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Review Article

Toward sustainable phosphorus management in Sri Lankan rice and vegetable-based cropping systems: A review

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ABSTRACT

Upland soils used for vegetable cultivation and lowland soils used for rice cultivation in Sri Lanka are inherently low in phosphorus (P) availability for plants. Rice is grown twice a year while vegetables are grown in intensive rotations. Heavy doses of inorganic and organic P sources are regularly applied to vegetable cultivating systems aimed at maximizing productivity, and disregarding the relatively lower P fertilizer application rates recommended by the government Department of Agriculture. This practice has led to the development of high P concentrations in intensive, high-value vegetable cultivating systems which is threatening environmental sustenance (267 mg available P/kg of soil). For rice, only inorganic P sources are widely being applied and the excessive soil P loading is less severe than that in vegetable cultivating systems (13 mg available P/kg soil). However, rice crops grown in most of the lowlands do not show positive responses to added P fertilizers. The development of chronic diseases among the inhabitants in certain intensively rice cultivated regions in Sri Lanka is suspected to be due to the presence of high concentrations of heavy metals in P fertilizers and the accumulation of those in food chains. Despite sustainable and updated P fertilizer recommendations being available, farmers continue to apply overdoses of P, seeking higher crop yields. Therefore, coordination and active intervention of all the related institutes are required when improving the awareness of farmers on this malpractice, and ensuring the sustainability of vegetable and rice cultivating systems in Sri Lanka with respect to P nutrition.

Introduction

Sri Lanka has three climatic zones; a 'Wet Zone' in the South-Western region, a 'Dry Zone' covering predominantly the Northern, North Central, Eastern and South-Eastern plains of the country, and an 'Intermediate Zone', skirting the central hills except in the North-West and the South as shown in Fig. 1 (Punyawardena, 2007). The Dry Zone receives mean annual rainfall of less than 1750 mm with a distinct dry season from May to September. The Intermediate Zone receives mean annual rainfall between 1750 and 2500 mm with a short and less prominent dry season, while the Wet Zone receives an annual rainfall of more than 2500 mm. With respect to crop cultivation, there are two major seasons coinciding with the 'major rainy season' from November to January and the 'minor rainy season' from May to July. Ultisol is the major soil group in the Up-Country (elevation >900 m above mean sea level) vegetable growing regions, and Alfisol is the major soil group in rice-based (*Oryza sativa* L.) cropping systems in the Low-Country Dry and Intermediate Zones (Mapa et al., 2010). Currently, more than 2 million ha (approximately 30% of the country's land extent) are under some form of agriculture (Wijewardena, 1996; Department of Agriculture, 2013). Rice is grown as a lowland crop across the country. Vegetables are intensively cultivated in uplands and in lowlands when the water available for rice cultivation is not adequate (Wijewardena, 1996). Due to the intensification of crop production in the past few decades and the application of inorganic phosphorus (P) fertilizers and organic manures, soil fertility has altered (Dissanayake and Chandrajith, 2009). Despite the increased crop productivity, public concerns on environmental sustenance and quality of life have also increased (Dissanayake and Chandrajith, 2009; Jayasumana et al., 2013). Therefore, this

