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Elemental Composition of Palm Kernel Expeller Used as Supplementary Stock Fodder

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Abstract: Palm kernel expeller (PKE) is a biowaste by-product of palm oil processing in Southeast Asia that is exported as stock fodder. Global production of PKE totals 11M t yr^{-1}, of which New Zealand imports 1.9M t yr^{-1}, worth >USD 325M, most of which supports NZ's dairy herd of 5.5M cows. We aimed to determine the concentrations of the chemical elements in PKE imported into New Zealand and compare this to pasture, as well as to assess chemical concentrations against maximum tolerable levels (MTLs) in stockfeed for animal health and ruminant requirements. Palm kernel expeller was analysed for a suite of essential and trace elements using a HNO_3 digestion and analysis by inductively coupled plasma-mass spectrometry. Palm kernel expeller contained statistically significantly higher concentrations of B, Mg, P, Cr, Mn, Fe, Ni, Cu and Zn than pasture. Magnesium, P and Fe exceeded MTLs in PKE, whereas Al, S, K and Cu were within 90% of their MTL. The N, P and K contained in PKE represent the equivalent of 14%, 20% and 28%, respectively, of dairy fertiliser use in New Zealand. As PKE contained 3.3 mg Cd kg P $^{-1}$, there may be potential for PKE to offset fertiliser use in dairy systems, with a low Cd source of P. There were statistically significant differences in elemental concentrations between different batches of PKE indicating that this product is not uniform. Further research of the effects of PKE on animal health is recommended. The excess elements contained in PKE may present risks or benefits to dairy farming systems and determining these would be beneficial in protecting both animal health and environmental sustainability.

Keywords: trace elements; dairy cattle; *Elaeis guineensis*; Indonesia; New Zealand; copper; iron

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1. Introduction

Elaeis guineensis (African oil palm) produces edible palm oil and palm kernel oil, which are expressed or solvent extracted from the mesocarp and endosperm, respectively, and palm kernel expeller (PKE), a biowaste product comprising the ground endosperm after oil has been extracted. Palm kernel expeller is sold as a supplementary stockfeed globally. New Zealand is the world's largest importer of PKE, buying 1.9M t, or approximately 17% of global supply, in 2021 [1,2] at a cost of $327–453 million USD (based on the January–April 2020 spot price range of PKE in New Zealand) [3]. This PKE is shipped from Southeast Asia to New Zealand, primarily for use on dairy farms [4]. The reuse of a biowaste such as PKE may be beneficial in terms of creating circular bio-economies that minimise waste and reuse nutrients, thereby adding value to by-products. However, the use of PKE is contentious, as the production of palm oil and PKE have been linked to deforestation of virgin tropical forests and habitat destruction for endangered animals [5]. The plant and animal nutrients that PKE contains may substantially offset the requirements for fertilisers and animal supplements, respectively. Conversely, the import of non-biologically essential elements or nutrients in excess of agricultural requirements may exacerbate soil contamination and potentially endanger animal or human health [6].

The effects of any excess elements contained in PKE on livestock will depend on various factors including the proportion of animals' diets made up of PKE, as well as trace element (TE) interactions that may help or hinder their metabolism [7]. Excess dietary elements may either be absorbed by the animal or excreted through dung, urine or milk [6,8]. Excess elements may endanger food safety or accumulate in soil. Dairy cattle in New Zealand are routinely monitored for element concentrations in liver and serum [6]. These concentrations may indicate whether these elements are absorbed and metabolised by animals, while elemental concentrations in faeces may indicate what excess elements are likely to be excreted.

While palm and palm kernel oils generally contain low levels of TEs [9], in PKE, there is a precedent for TE concentrations, which may approach or exceed Maximum Tolerable Levels (MTLs) for cattle feed. Iron, Cu and As in PKE may reach 6130, 29 and 3.1 mg kg^{-1}, respectively [10–12]. Maximum tolerable levels for these TEs are 500, 40 and 4 mg kg^{-1}, respectively [13,14]. Elevated concentrations of Cu, As and Pb have been measured in the soils where *E. guineensis* is produced, likely due to the use of agrichemicals which contain TEs as impurities (including phosphate fertilisers) and active ingredients (including Cu-based fungicides) [15]. Post-harvest processing and transport, as well as contamination with other (waste) products, may also contribute substantial concentrations of chemical elements [16,17]. Previous studies measuring chemical elements in PKE have focussed either on a limited number of elements or have deficiencies including a lack of specified PKE sources and chemical methods used for analysis. A wider study that analyses PKE from multiple sources and across multiple years for a wide range of elements is needed to elucidate the chemical profile of PKE and any risks or opportunities it may present for agricultural systems.

We hypothesised that PKE may contain elevated concentrations of Fe, Cu and As. We aimed to compare the elemental profile of PKE to that of New Zealand pasture and to MTLs for cattle feed and cattle requirements. Additionally, we sought to analyse preliminary data on the Cu concentrations of dairy cattle livers to gain insight into the potential effects of PKE on liver Cu status of dairy herds. We used these data as a pilot study to determine the sample size necessary for a comprehensive study on the effects of PKE on dairy cattle liver Cu concentrations in a New Zealand context. Based on this, we have offered directions for future research.

