Evaluation of the Knowledge Base in Agriculture and Food to Reduce and Prevent Chronic Kidney Disease of Unknown Etiology (CKDu)

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ABSTRACT

Kidney disease is a growing global problem, more so in tropical regions. The cause of CKDu is multifactorial and influenced by heavy metal (HM) contamination, inhibiting essential enzymatic reactions. Fertilizers and water contamination are believed to cause the disease. This study aimed to review the existing knowledge base, focusing on a transitional approach to advanced technologies with the least HMs and to use justifiable scientific reasoning supported by published data, to used to demonstrate the movement of Cadmium (Cd) at both low and high concentrations from applied fertilizer through the soil to grain and rice. The quantity of fertilizer applied per ha with the given Cd levels was equated to Cd concentrations in the harvested grain and rice per ha, considering positive or negative contributions from the soil. Weekly consumption levels of rice at the threshold limits by an average Sri Lankan were determined for low and high Cd levels in rice using the tolerance limits of two international standards. It is best to characterize watersheds and determine the movement of nutrients and HM in ferruginous soils. Hinderance to phosphate immobility in these soils can be overcome by applying biochar biofertilizer with possible enrichment of biofilm biofertilizers to replace totally inorganic fertilizers contaminated with HMs. Cd levels of 836.25 and 393.75 of the two publications equate to the assumed harvest: lowest 21.22, average 385.13, and the highest 1246.10 mg Cd ha^{-1}. Allowable standards indicate that the weekly limit of a Sri Lankan to consume rice is 300 g, containing a high concentration of 0.2618 mg Cd kg^{-1} and 1kg or 604 g, having 0.1339 mg Cd kg^{-1} for an average harvest of 4350 kg.ha^{-1}. Water contains HM, particularly arsenic from fertilizer and pesticides. Recommended researching while implementing phytoremediation, mechanized farming, preventing UVB, Integrated Pest Management (IPM), and organic agriculture with supporting technologies of watershed resource management.

KEYWORDS: *Biochar, Biofertilizer, Biofilm, Cadmium, CKDu, Heavy metals, Organic pollutants, Soil*

INTRODUCTION

There are many studies undertaken to find the origin or cause of worldwide CKDu occurrences. It surfaced in 1990 in the North Central Province (NCP) of the island [1], which is situated in the dry zone of the country. It was subsequently spread to the adjacent North-Western, Eastern, and Uva provinces. The endemic region covers approximately 24,000 km2, providing shelter for about 3 million people. Out of that, about 2 million are at high risk of contracting CKDu [2]. It is now recognized that the disease cause is multifactorial, because it may seem plausible with the number of publications on heavy metal (HM) contaminants, medical health issues, dehydration, and heat stress like non-communicable diseases, social behaviour, and poor-quality food and water intake [2]. Dehydration leading to chronic heat stress is now believed to be the triggering factor [3]. The focus in Central America, with less attention in Asia, is on dehydration and heat stress [2].

The studies were centered around the unknown ethnological aspect of the disease, except when the government decided to ban inorganic fertilizers [4]. Subsequently, the prohibition was lifted because it was not a planned implementation of an important policy decision. Intentionally or otherwise, it increased the costs of fertilizers. There were many protests for and against the ban, but there was a strong lobby opposing organic agriculture because it was necessary to safeguard the interests of the traders of inorganic fertilizers and pesticides. The belief that organic agriculture cannot compete with inorganic agriculture is strong and stern among academics, researchers, government officials, and private companies.

Such a notion is embedded in the Sri Lankan society and many parts of the world because, during the colonial period, traditional collective agricultural systems were often replaced with or significantly altered by systems controlled by colonial powers [5]. Over time, most developing economies became highly dependent on

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imports for food substitutions, and most importantly, for agricultural inputs. The country became more reliant on plant breeding to increase inorganic fertilizer uptake under the banner of the Green Revolution. Production systems on specific crops like rice culture made it convenient to apply weedicides for minimizing traditional land preparations and replaced conventional soil nutrient management with inorganic fertilizers. Yield comparisons between traditional and genetically modified crop varieties, as well as between organic and inorganic fertilizers, are often used to justify the use of chemical farming. Farmers, too, prefer convenient agricultural practices, and it is a daunting task to reverse the process.