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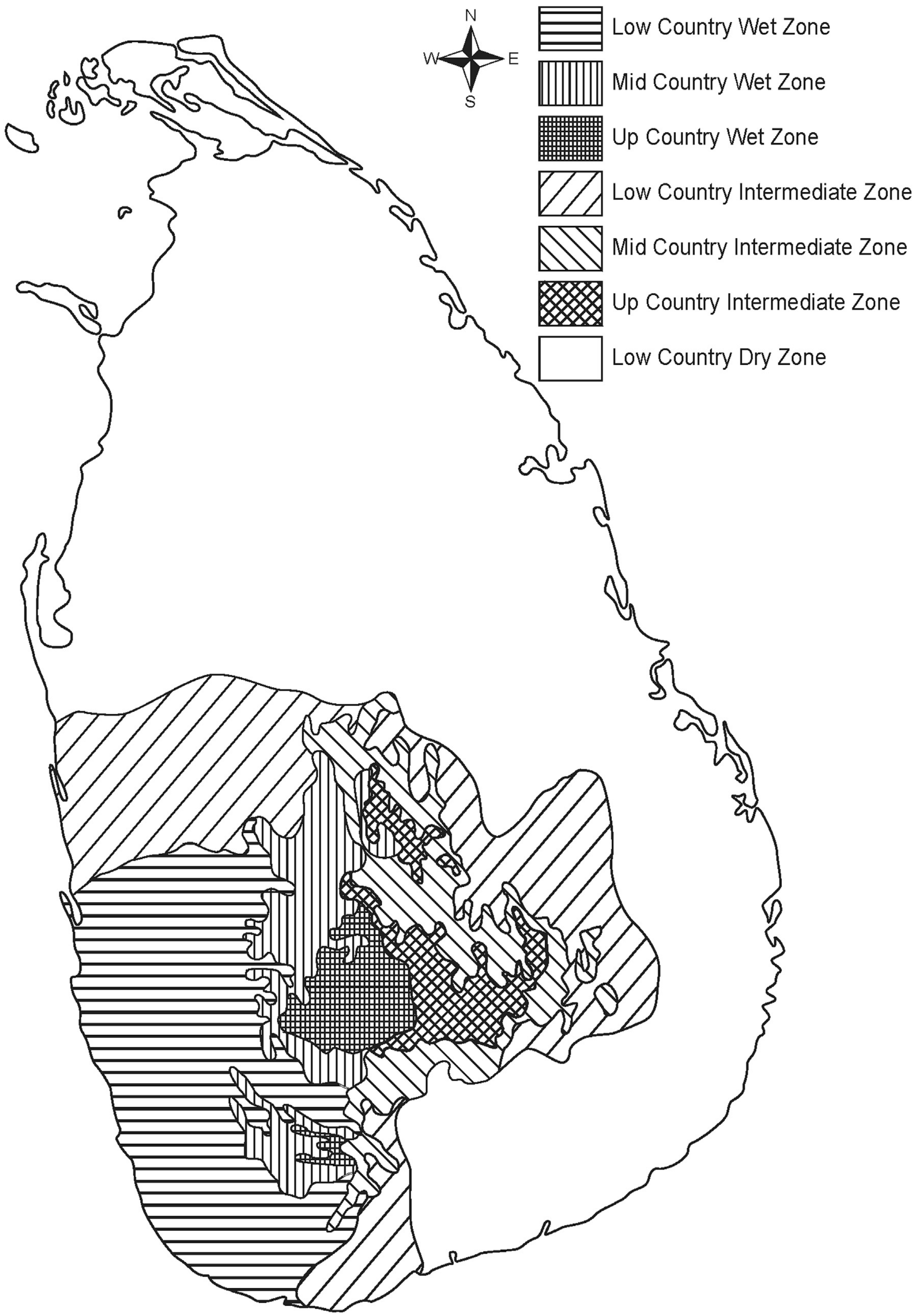

Fig. 1. Schematic representation of the seven agro-climatic zones of Sri Lanka, where categorization is based on elevation above mean sea level (Low Country < 300 m, Mid Country = 300–900 m and Up Country > 900 m) and annual rainfall zones (Dry < 1750 mm, Intermediate = 1750–2500 mm and Wet > 2500 mm; sourced: Punyawardena, 2007).

review studies the current status of P fertilizer use, soil P fertility status and environmental concerns, and suggests potential avenues to ensure sustainable P management in rice and vegetable-based cropping systems in Sri Lanka.