2. Materials and Methods

2.1. PKE Collection

Grab samples from five shipments (hereafter referred to as batches) of PKE imported into New Zealand were collected for analysis. Five or six sub-samples were analysed from each batch. Batch #1 and #2 were collected from separate Canterbury farms in May 2021. Batches #3–#5 were collected from a port facility in Timaru, New Zealand, in March 2019 (#3, #4) and March 2020 (#5). Batch #4 had been screened to ≤4 mm while Batch #5 had not been screened and was in chunks >4 mm. Samples were oven dried at 60 °C for 48 h.

2.2. Pasture Sampling

Pasture samples—79 in total—were collected from 26 farms across the South Island of New Zealand during the spring (September—November) of 2009. Locations of sample collection are detailed in Supplementary Information S1. A pasture sward was cut from each sampling location 2–3 cm above the ground's surface. Samples were rinsed with deionised water and dried until a constant weight was achieved at 60 °C. Pasture samples were then ground using a Cyclotech grinder.

2.3. Pseudo-Total Element Concentrations

Pseudo-total element concentrations (hereafter referred to as total concentrations) for PKE were determined using microwave digestion. Samples (0.20 ± 0.01 g) were weighed into digestion tubes and 5 mL of ~69% HNO_3 added. Samples were pre-digested overnight and following this digested using EPA Method 3051A [18] at 230 °C for 25 min. An Srl Milestone ultraWAVE single reaction chamber microwave digestion unit was used. With every 11 samples, two reagent blanks and two standard reference materials (SRMs) [19–22] were included for quality assurance. Inductively coupled plasma-mass spectrometry (Agilent Technologies 8900) was used to determine elemental concentrations in the digestates. Recoveries of certified values in SRMs ranged from 79–156% of the published values. A list of elemental recoveries is available in Supplementary Information Table S2.

Pasture samples (0.5 g) were digested in 5 mL ~69% HNO_3 and diluted to 25 mL with ultrapure water (Sartorius Arium®Pro UV), before filtering through Whatman 52 filter paper. Elemental concentrations were determined using inductively coupled plasma–optical emission spectroscopy (Varian 720 ES). Blanks and SRMs NIST [19] were also analysed for quality assurance. Recoveries were 92–105% of the published values.

2.4. Total C and N

A CN828 elemental analysis by combustion C and N analyser was used to determine total C and N of PKE samples. Blanks and SRMs [23,24] were included in analyses for quality assurance.

2.5. pH

Palm kernel expeller pH was measured following the method of Blakemore and Searle [25]. Five (± 0.05) g of sample was weighed into a falcon tube and 25 mL of deionised water added. This 1:5 ratio was used in place of the more common 1:2.5 ratio due to PKE's high organic matter content. Samples were then stirred vigorously and left to stand overnight. The pH of each sample was measured with a Hach HQ440d multi pH probe.

2.6. Cattle Liver Data

Secondary data on elemental concentrations in dairy cattle livers were collected from a New Zealand veterinary practice for a preliminary investigation into potential effects of PKE on dairy cattle liver TE status. During routine screening of dairy herds' nutritional status, liver biopsies were collected from dairy cows by veterinary staff and TE concentrations including copper were analysed in an IANZ-accredited veterinary pathology laboratory. This biopsy collection and analysis was completed as part of routine dairy herd management and was not undertaken on behalf of the authors. No ethical approval was required for this as the purpose of the biopsies was veterinary in nature. Data from 11 farms were collated by veterinary staff and passed on to the authors with the permission of farmers under the condition of farm anonymity. Between five and seven cows were sampled from each farm using convenience sampling. Liver data from a total of 58 cows were used for this analysis. Data were also provided on whether the farms fed PKE and if so at what rates, other feeds utilised and TE supplements that cows were receiving. Reported feeding rates of PKE were between 0.5–2.0 kg PKE cow^{-1} and cows were fed varying combinations of grass, grain, baleage and fodder beet. Every cow analysed from farms feeding PKE had been fed PKE, and it is unlikely that any of the cows analysed consumed any PKE from the same batches, as were analysed by the authors in this study; however, this cannot be confirmed.

2.7. Calculation of Nutrient Inputs to Soils through PKE

Considering the elemental concentrations in PKE, the quantities of N, P and K imported into New Zealand through PKE were calculated. These calculations used New Zealand's 2021 import figure of 1.85 Mt PKE [26] and the average concentration of N, P and K in our five PKE batches. These imported quantities were compared to New Zealand's annual fertiliser N, P and K use in dairy systems, based upon quantities of fertiliser sold in New Zealand in 2019 (the most recent figure available) [27] and the proportion of N, P and K fertilisers in New Zealand utilised by dairy farms [28].

2.8. Statistical Analysis

Statistical analyses were conducted using R (version 4.1.0) [29]. A one-way analysis of variance (ANOVA) was used to determine whether any statistically significant differences in mean elemental concentrations existed between batches of PKE. Where assumptions of normality were not met, data were log-transformed. Where assumptions of homoscedasticity were not met, a parametric permutational ANOVA was used to determine the robustness of the parametric ANOVA. The results of the parametric and non-parametric ANOVAs did not differ. Tukey's honest significant difference (HSD) test was implemented in multcomp package [30] to determine which batches were significantly different from each other when ANOVA identified statistically significant differences.

For each element mean concentrations in PKE and pasture were compared using repeated measures ANOVA. The packages lme4 [31] and lmerTest [32] were used for this analysis.