While HMs are known to be toxic and can hinder plant growth and reduce yields in high concentrations, some HMs, specifically in low concentrations, can act as micronutrients and contribute to increased crop yields. However, it's crucial to manage HM contamination in soil to prevent negative impacts on food production and human health [6]. HM contaminations are from industrial processing of inorganic or organic fertilizers, industrial wastewater, sewage sludge, weathering of soil minerals, and fallouts. Whatever the method of HM contamination, it should be prevented since almost all diseases, like CKDu stem from cadmium. If cadmium can be controlled, most of the other HMs would be evaded. Hence, this paper aimed to compile research demonstrating the movement of cadmium from fertilizers and other sources through the soil to rice consumed. And also, the paper aimed to discuss best management practices to support the development of an organic agriculture policy framework areas aimed at maintaining or increasing yields and perhaps particularly in poor soils, and increasing employment opportunities in affected areas. It is also useful for improving agricultural practices in the entire country because HM contamination is rising, and climate change issues are worsening.

MATERIALS AND METHODS

The study focused on the three aspects of enzyme activity, namely, ionic strength, pH, and temperature in relation to the mobility of minerals in the affected soils, because there are many misconceptions. Therefore, an analytical review was undertaken to identify some of the crucial scientific research frameworks needed to overcome health issues, improve agricultural practices, and social upliftment of farmers and their supporting communities. In undertaking the task, it is necessary to emphasize the existence of poor tropical soils in endemic locations. The influence of soil pH on the dynamics of soil organic matter (SOM) was analyzed to develop strategies for introducing improved cultural practices.

A direct relationship was developed to demonstrate the movement of Cd from fertilizer to rice from the available publications. From the publication of [7,8], Cd concentrations in fertilizer for: $[Cd]P_2O_5$ in mgCdkg^{-1} and $[Cd]Urea$ in mgCdkg^{-1}., were obtained separately for each publication. The recommended application rates for the phosphate and urea fertilizers were obtained from the Department of Agriculture, Sri Lanka. They are: RP_2O_5 in kgCdha^{-1} and $RUrea$ in kgCdha^{-1}. The Applied amount is:

$[Cd]P_2O_5 \times RP_2O_5 = x$ in mgCdha^{-1} and (1)
$[Cd]Urea \times RUrea = y$ in mgCdha^{-1}. (2)
The concentration in soil, $[Cd]soil = z = x + y$ in mgCdha^{-1}. (3)
There could be a residual concentration in the soil of α, thus, the total in soil,
$[Cd]soil = z + \alpha$ in mgCdha^{-1} (4)
If there is a loss of Cd from the soil of β, then the soil concentration,
$[Cd]soil = z - \beta$ in mgCdha^{-1}. (5)

It is assumed that the paddy plant root system covers the entire extent of one ha within the growing period. The amount of Cd taken out of the soil can be found in the rice. The values of Cd in rice given in the publication of [9] were used to determine the lowest, average and highest to compare with the field values. 68% was taken as the milling turnover (10). Although the Cd content is higher in husk and bran, the same concentrations of Cd in rice was used to compare with the field. In 2006, the Codex Alimentarius Commission established a maximum limit (ML) for cadmium in polished rice at 0.4 mgCdkg^{-1}. It is of high value. Japan supported the ML of 0.4 mg/kg because some rice samples in Japan contained relatively high levels of cadmium based on the high background levels of cadmium in soils in their country [11].