Intensive vegetable cropping systems

P removal by vegetables and P sources

The amount of P removed from soil varies with the crop species, P management strategy, and crop yield. For example, tomato (*Solanum lycopersicon* L.), cabbage (*Brassica oleracea* L.), leek (*Allium ampeloprasum* L.), eggplant (*Solanum melongena* L.), luffa (*Luffa acutangula* (L.) Roxb.), carrot (*Daucuscarota* subsp. *Sativus* (Hoffm.) Schübl. and G. Martens) and potato (*Solanum tuberosum* L.) remove high amounts of P while pole bean (*Phaseolus vulgaris* L.) and capsicum (*Capsicum annuum* (L.) *annuum*) remove less (Wijewardena and Amarasiri, 1990) as shown in Table 1. Adequate amounts of plant-available forms of P should be retained in the top soil to support fast growth of vegetables as they have shallow root systems and the use of animal manure in combination with inorganic fertilizers is a viable option to increase crop productivity (Wijewardena, 2001; Ariyapala and Nissanka, 2006). Triple super phosphate (TSP) is the main source of inorganic P recommended to vegetables (Wijewardena, 1996). Moreover, locally available alternative inorganic P sources are also applied such as rock phosphate mined at Eppawala, Sri Lanka (Eppawala rock phosphate; ERP), improved rock phosphate and selectively mined rock phosphate. However, these alternate P sources are not recommended as the sole P supplier, due to their low-solubility, though they are recommended in combination with TSP or organic manure or both (Wijewardena, 1996; Wijewardena and Amarasiri, 1990).

The mixed application of inorganic fertilizers, animal manure and green manure is a common management practice in intensively cultivated vegetable fields (Wijewardena and Yapa, 1999; Wijewardena, 2000). Similar rates of poultry manure (10 t/ha), cattle manure (10 t/ha) or a combination of poultry and cattle manure (5 t/ha of each) applications are being recommended irrespective of the vegetable crop grown (Wijewardena, 2000). This recommendation has its own disadvantages as different crops remove different amounts of P from soil, and therefore, revisions are required (Wijesundara, 1990). Poultry manure, poultry droppings and broiler litter contain more nitrogen (N), P and potassium (K) than in other organic nutrient sources (Wijewardena, 2000). However, an opposite response was observed by Maraikar and Amarasiri (1988) as the effectiveness of cattle manure was higher than that observed with poultry manure. Moreover, when comparing dry and wet forms of manures, the increase in soil P concentration was lower and slower in dry forms, than in wet and fresh forms (Ariyapala and Nissanka, 2006). Therefore, the differences in the observations made above could be due to the composition of nutrients in the manures, rates of application, stages and rates of decomposition, and moisture percentage. Despite such heterogeneities in the nutrient composition in manures and plant responses, the application of recommended rates of animal manure supplemented with inorganic fertilizer appears to be the most suitable approach to improve and maintain soil fertility in intensively vegetable cultivated soils. However, the rates and intensity of those applications when crops are grown in rotation have to be tested and adjusted regularly to maintain the long-term sustainability (Wijewardena, 2000, 2001; Sirisena et al., 2002).

Degree of P saturation in intensively vegetable-cultivated soils

High concentrations of available P are reported in vegetable cultivating systems due to the excessive application of mixtures of inorganic fertilizers and manures with a mean value of 267 mg available P/kg soil (Wijewardena, 1996; NSF, 2000) as shown in Table 2. Relatively lower P concentrations have been reported in rice-vegetable rotations (85 mg available P/kg soil) while the concentrations of P reported in continuous rice cultivating systems are the lowest (13 mg available P/kg soil) as shown in Table 2 (Wijesundara, 1990). The P budget of a system can be calculated by considering the pathways of P input and output (Suriyagoda et al., 2012; Shepherd et al., 2016). The amount of P removed with the harvest of vegetable crops is far less (5–30 kg P/ha) than the amount recommended for those crops (70–200 kg P/ha) as shown in Tables 1 and 3. This difference is due to the consideration of P fixation to soil particles, leaching and the run-off at the time of fertilizer requirement calculations. There are no comprehensive studies conducted in this region to quantify the amount of P loss through leaching and runoff. However, considering the available facts the Department of Agriculture, Sri Lanka has recommended the application of higher rates of P fertilizers than the actual amount of P removed with the crop harvest (Wijewardena, 2006). According to Amarawansha and Indrarathne (2010), 59% of the 27 soils studied in this region had water extractable P concentration above the level of P saturation indicating a high risk of losing P from those soils through runoff. Moreover, the mean available P concentrations in the tested forest, tea (*Camellia sinensis* (L.) O. Kuntze) and vegetable cultivating soils were 11.6, 14 and 63.3 mg/kg, respectively indicating an accumulation of P in the vegetable-cultivation soils (Kendaragama et al., 2001). Similar results were

Table 1
Amount of P removed with harvest of total aboveground biomass of widely grown vegetables in Sri Lanka.