Repeated measures ANOVA was used to compare the average Cu contents in the livers of dairy cattle between the farms with and without PKE in their feed. This was implemented via the lme4 and lmerTest packages. A post-hoc power analysis was run on this data to determine the statistical power with the current sample size. A power curve was then produced for the number of farms ranging from 10 to 1400, with five cows per farm in order to determine the minimum number of farms required to detect the observed effect at 5% significance level with at least 80% probability. It was then repeated for ten cows per farm. The power curve estimation was based on 10^3 simulations for each setting.

3. Results and Discussion

3.1. Elements in Palm Kernel Expeller

3.1.1. Essential Plant or Animal Nutrients

Macronutrients

Nitrogen is commonly used as an indicator for protein (not measured here) in food studies [33]. Mean N concentrations in PKE ranged from 2.0–2.2%. This is lower than concentrations measured in previous studies (Table 1). Nitrogen was statistically significantly higher in PKE (2.0–2.2%) than in *E. guineensis* endosperms (1.3–1.4%) [9]. Palm oils contain only 0.8% of the N contained in a whole fruit bunch (the fruit bunch cut from the tree containing whole *E. guineensis* fruitlets as well as the surrounding plant material) [34] meaning that the N concentrations in PKE are likely to reflect ca. 99% of N present in endosperms. It is unlikely that higher N concentrations in PKE are a result of contamination and therefore it is possible that the PKE we analysed was manufactured from plant material with higher N concentrations than have been reported by Thompson-Morrison and Gaw [9], Corley and Tinker [35], Woittiez and Slingerland [36], Rafflegeau and Michel-Dounias [37], Law and Zaharah [38] and Ng et al., as cited in Corley and Tinker [35], all of whom reported N deficiency in *E. guineensis* plant material. Alternatively, the higher N in PKE may result from the post-harvest mixing with other high N material, as reported in fish meal and soybean meal [17,39,40].

Mean P in batches of PKE ranged from 5229–7265 mg kg^{-1} (Table 1). This concentration range is comparable to the total range previously reported in Malaysian PKE of 4800–7900 mg kg^{-1} [10,11,41]. The mean concentrations of K in the analysed PKE ranged from 5834–18,927 mg kg^{-1}. A previous study found Malaysian PKE contained 7600–9300 mg kg^{-1} K [11], while PKE used in the United Kingdom contained 6900 mg kg^{-1} K [13]. Mean Mg in PKE ranged from 2723–6209 mg kg^{-1} (Table 1). All batches exceeded concentrations of Mg in Malaysian PKE from Yeong [10] of 2700 mg kg^{-1}, and Batches #1 and #2 exceeded the range of 1600–3300 mg kg^{-1} in Malaysian PKE reported by Alimon [11]. Sulphur in PKE ranged from 1916–2745 mg kg^{-1} which was comparable to previously reported concentrations (Table 1).

Table 1. Mean essential elemental composition of the five PKE batches analysed (standard error of the mean in parentheses), with mean pasture concentrations, MTLs for cattle feed and cattle requirements for comparison. Elements which are within 50% of the MTL in one or more batches in PKE are marked with *, elements which exceed their MTL in one or more batches of PKE are marked with **. Batches which share the same letter(s) for a single variable are not statistically significantly different from each other. All values are mg kg^{-1} dry weight unless otherwise specified.

PKE Batch	1 (n = 5)	2 (n = 5) +	3 (n = 6) ǂ	4 (n = 6) ǂ	5 (n = 6) ǂ	Concentrations Reported from Other Sources	Pasture Concentration	Cattle Feed MTL ⋏	Cattle Requirements ‡
C (%)	47 (0.45) a	49 (0.81) b	49 (0.36) b	48 (0.31) ab	47 (0.26) ab	—	43 χ	—	—
N (%)	2.2 (0.09) a	2.1 (0.11) a	2.0 (0.12) a	2.2 (0.03) a	2.1 (0.02) a	2.2 *̸ 2.9 ⊥	2.0 χ	—	—
**P ** **	5251 (107) a	5229 (90) a	5923 (100) ab	7265 (160) c	6325 (330) b	6500 ⊦ ‖ 7900 ɣ 4800–7100 ‖	3404 (148)	6000	3100
K *	17,034 (950) c	18,927 (496) c	6065 (45) ab	6757 (187) b	5834 (243) a	8000 ⊦ ‖ 7600–9300 ‖	22,428 (1265)	20,000	10,000
**Mg ** **	5948 (277) b	6209 (146) b	2826 (24) a	3083 (128) a	2723 (107) a	3000 ⊦ ‖ 2700 ɣ 1600–3300 ‖	998 (48)	6000	1400
S *	2038 (44) ab	1916 (37) a	2148 (27) ab	2745 (92) c	2325 (136) b	1900–2300 ‖	2538 (105)	3000 (high concentrate) 5000 (high forage)	2000
B	18 (3.5) a	20 (2) a	24 (1.4) a	21 (1.9) a	20 (2.6) a	—	6.4 (0.41)	150	—
Na	280 (71) b	63 (35) a	145 (17) ab	131 (18) a	126 (14) a	200 ⊦	2226 (282)	—	1200
Cr	4.8 (0.2) a	5.5 (3.1) a	2.5 (0.1) a	4.0 (0.58) a	2.3 (0.49) a	—	0.90 (0.13)	100	—
Mn	317 (7.6) a	298 (9.3) a	271 (0.92) a	468 (40) b	302 (31) a	225 ɣ 132–340 ‖	119 (10)	2000	25
**Fe ** **	2406 (174) c	786 (29) b	624 (49) ab	624 (28) ab	447 (107) a	4.1 ɣ 835–6130 ‖	433 (97)	500	40
Co	0.68 (0.07) c	0.1 (0) ab	0.07 (0.02) ab	0.13 (0.02) b	0.03 (0.02) a	—	0.93 (0.16)	25	0.06
Cu *	28 (0.43) b	29 (0.61) b	22 (0.32) a	36 (1.1) c	27 (1.8) b	22 ⊦ ‖ 29 ɣ 21–29 ‖	6.9 (0.28)	40 ⌉	9–11
Zn	54 (0.65) bc	47 (1.2) ab	44 (0.53) a	59 (1.4) c	49 (3.1) ab	77 ɣ 41–50 ‖	27 (1.5)	500	25
Mo	0.42 (0.04) a	0.42 (0.02) a	0.33 (0.02) a	0.35 (0.03) a	0.43 (0.03) a	0.70–0.79 ‖	0.43 (0.061)	5	—