The concentration $[Cd]$ in rice varied between $[Cd]a$ to $[Cd]c$ and the average $[Cd]b$ in mgCdkg^{-1}. Four harvesting levels were considered, namely, $h_l = 3000$, $h_{h1} = 5200$, $h_{h2} = 7000$, $h_a = 4350$ in kg. The total quantities in rice and gain were determined for the lowest, low, high, highest and average, stated as:

Lowest $[Cd]rice = [Cd]a.h_{h1}$ (6)
Low $[Cd]rice = [Cd]c.h_l$ (7)
High $[Cd]rice = [Cd]c.h_{h1}$ (8)
Highest $[Cd]rice = [Cd]c.h_{h2}$ (9)
Average $[Cd]rice = [Cd]b.h_a$ (10)
Another set of values was obtained by multiplying by 68%.

Because of the toxicity of Cd, the tolerable limits were deducted based on the US(Food and Drug Administration FDA (2023) and the European Food Safety Authority (EFSA) (1975). These limits are based on body weight and duration of one week. Hence, the average body weight of women and men was obtained as 55kg. The allowed limit for a week was determined, A_L. Therefore, the quantity of rice consumption to exceed the limit $= \frac{A_L}{[Cd]b \text{ or } [Cd]c}$ in kg (11) for FDA A_L has a range, and the minimum and maximum values were used to determine consumption limits.

RESULTS AND DISCUSSION

Dynamics of Mineral Fluxes

The geological formations of soils differ from one location to the next, but the movement of mineral contents within the soil profile depends on the ecosystems and agroecosystems [12]. In dry highland conditions, the movement of minerals, either HMs or otherwise, would be downward, caused by deep percolation of precipitation. Vegetation intercepts these minerals and absorbs them as nutrients. A combination of shallow and deep rooting systems allows the best conditions for carbon and mineral cycling. Since minerals from lower soil profiles get transported to the topsoil through the growth and decay cycles of the plant/tree species. It is an important phenomenon because it is the most rapid process of forming soils suitable for cultivation. The upward movements of minerals occur with the rise in the water table during the monsoon periods and sometimes with irrigation water. Salt also moves up with the effects of dehydration at high ET coupled with the capillary rise of mineral water in the soil profiles [13]. In paddy cultivation, the minerals move in all directions, downwards as well as upwards, depending on the concentration and water movement. In dry seasons, farmers in paddy fields used surface tillage to create and hasten deep cracks in the soil. This practice helped to facilitate the washing away of excess minerals with the first onset of rain. It also improves soil structure and aeration, which is useful for preparing seedbeds and incorporating organic matter [14].

In traditional farming practices, the cultivated lands will have very similar mineral contents in the soil profiles to those of uncultivated lands. It is likely to experience less concentration of heavy metals in cultivated lands because of continuous removal over many years. It has perhaps been an important facet of humankind's survival. Over many years of cropping, there may be mineral deficiencies in the soil. Mineral balances are being replenished or affected when flooding takes place or is induced by irrigation water. The charging of topsoil with ionic compounds during flood flow has both positive effects as well as negative effects, like fallouts. Renewing the mineral requirements for crops is a positive aspect, but heavy metals can cause serious issues for generations. Recycling organic plant materials is important. It maintains the required mineral content in intensive cropping. Heavy metal contamination of soils from different sources causes many issues [15,16] in an otherwise difficult soil.