Crop	P removed (kg P/ha)
Bitter gourd; *Momordica charantia* (L.)	19
Brinjal; *Solanum melongena* (L.)	18
Cabbage; *Brassica oleracea* (L.) var. *capitata* (L.)	18
Capsicum; *Capsicum annuum* (L.) *annuum*	5
Carrot; *Daucus carota* subsp. *sativus* (Hoffm.) Schübl. and G. Martens	24
Luffa; *Luffa acutangula* (L.) Roxb.	24
Okra; *Abelmoschus esculentus* (L.) Moench	14
Pole bean; *Phaseolus vulgaris* (L.)	10
Potato; *Solanum tuberosum* (L.)	27
Radish; *Raphanus sativus* (L.)	11
Snake gourd; *Trichosanthes cucumerina* (L.)	10
Sweet potato; *Ipomoea batatas* (L.)	20
Tomato; *Solanum lycopersicon* (L.)	18

Sourced: Wijesundara (1990).

Table 2
Plant available P concentration in major types of cropping systems in Sri Lanka.

Soil P (Olsen P) range (mg/kg)	Cropping system		
	Rice-Rice (% fields)	Rice-Vegetable (% fields)	Vegetable-Vegetable (% fields)
<5	9		
6–10	35		
11–15	24	5	
16–25	29	20	
26–50	3	32	15
51–100		14	17
101–300		29	32
301–600			21
>600			15

Sourced: Wijesundara (1990).

Table 3
Recommended P application for upland annual crops grown in Sri Lanka.

Crop	P recommendation (kg P_2O_5/ha)	
	1980	1998
Maize; *Zea mays* (L.)	52.5	45
Sorghum; *Sorghum bicolor* (L.) Moench	52.5	45
Finger millet; *Eleusine coracana* (L.) Gaertn.	22.0	22
Greengram; *Vigna radiata* (L.) Wilczek	62.5	45
Blackgram; *Vigna mungo* (L.) Hepper	62.5	45
Cowpea; *Vigna unguiculata* (L.) Walp.	62.5	45
Soy bean; *Glycine max* (L.) Merr.	75.0	45
Ground nut; *Arachis hypogaea* (L.)	62.5	45
Sesame; *Sesamum indicum* (L.)	54.0	54
Chili; *Capsicum annuum* (L.)	101.75	45
Onion; *Allium cepa* (L.) cv. group *Cepa*	52.7	45
Pole bean; *Phaseolus vulgaris* (L.)		125
Tomato; *Solanum lycopersicon* (L.)		100
Cabbage; *Brassica oleracea* (L.) var. *capitata* (L.)		125
Potato; *Solanum tuberosum* (L.)		125

Sourced: Wijewardena and Yapa (1999).

reported by Wijesundara (1990), Sirisena et al. (2002) and Amarawansha and Indrarathne (2010). As most of the soils contained high concentrations of plant available P, that is higher than the optimal range of 10–20 mg P/kg soil, vegetables grown in this region did not respond to P fertilizer applied (Wijewardena and Amarasiri, 1990; Kendaragama et al., 2001; Amarawansha and Indrarathne, 2010). Despite all these observations, farmers apply 2–3 times higher P rates than recommended, leading to a gradual development of P in vegetable-cultivated soils. Such P fertilizer application, in situations where crops do not respond to applied P, is considered as P over-fertilization. Under such situations P demand by different crops when grown in rotations, multiple or mono cropping systems, P buffer capacities of those soils, temporal changes in P dynamics at the recommended and farmer practiced rates of fertilizers are urgently required to be identified to develop sustainable P application plans and educate farmers.