+ Na n = 2. ǂ C, N n = 5. ⋏ [13]. Although PKE can be used as a stockfeed for animals including sheep, goats and poultry, MTLs specific to cows are used where available as the prevailing use for PKE as a stockfeed is in New Zealand dairy farms [1,4]. ‡ [42]. χ [43]. *̸ [44]. ⊥ [45]. ⊦ [41]. ‖ [11]. ɣ [10]. ⌉ Based on Mo 1–2 mg kg^{-1} and S 1500–2500 mg kg^{-1}, Cu may become toxic at lower doses if Mo and S are below these values.

Micronutrients

The mean Fe concentrations in PKE (447–2406 mg kg^{-1}) were of comparable ranges in Malaysian PKE of 835–6130 mg kg^{-1} [11]. The Fe present in PKE is likely a result of processing or shipping that occurs post-harvest, and not a result of plant uptake. This is corroborated by the lower Fe concentrations reported in *E. guineensis* plant tissues by Thompson-Morrison and Gaw [9], and the recognition that production and storage processes are potential sources of contamination—particularly heavy metals—for palm products [16]. Metal contamination of PKE has been a known issue, evidenced by regulations for screening and magnet-scanning of PKE imported into New Zealand [46].

The mean Cu in PKE ranged from 22–36 mg kg^{-1}. This concentration range is higher than has been previously reported in PKE (Table 1). Copper may enter PKE as a result of Cu-fungicide use in oil palm plantations where it is applied directly to soil and plants [47]. It can then be absorbed by plants and transported to fruit tissues [48].

The concentrations of Mn (271–468 mg kg^{-1}) and Zn (44–59 mg kg^{-1}) in the PKE we analysed were higher than ranges previously reported from Malaysian PKE (Table 1).

Concentrations of Mo in PKE were less than those previously reported which is consistent with Mo deficiencies in the soils and leaves of *E. guineensis* [9,15].

3.1.2. Non-Essential Elements

Concentrations of Ag, Cd, Sb, Te, Au and Hg in PKE were $\leq$0.03 mg kg^{-1} and unlikely to pose toxicity risks (Table 2). Concentrations of TEs including Ti, As, Sr and Pb were higher in PKE (11–179, 0.20–0.52, 11–26 and 0.27–1.2 mg kg^{-1}, respectively) compared to *E. guineensis* endosperms (0.30–0.39, <0.01, 3.9–5.0 and 0.021–0.031 mg kg^{-1}, respectively)—the plant material PKE is produced from [9]. These TEs may have entered PKE through pathways other than plant uptake, including contamination during processing and shipping.

Table 2. Mean non-essential elemental composition of the five PKE batches analysed (standard error of the mean in parentheses), with mean pasture concentrations and MTLs for cattle feed for comparison. Elements which exceed their MTL in one or more batches of PKE are marked with **. Batches that share the same letter(s) for a single variable are not statistically significantly different from each other. All values are mg kg^{-1} dry weight unless otherwise specified.

Batch	1 (n = 5)	2 (n = 5)	3 (n = 6) +	4 (n = 6) +	5 (n = 6) ǂ	Concentrations Reported from other Sources	Pasture Concentration	Cattle Feed MTL
Al **	2767 (97) c	867 (211) b	420 (88) ab	226 (34) a	257 (82) a	178 ^	469 (127)	1000 ‡
Ti	179 (13) e	25 (0.95) d	19 (1.5) c	15 (0.38) b	11 (0.51) a	—	—	—
Ni	2.3 (0.05) ab	1.8 (0.2) a	1.4 (0.05) a	4.2 (0.77) b	1.6 (0.16) a	—	0.77 (0.070)	100 ‡
As	0.52 (0.05) b	0.31 (0.04) ab	0.29 (0.02) a	0.20 (0.04) a	0.24 (0.07) a	0.18–3.1 χ	0.41 (0.030)	30 ‡ 4 ⊥
Sr	26 (0.94) b	12 (0.3) a	11 (0.41) a	21 (2.7) b	11 (0.5) a	—	—	2000 ‡
Zr	0.49 (0.06) c	0.025 (0.02) a	0.13 (0.02) b	0.17 (0.01) b	0.12 (0.02) ab	—	—	—
Ag	<0.01a	<0.01a	<0.01a	<0.01a	<0.01a	—	—	—
Cd	0.024 (0.0024) bc	<0.01a	0.023 (0.0021) bc	0.027 (0.0021) c	0.017 (0.0021) ab	—	0.14 (0.014)	10 ‡ 1 ⊥
Sb	0.018 (0.0012) a	0.021 (0.0028) a	0.021 (0.0030) a	0.022 (0.0039) a	0.014 (0.0021) a	—	—	—
Te	0.014 (0.0012) c	<0.01b	<0.01ab	<0.01a	<0.01a	—	—	—
Cs	1.1 (0.037) d	0.80 (0.032) c	0.43 (0.021) b	0.22 (0.060) a	0.35 (0.022) ab	—	—	—
Ce	3.7 (0.28) b	0.24 (0.024) a	0.22 (0.060) a	0.15 (0.022) a	0.10 (0) a	—	—	—
Au	<0.01b	<0.01b	<0.01a	<0.01a	<0.01a	—	—	—
Hg	<0.01a	<0.01a	<0.01a	<0.01a	<0.01a	—	—	2 ‡ 0.1 ⊥
Pb	1.2 (0.084) b	0.35 (0.024) a	0.44 (0.10) a	0.30 (0.058) a	0.27 (0.067) a	—	0.37 (0.054)	100 ‡ 10 ⊥