Sesquioxide is formed on the application and precipitation of phosphorus from the plant [17,18], and thus, is not available to the plant for growth and during growth. Sattell (1989), [19] in his findings of Sri Lankan Alfisols, was stated that oxalate extractable Fe was the soil component most active in phosphorus sorption. Ever since, there have been many studies. Some soils are more affected than others by phosphate immobility. It is reflected in paddy yields in most parts of the dry zone. Certain soil types, like Low Humic Gley soils, may have adequate soil phosphorus for rice cultivation, even without added fertilizers. However, other soils, especially those with acidic conditions, may have reduced phosphorus availability, leading to potential deficiencies and lower yields [20]. In a three-consecutive-season study, [21] concluded that the application of phosphorus fertilizer for rice can be terminated for at least 11½ years without affecting grain yield, no matter the level of grain yield, as P is available in the soils in adequate quantities in the Dry Zone of Sri Lanka. In the case of the potassium two-season trial, they found that there was no yield response of rice to added K up to the yield level of about 4 t/ha. Thus, the application of K fertilizer can be avoided over two consecutive seasons without affecting grain yield in rice in Low Humic Gley soils in the Dry Zone of Sri Lanka if the yield level is 4 t/ha or lower. In poor soil conditions, where disease levels are low, the need for potassium might be somewhat less, but not necessarily zero. Poor soil can limit nutrient availability, including potassium, which can lead to deficiencies even if disease pressure is low. Potassium plays a crucial role in plant health, even in the absence of disease. It helps with water regulation, enzyme activation, and overall plant vigor, which are important for plant resilience.

The soluble inorganic phosphorus (P_i) available to plant roots typically represents only a small fraction of the total P present in the soil. Most P_i are immobile, being strongly sorbed onto soil particles and forming insoluble complexes with calcium, as well as oxides and hydroxides of iron or aluminum, processes that are strongly influenced by soil composition and pH. Phosphorus is one of the least mobile plant macronutrients in soil, being much less mobile than nitrate and potassium. A substantial portion of P in the soil is also present as organic phosphorous (P_o), such as nucleic acids and inositol phosphates, which are obtained from digested and decaying plants, animals, and microbial biomass. Although P_o is more abundant than P_i in many soils, it remains unavailable to plants until the P_i moiety is released into the soil solution via hydrolytic processes [22] SOM plays an essential role in the transformation of P [23]. An 11-year field experiment conducted by [24] demonstrated that it is possible to partially substitute mineral P by a mixture of manure and straw to the soil for the effective promotion of P availability with long-term benefits for environmental sustainability. The target for any research should primarily address low-yielding soils. The addition of biochar has proven to be one of the most remarkable solutions to release phosphorus in ferruginous soils. The unstable, stable char and SOM play important roles in providing the carbon source and energy to form and store urea, amino acids, nitrite, and nitrate derived from atmospheric nitrogen, and to preserve applied nitrogen [25-27]. The pathways of preferences are governed by the plant, soil, microbial activities, and climatic conditions, which define the biome and microbiome. It is likely that the most elaborate microbiomes are formed by the application of biochar to soil with organic materials [28].

The addition of biochar enhanced the soil microbial biomass and enzyme activity, while shifts in the bacterial community composition related to N cycling via the increase in soil pH, and thus, reduced N leaching and increased the retention of N in tea soils [29]. The results of [30] suggest that biochar improves soil pH [31], and reduces soil extra N in the acidic tea soil. It is then a soil buffer controlling pH, where nutrients and water are retained and regulate movement to and from the plant to the exceptionally large biochar active surfaces, adsorbing, absorbing, and desorbing, thus serving also as a receptor. It enhances and supports the phosphorus cycle without being locked in ferruginous-derived soil by releasing enzymes and microbial enzymes, substrates with the required balance of nutrients to the plant [32], likely to be at lower suction pressures exerted by the plants. Also demonstrated the capacity to replace 70% of inorganic fertilizer by paddy husk biochar in paddy cultivations. Rice husk biochar-coated urea can potentially be used as a slow-releasing nitrogen fertilizer. In addition, the urea coated with biochar is less costly and contributes to mitigating pollution of water bodies by inorganic fertilizers (NPK) [31,32]. A number of nutrients was examined by [33] and according to them the biochar from bamboo and paddy straw increased the soil-available N, P, K, and Mg concentrations, and tea P, K, and Mg levels, which contributed to the observed growth improvement. Mycorrhizae, symbiotic fungi that form a mutualistic relationship with plant roots, play a crucial role in paddy cultivation by enhancing nutrient uptake, plant growth, and overall productivity. Mycorrhizal fungi improve the availability of phosphorus, nitrogen, and other essential nutrients, leading to increased plant biomass, yield, and tolerance to various stresses, including insect herbivores and flooding [34]. A Number of microbes are used in the manufacture of biofilm biofertilizers that can replace urea [35].

