mg/kg^{-1})	Seed Concentration *P. dactylifera* (mg/kg^{-1})	Leaf Concentration *P. dactylifera* (mg/kg^{-1})	Mesocarp Concentration *E. oleracea* Mart. (mg/kg^{-1})	Mesocarp Concentration *E. edulis* Mart. (mg kg^{-1})
Li	<0.007–0.17 [a]	<0.007–0.017 [a]	—	—	—
Al	48.4 (2.6) [b]	—	—	—	—
Cl	3340 (280) [b]	—	—	—	—
Sc	0.028 (0.004) [b]	—	—	—	—
V	<0.008–0.016 [a]	<0.008–0.021 [a]	—	—	—
Cr	0.49 (0.5) [b]	—	0.18–0.99 [c]	—	—
Mn	1.0–7.0 [a] 7.5 (0.3) [b]	2.4–11.5 [a]	0.35–0.96 [c]	—	—
Fe	2.0–7.0 [a] 197 (10) [b]	3.2–30.9 [a]	1.6–9.4 [c]	—	—
Co	0.026–5.1 [a] 0.025 (0.003) [b]	0.075–3.20 [a]	—	—	—
Ni	0.071–0.70 [a]	0.15–0.69 [a]	0.022–0.083 [c]	—	—
Cu	0.7–7.2 [a]	1.3–8.4 [a]	2.0–9.6 [c]	—	—
Zn	1.4–12.6 [a] 9.5 (0.5) [b]	3.9–28 [a]	0.6–3.5 [c]	—	—
As	<0.04–0.051 [a] 1.9 (0.17) [b]	<0.04–0.089 [a]	—	0.0095 [d]	—

Table 4. *Cont.*

Element	Mesocarp Concentration *P. dactylifera* (mg/kg^{-1})	Seed Concentration *P. dactylifera* (mg/kg^{-1})	Leaf Concentration *P. dactylifera* (mg/kg^{-1})	Mesocarp Concentration *E. oleracea* Mart. (mg/kg^{-1})	Mesocarp Concentration *E. edulis* Mart. (mg kg^{-1})
Se	<0.1–0.120 [a] 0.102 (0.013) [b]	<0.1–0.3 [a]	—	—	—
Br	3.2 (0.15) [b]	—	—	—	—
Rb	5.4 (0.5) [b]	—	—	—	—
Sr	1.1–14.8 [a] 13.9 (1.2) [b]	0.21–5.2 [a]	—	—	—
Mo	0.18 (0.05) [b]	—	—	—	—
Cd	<0.002–0.013 [a] 0.08–0.23 [e]	<0.002–0.012 [a]	0.043–0.19 [c]	0.0094 [d]	—
La	0.36 (0.04) [b]	—	—	8.03–230 [f]	17–199 [f]
Ce	0.47 (0.05) [b]	—	—	20.1–575 [f]	36–319 [f]
Hg	0.051 (0.003) [b]	—	—	0.0016 [d]	—
Pb	<0.02–0.14 [a] 0.84–2.3 [e]	<0.02–0.11 [a]	0.22–1.98 [c]	0.037 [d]	—
Th	—	—	—	0.99–179 [f]	15–87 [f]

[a] Spain [72]. [b] Pakistan, number in brackets assumed to be standard deviation of the mean, $n \geq 6$ [73]. [c] Turkey, range of means [76]. [d] [74]. [e] Saudi Arabia, range of means [75]. [f] [40].

Accumulation of Cr, Co and Ni has been reported in mesocarp and seed up to concentrations of 0.5, 5.1 and 0.7 mg kg^{-1}, respectively [72]. In a separate study, As was reported in mesocarp samples at 0.17 mg kg^{-1}, although this did not exceed tolerable dietary levels [73]. Comparable concentrations were reported for Cd in *P. dactylifera* and *E. oleracea*, of up to 0.13 and 0.0094 mg kg^{-1}, respectively [72,74]. Both leaves and mesocarp of *P. dactylifera* have been shown to take up TEs from the air in contaminated environments, with TE concentrations increasing in areas with increased anthropogenic air pollution sources [75,76].

Rare earth element concentrations of *E. oleracea* and *E. edulis* were reported by Santos et al. [40]. *Euterpe oleracea* contained the highest concentrations of REEs, up to 230, 575 and 179 mg kg^{-1} for La, Ce and Th, respectively. It was also reported that geographical location affected REE concentrations of both *E. oleracea* and *E. edulis*. This emphasises the variation which can occur in the TE content of plant tissues due to geographical and geological factors. Tables of REE contents in Arecaceae species are provided in the Supplementary Materials.