+ C, N n = 5. ǂ Ag, C, N n = 5. ^ [49]. ‡ [13]. χ [12]. ⊥ [14].

All batches contained higher concentrations of Al than Malaysian PKE (sourced in New Zealand in a previous study), which measured 178 mg kg^{-1} [49]. The range of As present in our analysed PKE—0.20–0.52 mg kg^{-1}—was within the range of As in Malaysian PKE of 0.18–3.05 mg kg^{-1} [12]. Some of the As levels reported by Hammid and Kuntom [12] were within 75% of the MTL for As in cattle feed (4 mg kg^{-1}), and thus this element has been identified as an element of concern in PKE [50]. The As present in the PKE we analysed indicates that concentrations in PKE imported into New Zealand are low and not of concern, which falsifies our hypothesis that PKE would contain elevated As concentrations. Given the large variation in sample TE concentrations, it is possible that some batches will contain unacceptable As concentrations.

3.2. Implications for Stock Fodder

Compared to pasture, PKE contained higher concentrations of essential elements P, Cr, Mg, B, Mn, Fe, Cu and Zn. Concentrations Mg, Al, P and Fe in PKE exceeded the MTL for cattle feed in one or more batches, while S, K and Cu were within 90% of MTLs in one or more batches (Table 1). Except for Al, these elements are essential for livestock and thus their high concentrations in PKE may represent a potential benefit if animals are deficient in these elements or grazed on deficient soils, or conversely a risk if their concentrations are high enough to induce toxicity in animals. All other elements analysed were either below MTLs for cattle feed, or values for MTLs or cattle requirements could not be identified. If elements were within 50% of their MTL they were noted and discussed, as this is a benchmark commonly used in environmental monitoring [51]. Effects of TEs contained in PKE on animal health and nutrition will be dependent on the diet-proportionality of PKE which is determined on-farm.

Phosphorus exceeded the MTL for cattle feed of 6000 mg kg^{-1} in Batches #4 and #5 at 7265 and 6325 mg kg^{-1}, respectively, and was within 87% of the MTL in Batches #1–#3 (5229–5923 mg kg^{-1}). Exceedance of this MTL has also been previously reported in Malaysian PKE (Table 1). Effects of excess P in the diet depend on its bioavailability and solubility, and the concentration of other elements including Ca. In cows, the majority of dietary excess P is excreted once nutrient requirements have been met and no adverse health outcomes or effects on milk production have been observed as a result of excessive P in the diet [8]. Phosphorus is excreted via milk as well as urine and faeces [52], so excess P through PKE may affect milk composition. The factors governing P excretion via milk are not fully understood and may vary between cows [52]. Excess P can adversely interact with Mg, and Ca: P ratios <1:1 in feed are likely to affect animal health and performance regardless of whether P concentrations are below the MTL [53]. A Ca: P ratio of between 1:1 and 6:1 is tolerated in cattle, and if this is well-managed, P concentrations in feedstock above the MTL can be tolerated [53]. Both Ca and P have been flagged by the National Research Council as being of concern for toxicity in livestock. The excretion of excess P may present a substantial input of nutrients to grazed soils in addition to calculated fertiliser inputs, increasing the risk of eutrophication of surface water bodies through runoff of topsoil and nutrients. On-farm nutrient balance calculations which consider inputs through PKE may be beneficial in determining and mitigating this risk.

Batches #1 and #2 contained 17,034 and 18,927 mg kg^{-1} of K, respectively, which were within 85% of the MTL of 20,000 mg kg^{-1}. All PKE contained lower concentrations of K than pasture. Potassium has been flagged by the National Research Council [13] as being of potential concern for toxicity, and excess K, while usually excreted in urine [54], can interfere with absorption of Ca and Mg [13].