Phosphorus is the chemical energy carrier that enhances the uptake of nitrogen. Enzyme urease perhaps dictates the functions of the microbiome. Urease in the presence of nickel or cobalt is only able to catalyze the hydrolysis of urea to give ammonia and CO_2, and because of the exceedingly high activities of the enzyme urease, some bacteria like rhizobium and specific fungi can fix atmospheric nitrogen at normal temperature and pressure, thus forming urea [36]. It is likely that in the presence of urea, urease is formed to conjugate the microbiome N cycle. The hypothesis that enzymes are formed from the substrates and the enzymes influence substrate formation could very well be valid as described by [37].

Microbiomes, thus, enzyme activities change with the application of industrial inorganic fertilizers. Fertilizer applications in increasing crop production have negative implications due to impurities in the production of N-fertilizers. In India, most of the naphtha plants have been converted to gas, but high-temperature steels in the piping and reactors contaminate the urea production processes [38]. The momentum created with the use of industrial fertilizer production can not be reversed without adequate justification. Moreover, it is a necessity to find the causes and origins of the disease. Hence, a number of studies were initiated to nullify the effect of inorganic fertilizer applications. They were centered around permissible levels in the soil, thus fertilizer and the amount up taken into food and food products.

One such study, [8] reported on a wide-scale, systematic sampling program over two consecutive years investigating As and Cd in one of the affected regions of chronic kidney disease with unknown etiology (CKDu) that is endemic. Surface soil (0–15 cm), fertilizer, and rice seed samples were collected in 2017 and 2018 from three CKDu affected areas Medawachchiya (M), Padaviya (P) and Giradurukotte (G), and a non-affected control site at Hambanthota (H). All inorganic fertilizer samples showed low As (< 30 mg kg^{-1}) and Cd (<1.25 mg kg^{-1}) concentrations, less than European Union guideline values, and no correlation with soil concentrations. Arsenic (≤ 3.8 mg kg^{-1}) and Cd (≤ 3.0 mg kg^{-1}) in the 400 soil samples analyzed were low at all four locations, and soils were considered suitable for sensitive and agricultural use. A human health risk assessment demonstrated that the As and Cd concentrations in surface soil provided no concern for non-carcinogenic risk and negligible or acceptable carcinogenic risk for all locations sampled. The As and Cd in rice seeds harvested were also less than the detection limits (< 0.1 mg kg^{-1}). They concluded that their work provides clarity around As and Cd baseline values in certain farm soils of the dry zone of Sri Lanka, and no substantive evidence that the levels of As and Cd in the surface soils contribute to CKDu in local agricultural populations. Additional sampling of subsurface soil and water resources would satisfy some uncertainties with the risk assessment described in their paper.

The paper in reference compared heavy metal concentrations in CKDu locations to higher levels elsewhere. Hambanthota soils, as published, accumulate more heavy metals than Giradurukotte. It stands to reason that the applied heavy metals by means of fertilizer, directly and indirectly through irrigation water, have been up taken by the plants in the three endemic locations than in Hambanthota. Or else, the HMs were percolated through the soil profile, because these minerals did not appear within the watershed. We must interpret in terms of uptake rates rather than based on simple conclusions made in the study. We must also compare with uncultivated lands as [39] did. They reported that the mean Cd content in cultivated vs. uncultivated soils in the Anuradhapura district was 0.02 ± 0.01 vs. 0.11 ± 0.19 mg/kg, while in Polonnaruwa district, it was 0.005 ± 0.004 vs. 0.016 ± 0.005 mg/kg. Also, other publications of [39] give different ways of heavy metal entering the food chain.