The TE concentrations detailed in Table 4 indicate that TE accumulation occurs in palm species when exposure pathways are present. This indicates that TE accumulation in *E. guineensis* tissues and associated products may occur when plants are grown in contaminated environments.

4. Trace Elements in Palm Oils

The *E. guineensis* tree produces two types of oil from its fruit: palm kernel oil from the endosperm; and palm oil from the mesocarp. While the two names are often used interchangeably, palm oil is commonly used for food products due to its near-even balance of unsaturated and saturated fatty acids and its alpha- and beta-carotenes, while palm kernel oil is more commonly used in other products such as soaps and cosmetics and is less saturated relative to palm oil [77]. Red palm oil is a further differentiated oil and refers to palm oil with a high carotenoid content giving it a dark red colour.

Trace elements may be present in palm and palm kernel oil as a result of processing (including refining, manufacturing, storage, shipping and packaging) and processing equipment due to *E. guineensis* plant uptake from soils or from soil contamination on kernels (i.e., dust from harvesting on associated soils) [7,78]. Trace elements in palm oils may occur as complexed impurities and contribute to dietary trace nutrient intake, which may provide nutritional benefits or, in excessive quantities, may breach food safety standards and pose risks to human health when ingested [7,79]. Here, research on TEs in palm oils is reviewed. A summary of available data of TEs in palm and palm kernel oils is presented in Table 5.

Crude palm oil is extracted from the mesocarp of *E. guineensis* either by solvent (chemical) or physical (manual crushing of palm kernels) extraction [80]. It may then be further refined by rinsing with hot demineralised water; degumming with citric acid; adsorptive cleaning, bleaching, and filtering to remove TEs and other impurities; and deodorising to remove volatile compounds [7]. Non-uniform manufacturing processes can affect TE concentrations in palm oil. In an analysis of oil at all stages of the above refining process, Szydłowska-Czerniak et al. [7] found that refining removed 72%, 94% and 63% of Fe, Cu and Pb from crude palm oil, respectively. A more than three-fold increase in Pb was noted between the filtering and deodorising steps and attributed to contamination from the equipment used in this step of the refining process. Copper concentrations in crude palm oil (0.46 mg kg^{-1}) exceeded Polish standards of 0.40 mg kg^{-1}. However, the final product fell within the acceptable range of <0.10 mg kg^{-1}. No other exceedances of standards were noted by the authors. A similar study of the same TEs was conducted on Indonesian crude palm oil by Rossi et al. [81]. They concluded that using phosphoric rather than citric acid as a degumming agent increased Pb concentrations in degummed oil; however, concentrations of Cu and Pb in the fully refined product were less than the suggested limit of 0.1 mg kg^{-1} [82]. These two studies demonstrate how non-uniform manufacturing processes impact the TE content of marketed palm oils.

Two studies by Chen et al. [83] and Chen et al. [84] determined As concentrations in refined and fractionated palm oils from Taiwan, with both studies reporting low As concentrations ($\leq$0.025 mg kg^{-1}). Limits for As in oils have not yet been determined, and the toxicity risk depends on the type of As present (organic or inorganic) [85]. Australasian food standards set a limit of 1 mg kg^{-1} total As for cereals and 0.5 mg kg^{-1} for salt; however, limits are often set only for inorganic As due to its higher toxicity [86]. Consequently, research on As speciation in palm oils may be beneficial for the purpose of addressing the risk of As-toxicity.

Various studies have investigated elemental concentrations of Nigerian palm oil [87–90]. Collectively, Al, Cr, Mn, Fe, Co, Ni, Cu, Zn, As, Cd, Hg and Pb have been analysed using atomic absorption spectrometry methods. All elements were reported present at concentrations that posed no risk to human health according to standards set by Nigerian regulatory bodies; however, atomic absorption spectrometry may not be a sufficiently sensitive method for this analysis [91]. Further research analysing TEs in Nigerian palm oil using more analytically sensitive methods, e.g., optical emission spectrometry or mass spectrometry, would be beneficial.

Two studies were identified which investigated TE concentrations in palm kernel oil [92,93]. Here, reported Al, Cl, V, Mn, Fe, Cu and Zn concentrations were comparable to those of palm oils in other studies (Table 5).

While multiple studies have addressed TEs in Nigerian palm oils, there is a scarcity of research on palm kernel oil and oils from other countries, particularly Malaysia and Indonesia. This is significant since these countries produce almost 85% of the world's traded palm oil supply [95]. Malaysian and Indonesian production soils differ from each other and from other palm-producing countries, and there are various methods of oil extraction used across different plantation types. There is little current knowledge on the risks or benefits of TEs in palm oil and palm kernel oil as a result of these differing soils, plantation types, and production practices in Southeast Asia.