Magnesium exceeded the MTL for cattle feed of 6000 mg kg^{-1} in Batch #2 (6209 mg kg^{-1}) and was within 99% of the MTL in Batch #1 (5928 mg kg^{-1}). All Batches exceeded cattle requirement concentrations for Mg of 1400 mg kg^{-1}. The excess Mg in PKE may be beneficial in the prevention of milk fever, as Mg supplementation is often used for this purpose [55]. This benefit may be realised during pre- and post-calving when Mg supplements are traditionally used. While excess dietary Mg is excreted in urine in dairy cows, Mg-rich diets may lead to an increase in phosphatic calculi (kidney stones) in animals if the diet is also high in P [13]. As PKE contains higher concentrations of both Mg and P than pasture, monitoring dairy herds for signs of kidney stones may be beneficial when feeding high rates of PKE.

Concentrations of S approached the MTL for high-concentrate diets (3000 mg kg^{-1}) in all batches of PKE, which ranged from 1916–2745 mg kg^{-1}. Cattle requirements (2000 mg kg^{-1}) were exceeded in every batch except Batch #2. For cattle fed a high-forage diet, the MTL for S is 5000 mg kg^{-1} and thus any risk associated with S in PKE will depend on the individual feeding patterns of farms [13]. Despite higher MTLs, adverse effects on growth performance may be possible when cattle are fed diets with

>2000 mg kg^{-1} S [53]. Our results exceeded the previously reported range of S in Malaysian PKE, 1900–2300 mg kg^{-1} [11].

Iron exceeded the MTL of 500 mg kg^{-1} in Batches #1–4 (624–2406 mg kg^{-1}) and was within 89% of the MTL in Batch #5 (447 mg kg^{-1}). Chronic Fe toxicity in mammals causes damage to the intestinal tract and liver and delays in blood clot formation [56]. Excessive Fe intake in bovines can reduce milk production and decrease body weight, with <30 mg kg^{-1} day^{-1} estimated as the minimum harmful dose [57]. Cattle deaths due to suspected Fe toxicity have occurred when fed feedstuffs containing 1992 mg kg^{-1} Fe [58]. The effects of excessive Fe intake will of course depend on the solubility and bioavailability of Fe in the diet [42].

Mean Cu in PKE was within 55–90% of the MTL (40 mg kg^{-1}) in all five batches. Copper may become toxic at lower levels than MTLs suggest if Mo and S are not present in the diet at concentrations of 1–2 and 1500–2500 mg kg^{-1}, respectively [13]. It has been suggested that excess TEs in PKE such as Cu may present a potential benefit to livestock in countries where soils are deficient in essential nutrients, such as New Zealand [50]. The plausibility of this depends heavily on TE interactions and possible antagonism with respect to elements found in PKE. Effects of excess dietary Cu will be affected by the S, Mn, Fe, Zn and Mo (all Cu antagonists) concentrations in animal feed [11,13,42]. For example, intake of dry matter containing 500–800 mg kg^{-1} Fe has been shown to cause depressed Cu concentrations in serum and livers of dairy cattle due to interference with Cu metabolism [59,60]. Thus, benefits which may be provided through the addition of Cu to animals' diets through PKE may be negated by the antagonistic effects of Fe also present in PKE. Investigating this would be beneficial, as in New Zealand Cu supplements for livestock are often reduced when feeding PKE [41]. Alimon [11] noted that animals may develop symptoms of Cu-toxicity when their diets contain >50% PKE. Mortality rates in sheep fed PKE were 100% when their diet was not supplemented with Zn [61]. This was attributed to Cu-toxicity. Appropriate management of elements in animals' diets is essential if using PKE as a stockfeed, and future studies should address the digestibility/bioavailability of elements in PKE, and interactions that occur between these including K and Mg, Mg and P, and Fe and Cu.

Aluminium was the only non-essential element in PKE that exceeded MTLs. The mean Al concentration of Batch #1 (2767 mg kg^{-1}) exceeded the MTL of 1000 mg kg^{-1}, while Batch #2 was within 86% of the MTL at 867 mg kg^{-1}. No cases of Al toxicity in cattle as a result of Al in feedstock could be identified, although Al is identified as a potentially toxic element by the National Research Council [13]. A risk assessment of the excess Al and other elements contained in PKE and their potential effects on animal health is recommended.

Batches contained statistically significantly different concentrations of both essential and non-essential elements, and thus the non-uniformity of PKE should be factored into decisions surrounding its use where animal mineral nutrition is concerned, as consistent levels of elements in each batch cannot be relied upon. Statistically significant differences existed between the pH of different batches of PKE (5.4–5.5). This may be a result of variation in production conditions, including fertiliser and pesticide applications in oil palm plantations [62]. Palm kernel expeller contained statistically significantly higher concentrations ($p < 0.05$) of B, Mg, P, Cr, Mn, Fe, Ni, Cu and Zn compared to pasture and thus may be a dietary source of these elements. Concentrations of Na, K, Co and Cd were statistically significantly lower ($p < 0.05$) in PKE than in pasture, while concentrations of Al, S, As, Mo and Pb were comparable between PKE and pasture (Table 1). Palm kernel expeller represents a substantial source of TEs for farm systems utilising this by-product.

In addition to effects on animal health and performance, excess dietary elements may affect the composition of meat and milk products, as well as elemental concentrations of grazed soils [8,53]. This may have implications for the use of mineral supplements for livestock. On-farm mass-balance calculations that take into account element inputs through PKE would be beneficial in understanding the tangible and long-lasting impacts the use of PKE may have on importing agricultural systems. However, the variation in concentrations of essential nutrients (Mg, P, S, K, Cu and Zn) across PKE batches will make farm nutrient balance calculations complex.