It is best to quote a review paper [2], summarising the present knowledge base. According to them, the disease is more prevalent among farmers and has a unique locality. Numerous nephrotoxins, irrigation networks, genetic susceptibility, soil factors, and even bioterrorism as possible etiologies have been considered. Drinking water was proven to be hard and to contain high fluoride levels, but toxins in food and water were controversial. The urine and tissues of affected patients contained some of the suspected toxins at higher levels. Though the majority of the researchers agreed on a toxic nephropathy, none of their hypotheses explained the clinical findings, the unique locality of the disease, and its appearance in the 1990s. The absence of an identifiable cause has hampered efforts to control the disease. Careful use of agrochemicals and more research to unravel the mystery is recommended.

It is interesting to note that, similar to other diseases in Europe, urine and tissues of affected patients contained some of the suspected toxins at higher levels. Inorganic fertilizers or organic fertilizers formulated with cadmium sources promote chelation of Cd and N. Organometallic uptake is always preferred, as reported by [40]. Underdetection of cadmium (Cd) derived from organocadmium compounds can occur due to various factors, including the nature of the compound, analytical methods, and environmental conditions. Specifically, the volatility, reactivity, and tendency to form complexes can make it difficult to accurately quantify Cd in its organometallic forms [41, 42].

Quantifying the Movement of Cd

Perhaps, the quality of the fertilizer varies greatly [43]. According to them, the application of fertilizers, which contained a high dose of toxic metals, could be the driving force for agricultural soil pollution, and the limitless application of low-quality fertilizer would lead to more soil contamination with heavy metals. Hence, hazardous metals can be incorporated into the food chains via contaminated paddy soil. It could be possible to have levels reported by [7] of trace metal levels in inorganic fertilizers commercially available in Nigeria or it is possible that accumulated levels of organocadmium and arsenic could be transported to the grain in small quantities. The levels detected by [9] can be used to undertake a simple mass balance with that of [7, 8] as given in Table 1. The findings of [8] for both fertilizer and rice fall within [7, 9]. The results of [9] are more comprehensive because the uptake of cadmium will depend on field conditions. If the cadmium concentrations in the field remain the same from one season to the next and one year to the next, there will only be the uptake equivalent to the applied cadmium from the fertilizer. This hypothesis can be deduced from the results of [8] because all the cadmium in the leaves and stems from the previous season too will eventually end up in grains. But the cadmium levels are within the acceptable EU standards as can be deduced from Table 1, amounting to 0.0931 mg.kg^{-1}. When a higher amount of inorganic fertilizer is applied, this balance will no longer remain static, it will either increase storage of cadmium in the soil or get transported more to the grain and stored mainly in the bran and husk due to their role in metal sequestration [44]. Plant uptake will be further aggravated by low pH under submerged conditions [45]. Increasing nitrogen fertilizers increases cadmium uptake and could reach maximum levels reported by [9]. Increasing N fertilization increases Cd uptake and accumulation in plants grown under field conditions where Cd is freely available. Numerous studies reported that N fertilizer, regardless of its form, has a positive relationship with Cd accumulation in plants [46] such as durum wheat [47, 48], rice [49]. Rice, particularly, has a notable tendency to accumulate cadmium and other heavy metals in the soil [50].

Table 1. A hypothetical mass balance of applied fertilizer and uptake of Cd into rice and grain