Table 5. Elemental concentrations in palm and palm kernel oils.

Element	Concentration in Palm Kernel Oil (mg kg^{-1})	Concentration in Palm Oil (mg kg^{-1})
Al	38.30 (0.58) [a]	31.00 (0.56) [a] 1.9 [b]
Cl	22.21 (0.79) [a]	29.60 (0.74) [a]
V	0.055 (0.009) [a]	0.065 (0.007) [a]
Cr	—	2.3 [b] 0.101–0.298 [c] 0.021–0.033 [d]
Mn	1.45 (0.03) [a]	0.94 (0.02) [a] 0.24–1.1 [e] 6.55–12.05 [c]
Fe	20.04 (0.20) [f]	11 [b] 15–35 [e] 65–232 [c] 38.3–78.3 [g] 0.12 (0.0058) [h] 0.27–2.40 [i]
Co	—	0.000–0.064 [e]
Ni	—	0.000–0.79 [e] 0.15–0.81 [c] 0.044–0.068 [d]
Cu	6.0 (0.35) [a]	1.4 (0.09) [a] 0.071 [b] 0.000–0.25 [e] 0.56–2.09 [c] 0.030 (0.001) [h] 0.03–0.05 [i]
Zn	2.82 (0.30) [f]	0.45–1.6 [e] 3.6–14.6 [c] 0.05–0.24 [g]
As	—	0.001–0.0025 [d] 0.025 [j] <0.015 [k]
Cd	—	0.022 [b] 0.024–0.094 [c] 0.025–0.065 [d]
Hg	—	0–0.055 [d]
Pb	—	0.018 [b] 0.024–0.067 [c] 0.023–0.038 [d] 0.0060 (0.0003) [h] <0.005 [i]

[a] Nigeria, neutron activation analysis, number in brackets assumed to be standard deviation of the mean, number of samples not indicated [93]. [b] Nigeria [88]. [c] Nigeria [90]. [d] Nigeria, range of means, red palm oil [94]. [e] Nigeria, range of means [87]. [f] Nigeria, number in brackets assumed to be standard deviation of the mean, number of samples not indicated [92]. [g] Nigeria [89]. [h] Poland, number in brackets is standard deviation of the mean (n = 3) of final palm oil product after deodorising, analysed by inductively coupled plasma [7]. [i] Indonesia, steam refined oil [81]. [j] Taiwan [83]. [k] Taiwan [84].

5. Trace Elements in Palm Kernel Expeller

Palm kernel expeller is the dry matter by-product of palm oil production, which is exported by manufacturing countries—primarily Indonesia and Malaysia—and utilised as a stockfeed in many Asian, European and Oceanic nations. Of these, New Zealand imports the largest amount of PKE annually, at 2,300,000 t in 2019 [96]. Although studies (and indeed importers) rarely differentiate between palm oils produced by physical and solvent extraction, Alimon [80] asserts that the latter leaves less oil in the PKE by-product (1–2%) compared to physical extraction (4–8%). Oil contents ranging up to 17.3% have been reported elsewhere [97]. Physical extraction is most commonly used as it is a more economical option [80]. As with palm oils, TEs may occur in PKE as a result of plant TE-uptake from soil, machinery and equipment used in manufacturing processes, and from soil contamination [7,78]. The TE content of PKE as a supplementary stockfeed has implications for animal and human health. Accordingly, Grace and Knowles [98] acknowledged that attention must be paid to the cumulative intake of minerals by animals from non-pasture-based feeds to ensure TE toxicity does not occur. Available information on PKE TE concentrations is presented in Table 6.

Three studies could be identified which have investigated TE concentrations of PKE [80,99,100]. Of these, two reported TE concentrations within acceptable ranges, or below Maximum Tolerable Levels (MTLs), for animal feed [80,100]. These include Mn, Zn, Se and Mo at concentrations below 2000, 500, 5 and 5 mg kg^{-1}, respectively [101].