3.3. Pilot Study Using Dairy Cattle Liver Data

The potential effects of PKE on animal health concerning TEs may be elucidated by preliminary analysis of data on the TE status of dairy cattle livers. Our analysis failed to find a statistically significant difference ($p = 0.804$) between the liver Cu concentrations of cows fed PKE and those not fed PKE using data from 11 farms in Canterbury. A weighted mean estimate for cows fed PKE was 2023 μmol kg^{-1} while cows not fed PKE had a mean estimated liver Cu concentration of 2116 μmol kg^{-1} (Figure 1). Both fall within the adequate range of 95–3000 μmol kg^{-1}. The variation in cows both between farms and within farms is large, and some individual cows have liver Cu concentrations above the adequate range (Figure 1). The lack of statistical difference in the liver chemistry between the PKE-fed cows and the non-PKE-fed cows may be due, in part, to the limited sample size. Our analysis did not have sufficient statistical power to draw generalisable conclusions. A more extensive study is required to determine categorically whether PKE affects liver chemistry. A comprehensive study assessing the potential effects of PKE on liver Cu concentrations in dairy cattle would require approximately 1310 farms with five cows sampled each to achieve statistical power—the probability that an existing effect will be detected—of 0.8 at a 5% statistical significance level. (Figure 2). This would represent data from approximately 12% of New Zealand's dairy herd. Testing a larger number of cows from each farm would slightly decrease the number of farms needed: if testing 10 cows from each farm, approximately 1260 farms would be needed (Figure 2). Despite the large number of farms required, this data is routinely collected from dairy herds and thus such a study may be feasible with a dedicated effort. The primary challenge would be coordination between researchers and veterinarians and the increased administration on the part of vet practices around gaining farmers' consent for the study as well as anonymising and sending data. Our preliminary analysis shows no clear evidence for PKE having profound effects on animal Cu status. However future work is clearly needed to confirm this.

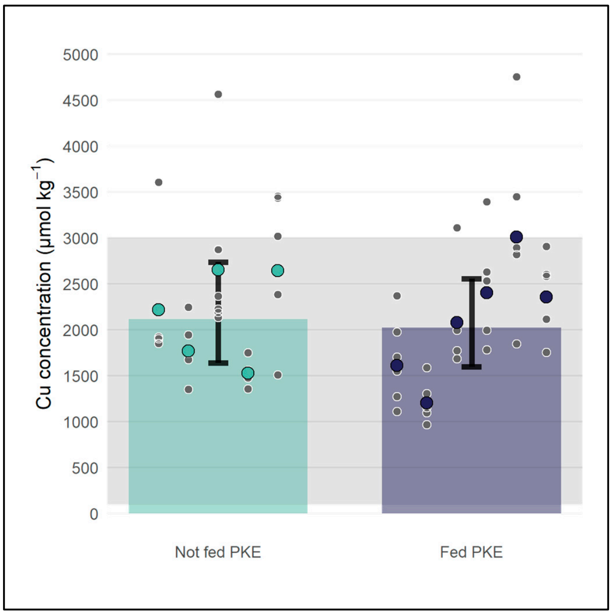

Figure 1. Bar graph shows weighted mean estimates for dairy herd liver Cu concentrations by feed regime. Error bars indicate 95% confidence around the mean. Shaded area represents adequate concentration range. Points stratified in each vertical line overlaid on the bar graph represent data from one of 11 farms in Canterbury. The coloured circle indicates the farm mean while the grey circles represent Cu concentrations from livers of individual cows from that farm.

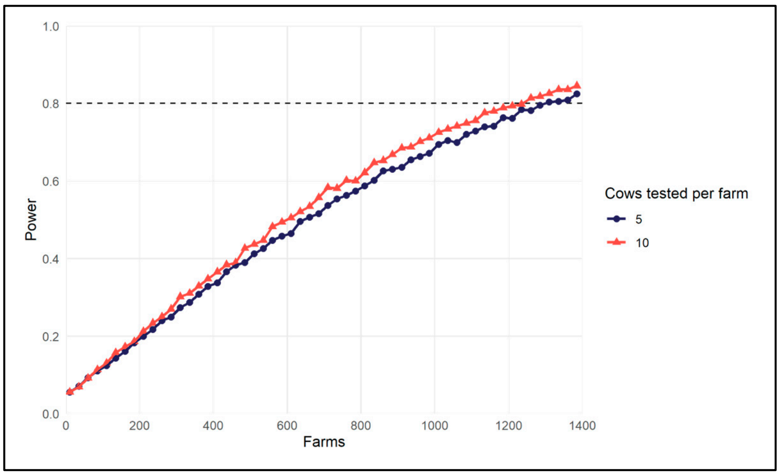

Figure 2. Power curve showing statistical power against number of farms needed to test effects of PKE on liver Cu concentrations, with either five or ten cows tested per farm. Commonly recognised sufficient statistical power of 80% is indicated by the dashed line.

3.4. Elements in PKE as Soil Nutrient Inputs

Given dairy systems in New Zealand use 63% of total N fertiliser, 36% of total P fertiliser and 56% of total K fertiliser [28], N, P and K inputs to dairy systems through PKE represent the equivalent of 14%, 20% and 24% of total nutrient inputs through fertilisers, respectively (Table 3). In comparison, the equivalent amount of N, P and K fertilisers in New Zealand based on June 2022 prices [63] and exchange rates would cost approximately USD 78M for N (as urea), USD 39M for P (as superphosphate) and USD 22M for K (as standard KCl)—a total of USD 138M (Table 2). This represents approximately one third of New Zealand's total expenditure on PKE [3]. Thus, there may be potential to offset the use of fertiliser nutrients on dairy systems through PKE. However, the economic and environmental cost of shipping PKE between continents should be factored into any calculations of this offset.