Fertilizer type	**Reported Cd concentration in fertilizer (mgCdkg^{-1})**	**Fertilizer application rate (kgha^{-1})**	**Total Cd concentration in the field (mgCdha^{-1})**			**Notation**
[7]						
P_2O_5	2.59	60	155.4			
Urea	2.67	255	680.85			
Total	**5.26**	**315**	**836.25**			Z
[8]						
P_2O_5	1.25	60	75			
Urea	1.25	255	318.75			
Total	2.5	315	393.75			
In Rice				**In Grain**		
<6.00-261.786 µg.kg^{-1} [9]						
Value	Reported Cd concentration (mg.kg-^{1} of rice)	Harvest (kgCdha^{-1})	Total (mgCdha^{-1})	Harvest (kgha^{-1})	Total (mgCdha^{-1})	
Lowest	0.0060	3536	21.22	5200	31.2	$z-\beta$
Low	0.2618	2040	534.04	3000	785.4	$z-\beta$
High	0.2618	3536	925.68	5200	1361.3	$z+\alpha$
Highest	0.2618	4760	1246.10	7000	1832.50	$z+\alpha$
Average	0.1339	2876.4	385.13	4230	566.37	$z-\beta$
Derived from rice	0.1369	2876.4	393.75	4230	393.75	$z-\beta$
Derived from grain	0.0931					

Average yields given by [51].

Safe Rice Consumption Limit

The mass balance given in Table 2, was undertaken to counter notions that the applied fertilizer cannot reach high quantities of cadmium in rice. According to [52], cadmium levels found in the rice grown in the rain-fed wet zone exceed the amounts in the dry zone by 40–60%. The researcher pointed out that even an extremely contaminated sample of fertilizers containing 50 mg of cadmium per kg will take 1.2 millennia for the soil to impregnated with cadmium to a hazardous level. It is then necessary to find out if the values given by [9] are within food safety limits. According to the (FDA, 2023), for example, uses a toxicological reference value (TRV) range of 0.21-0.36 micrograms (µg) per kilogram body weight per day. The EFSA (1975) has a provisional tolerable weekly intake (PTWI) of 2.5 µg/kg bw/week. The lowest consumption limit is 309 g/week for FDA limit, and the maximum according to EFSA standards 1kg/week, thus the populations are vulnerable to Cd toxicity.

Table 2. Determination of rice consumption limits to avoid cadmium toxicity

Description	FDA	FDA	EFSA	Unit
Tolerance limit	1.47E-06	2.17E-06	2.50E-06	g/bw/week
The average body weight of Sri Lankan	55	55	55	Kg
Allowable per week	8.09E-05	1.19E-04	1.38E-04	g/week
Comparative study				
Available derived (low value) in rice from Table 1	1.3E-04	1.3E-04	1.3E-04	g/kg
Quantity of rice consumption to exceed the limit	0.604	0.891	1.027	kg/week
Available in rice (Highest)	2.62E-04	2.62E-04	2.62E-04	g/kg
Quantity of rice consumption to exceed the limit	0.309	0.456	0.525	kg/week

Identifying Cd Occurrences and Their Management

It is evident that there is HM contamination in the soils of Sri Lanka and also chelation through many pathways including gyphosate [53,54], making it significant in relation to the accepted standards. Degradation of gyphosate depends on soil conditions, applied concentration and frequency, microbial populations, and temperature [53 - 55]. HM contamination is also high in the case of Europe, with and without the influence of pesticides. The average soil Cd concentration in European soils is about 0.3 mg Cd kg^{-1}, equivalent to about 900 g Cd ha^{-1} in the plough layer [56]. Between 1980 and 1995, the annual net input fluxes of Cd in European soils were estimated to range between 1 to 10 g Cd ha^{-1}, indicating that annual fluxes are much smaller than the total Cd stock in soils [57]. The European median Cd concentration is 0.182 mg/kg in agricultural soil and 0.197 mg/kg in grazing land soil (including eastern Ukraine) [58]. Nevertheless, the EU has recently adopted regulation (EU) 2019/1009 with the aim of establishing stricter limits for Cd presence in fertilizer products and to promote a higher use of fertilizers from organic sources [59]. No doubt there are great improvements in lowering Cd in the soil and food chain over the years since ESDAC (2023) indicates that out of the total, 72.6% of the samples have Cd values <0.07 mg kg^{-1}, 21.6% in the range 0.07–1 mg kg^{-1} and the remaining 5.5% higher than the threshold of 1 mg kg^{-1}, which is generally considered the limit for risk assessment. In the Sri Lanka context, the opposite has taken place because the values stated by [39] were much less than [8]. Moreover, as can be deduced from Table 1, the Cd fluxes per season are higher in endemic locations in Sri Lanka than in Europe because conjugated microbiomes under tropical conditions within the rooting systems cover the entire extent of land applied with fertilizers. Deep tillage is also not practiced, breaking the plough/hard pans formed in the paddy fields; however, Cd can reappear in the lower parts of the catena in soil and water.