Copper and As have been reported at concentrations that exceed 50% of their MTLs of 40 (This MTL is for animals fed a diet of 1–2 mg kg^{-1} Mo and 1500–2500 mg kg^{-1} S: Cu may become toxic at lower concentrations if dietary Mo and S are below these levels) and 4 mg kg^{-1}, respectively [80,99,100]. Alimon [80] noted that Cu concentrations of PKE up to 28.9 mg kg^{-1} exceeded ruminant requirements, and animals fed a diet of >50% PKE may develop Cu-toxicity symptoms. An ovine feed experiment on the occurrence of Cu-toxicity by Hair Bejo and Alimon [102] corroborates this point: all animals in PKE-fed groups not supplemented with Zn died before the study was completed due to Cu-toxicity from PKE, while those in Zn-supplemented and control groups survived. Thus, while high Cu concentrations in PKE can be a source of risk for livestock in receiving environments, this may be mitigated with appropriate TE management. Conversely, if managed correctly, the Cu content of PKE may provide a benefit to countries such as New Zealand, where background soil Cu concentrations are low, and farmers must supplement livestock at an expense [103].

Table 6. Trace element concentrations in PKE from Malaysia and MTLs for cattle feed.

Element	Reported Concentration (mg kg^{-1})	MTL for Cattle Feed (mg kg^{-1})
Mn	225 [a] 132–340 [b]	2000 [d]
Fe	4.05 [a] 835–6130 [b]	500 [d]
Cu	28.5 [a] 20.5–28.9 [b]	40 [d,e]
Zn	77 [a] 40.5–50.0 [b]	500 [d]
As	0.18–3.05 [c]	4 [f]
Se	0.23–0.30 [b]	5 [d]
Mo	0.70–0.79 [b]	5 [d]

[a] [100]. [b] [80]. [c] [99]. [d] [101]. [e] This value assumes a dietary Mo concentration of 1–2 mg kg^{-1} and S concentration of 1500–2500 mg kg^{-1}. With less Mo and S in animals' diets, Cu toxicity may occur at lower levels. [f] [104].

Iron has been reported in PKE in concentrations up to 6130 mg kg^{-1} [80]. This upper concentration range is >10-fold higher than is permissible in cattle feed (500 mg kg^{-1} [101]). It is likely that this Fe is a result of contamination during manufacturing processes, as this concentration is far in excess of upper range kernel concentrations reported by Akpanabiatu et al. [71] (220 mg kg^{-1}) and average land plant Fe concentrations (140 mg kg^{-1} [26]). Excessive Fe intake in bovines can decrease milk production and body weight, with minimum deleterious doses estimated below 30 mg kg^{-1} day^{-1} [105]. Thus, there is an apparent risk of TE-toxicity for animals fed PKE containing TEs of these concentrations.

While attention has been given to Cu-toxicity risk in animals consuming PKE, other elements identified in the above-mentioned publications may also be of concern. In particular, Fe may be present in concentrations that pose risks to milk yield and animal health. Further research on the overall mineral composition of PKE would be beneficial, as there is a lack of data available on the concentrations of other non-essential biotoxic TEs, including Pb and Cd, which may be present in PKE due to their presence as impurities in phosphate fertilisers used in *E. guineensis* production [17,37]. Furthermore, there is a lack of research on PKE sourced from outside Malaysia and from different plantation types (including smallholder, community managed, government- and corporate-owned), whose management practices result in non-uniform application and accumulation of TEs in soil, plants and end-products [37]. Overall, there are scarce data available on the TE content of PKE, and filling this knowledge gap would be beneficial for all countries utilising this by-product in their agricultural systems by way of maintaining livestock well-being and soil nutrient status.

6. Conclusions

This review has identified the elements of concern in *E. guineensis* production systems as Fe, Cu, Zn, Cd and As. Copper, Zn and Cd have been reported in production soils at elevated concentrations and may pose risks to production if allowed to accumulate past soil guideline values. These TEs are present and accumulate in *E. guineensis* production soils, likely as a result of phosphate fertiliser and Cu-fungicide use in plantations. Iron may be present in PKE in concentrations >10-fold higher than its MTL—likely as a result of contamination during PKE processing—while Cu and As have been reported to be in excess of 50% of their MTLs. Using PKE for animal fodder may present risks or a benefit to the agricultural systems of importing countries depending on what TEs are present and in what concentrations. There is a disparity between regions where *E. guineensis* is produced—namely Indonesia and Malaysia, and regions producing research on TEs in *E. guineensis* systems—most often Nigeria. The critical knowledge gaps concerning TEs in *E. guineensis* production systems are: data on the elemental composition of PKE; the concentrations of Cu, Zn, As and Cd in Southeast Asian production soils; and data on mercury across the entire production system, from soils to products. Future research should focus on a whole-systems analysis to determine the viability of *E. guineensis* production systems and identify appreciable risks to allow the development of mitigation strategies that may be applied at the plantation level and address the emerging issue of TE contamination.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/su14084553/s1, Table S1: Rare earth element concentrations in Aceraceae species.

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