Table 3. Use of N, P and K fertiliser in New Zealand dairy systems with the equivalent proportion of nutrient inputs through PKE and the equivalent cost of these nutrients as fertilisers.

Element	NZ Dairy Farm Fertiliser Use (t yr^{-1})	Mean NZ Imports through PKE (t yr^{-1})	Mean Fertiliser Equivalent Imports through PKE to NZ Dairy Farms (t yr^{-1})	Fertiliser Equivalent Cost (USD)
N	284,760	39,258	14%	77,879,500
P	55,440	11,097	20%	38,500,729
K	73,360	20,208	28%	21,756,711

Using an average concentration of Cd in PKE, we calculated that the Cd:P ratio in PKE is 3.3 mg Cd kg P^{-1}. Phosphate fertilisers in New Zealand contain on average 184 mg Cd kg P^{-1}, and are voluntarily capped at 280 mg Cd kg P^{-1} [64]. This is due to New Zealand's history of high-Cd phosphate fertiliser use, leading to issues of Cd accumulation in productive soils [65]. This accumulation presents risks for food chain transfer and land use flexibility. Palm kernel expeller represents a low-Cd source of P for farms and may have potential for the offsetting of high-Cd phosphate fertiliser use. Offtake of P by animals is assumed negligible, as most excess dietary P is excreted [8]; however, the bioavailability of excreted nutrients including P is not clear. As some elements may be excreted in milk [6,8], the potential for release into milk for the range of excess dietary elements contained in PKE should be assessed. The bioavailability of excreted elements through urine and faeces warrants investigation to determine the feasibility of any fertiliser offsets through PKE.

The practicality of offsetting fertiliser use would also depend on several factors including cost, feeding methods and TE concentrations in PKE. Importantly, imports of Cu and Zn to farm systems should be considered. Based on our PKE analyses, Cu and Zn have average concentrations in PKE of 28 and 50 mg kg^{-1}, respectively. In total, an average of 53 t Cu and 93 t Zn are brought into New Zealand dairy systems through PKE each year. Zinc is fed to cows to prevent facial eczema, particularly in warm, humid farming environments, and this has led to Zn accumulation in soils in some areas of New Zealand [66]. It is unclear how much further inputs of Zn, such as those through PKE, may exacerbate this issue. As mentioned in Section 3.2, there are potential benefits to animal nutrition from the Cu contained in PKE; however, a full investigation into the interaction of Cu with other TEs and the resulting bioavailability of Cu to animals is needed to understand this. Furthermore, as nutrients contained in PKE are applied to farm soils through animal excretions, their distribution to pasture should be considered. Unlike fertiliser applications which are evenly applied to pasture, animal urine and faeces are concentrated and non-uniform and this may exacerbate the challenges of 'urine patches' [67], whereby concentrated nutrient excretions lead to increased nutrient losses.

Potentially, other biowastes sourced in New Zealand may provide similar benefits to PKE for agricultural systems in terms of beneficial nutrient inputs. Each year, a total of 2.2M t of biowastes, including horticultural and viticultural wastes, are produced in New Zealand, of which the majority end up in landfill [68]. Further work might assess the suitability of some of these locally sourced biowastes for potential use as stock fodder. Reducing the transport requirements of stock fodder may further contribute to the creation of circular bio-economies, recovering resources from and thus adding value to waste products which can be used to sustainably feed New Zealand's agricultural sector.

4. Conclusions

Potentially, the chemical elements in PKE may offset nutrient deficiencies in agricultural systems. However, concentrations of Mg, Al, P and Fe exceeded MTLs for cattle feed and concentrations of S, K and Cu in PKE were within 90% of the MTL for cattle feed in one or more batches analysed. Concentrations of B, Mg, P, Cr, Mn, Fe, Ni, Cu and Zn were higher in PKE compared to pasture. Nutrient management on farms utilising PKE may be complicated by the statistically significant differences in essential and non-essential elements between batches of PKE. Our preliminary data analysis did not show a profound effect on liver Cu concentrations explained by the feeding of PKE to dairy cattle. The power analysis indicated that data from around 1300 farms would be needed to achieve adequate statistical power to produce meaningful and extrapolatable results if investigating potential effects of PKE on dairy cattle liver Cu concentrations. The concentrations of N, P and K represent a substantial source of nutrients into New Zealand dairy farms that may have potential for offsetting fertiliser use. In particular, PKE is low in Cd with a P: Cd ratio of 3.3 mg Cd kg P^{-1}. Thus, PKE may be useful as a low-Cd source of P. There is potential for future work to assess the feasibility of PKE to offset fertiliser use, including investigating the bioavailability of excreted nutrients, the potential excretions of elements through milk and any potential effects of excess elements such as Cu and Zn on dairy soils. Additionally, a risk assessment concerning elements that breach MTLs in PKE would be beneficial to ensuring that the use of this by-product as a supplementary stockfeed is sustainable.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/su142315752/s1, Table S1: Sampling locations for pasture; Table S2: SRM recoveries of elements. Reference [69] is cited in the supplementary materials.

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