There is also evidence of HM contamination from water sources. According to [60], CKDu subjects had significantly higher pesticide and surface water usage, which may be the source of differential As exposure in these subjects. Modern integrated pest management (IPM) strategies emphasize reducing reliance on broad-spectrum insecticides by incorporating various techniques, including the use of natural predators, pest-resistant plants, and other methods to maintain a healthy environment [61, 62] in a comparative study on drinking water from ground and surface water sources reported that the nephrotoxic heavy metals contents including Cd, Pb, As, and Cr in CKDu hotspot fluctuated in the ranges of 9.78-187.25 µg L^{-1}, 0.08-0.66 µg L^{-1}, 20.76-103.30 µg L^{-1}, and 0.03-0.34 µg L^{-1}. The frequency of occurrence above the threshold limit of fluoride was 28% in non-CKDu water samples, while 81% in CKDu prevalent sites. Their results have emphasized a strong association between fluoride and water hardness. The frequency of occurrence above the threshold limit of fluoride was 28% in non-CKDu water samples, while 81% in CKDu prevalent sites. The hardness values in the CKDu prevalent site indicated "moderately hard water," while the non-CKDu area indicated "soft water."

Limiting or eliminating cadmium is imperative since it is characterized by a strong cumulative effect in humans, and its content in living organisms increases with diet and age [17]. Among the factors that determine the absorption and accumulation of this xenobiotic, the duration of uptake, the chemical form of the metal, and the diet should be included, as well as age, sex, and health conditions of the exposed people. Therefore, it is recommended to undertake an applied research project based on a project evaluation model and a plan optimization model developed by [63].

Moreover, one of the most important tasks will be to investigate the need for soil remediation requirements in HM contaminated soils. It will require a hydrogeology study of the watersheds by systematic monitoring of HM movements and conducting extensive monitoring of soil and fertilizer as in Europe. Therefore, it is recommended to undertake an applied research project based on a project evaluation model and plan optimization model developed by [63]. For example, the project will be implemented in stages, like a 70% reduction of urea fertilizer by biochar. So that there is visibility of the comprehensive results in the project evaluation stage. It will involve individuals, farmer collective organizations, like cooperatives, and research scientists to develop technological approaches suitable for advancing mechanized farming systems to reduce drudgery and create employment throughout the year. It may require land consolidation and land development to improve irrigation and drainage with the required SOM and nutrient management with the developed technologies.

CONCLUSION

This analytical review indicates that it is essential to conduct both basic and applied research to prevent CKDu occurrence. An extensive study on the movement of heavy metals in the watersheds is required to introduce remedial measures of HM contaminated soils. The outcome of the mass flow study from inorganic fertilizer through or directly to paddy plants, embedding in the rice and its obligated low consumption levels exceeding tolerance limits, is useful to convince policymakers to launch a well-defined plan to produce organic fertilizers with the required mechanization scheme while controlling cadmium in fertilizers. The existing knowledge base is adequate to implement advanced agricultural practices like biochar biofertilizers to mobilize phosphate and provide the required combination of nutrients, mechanization to reduce overexposure to UVB, land consolidation, phytoremediation of contaminated soils, improvements to irrigation and drainage systems, IPM, and increasing production. Such measures will be adequate to avoid CKDu cases with the reduction of HM contamination. It will empower farmers to control their production systems from land preparation to marketing their products.

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