The degree of P saturation is an environmental index to assess the potential of a soil to release P through runoff and leaching (Allen and Mallarino, 2006). The degree of P saturation relates the extractable P of a soil to its P adsorption capacity. Therefore, it provides a reliable and unifying criterion for making environmentally acceptable and agronomically efficient P fertilizer recommendations (Khiari et al., 2000). With this background Amarawansha and Indrarathne (2010) estimated the degree of P saturation of 27 soil samples collected from different fields and stated that intensive vegetable-cultivated soils exhibit high P availability (151 ± 15 mg/kg) despite their high P adsorption capacities (676 ± 44 mg/kg) posing negative impacts on water quality. MacDonald et al. (2011) also found that most of the intensive vegetable-cultivated soils in Sri Lanka have a surplus of P, lowering their P-use efficiency. Therefore, the evaluation of P in runoff and reservoirs, temporal change in soil P reserves and experimentation to revise P fertilizer application plans in intensive vegetable-growing regions are of paramount importance. As a result of the accumulation of P in vegetables cultivated lands, the Department of Agriculture has revised the P fertilizer application plan with reduced rates as shown in Table 3 (Wijewardena and Yapa, 1999). Despite the existence of a revised P fertilizer recommendation, farmers are reluctant to reduce the application rates due to: (i) unfavourable weather events, (ii) strong influence from private sector input suppliers and/or, (iii) weak extension mechanisms and inter-institutional collaboration to educate farmers (Ariyapala and Nissanka, 2006; Wijewardena, 2006; Wijerathna et al., 2014). Private sector enterprises frequently provide extension, training and promotion campaigns to sell their products (Wijerathna et al., 2014). Moreover, farmers have not been exposed to nor convinced by evidence-based, sustainable agricultural practices due to the inefficient and ineffective extension network of the government Department of Agriculture. Therefore, these hostile farmers adopt the attractive introductions made available to them by private sector organizations.

Status in the rice sector

Status of P in lowland rice soils

The evolution of fertilizer recommendations for rice, including the types of nutrients, rates of application, number of formulations and P fertilizer sources are given in Table 4 (Bandara, 2006; Department of Agriculture, 2013). In the earliest recommendations, P was supplied through mixtures of rock phosphate (RP) and TSP, and with the development of high yielding rice varieties the application of TSP was recommended. Organic manure application is not practiced by rice farmers due to the lack of availability, cost and time constraints even though the application of manures is recommended (Wijesundara, 1990; Wijewardena, 2006; Suriyagoda et al., 2014). A rice crop with an average yield of 6 t/ha is estimated to remove 20 kg of P per season (Suriyagoda et al., 2014; Somaweera et al., 2017). Less than 44% of rice-growing soils in Sri Lanka have an available P concentration of less than 10 mg/kg, while the rest have higher P concentrations, and the mean P concentration reported was 13 mg/kg as shown in Table 2 (Wijesundara, 1990). However, none of the rice crops showed P deficiency (Wijesundara et al., 1990; Bandara, 2006; Sirisena et al., 2013; Somaweera et al., 2017). Due to the continuous accumulation of P in lowland rice fields with the application of P fertilizers, the Department of Agriculture has revised the P fertilizer recommendations as shown in Table 4 (Bandara, 2006; Department of

Table 4
Nutrient recommendation for rice 1950–2001.

Year	Number of formulations	Recommended amount (kg/ha)				
		N	P_2O_5	K_2O	$ZnSO_4$	Form of P fertilizer
1950	3	10–20	16–23	8–10	–	TSP and RP
1956	3	34–48	30–40	28–56	–	RP, TSP
1959	10	12–51	17–53	15–31	–	RP
1964	28	21–57	17–51	18–56	–	RP
1967	13	43–57	34–84	18–56	–	RP, TSP
1971	31	35–108	19–74	12–56	–	RP, TSP
1980	19	30–108	36–55	30–68	–	TSP
1990	9	45–100	28–45	25–35	–	TSP
1996	14	30–100	20–30	20–30	–	TSP
2001	9	45–140	25–45	35–45	5	TSP
2013	4	45–105	15–25	30–35	5	TSP

TSP = triple super phosphate; RP = rock phosphate.
Sourced: Bandara (2006); Department of Agriculture (2013).

Agriculture, 2013). Accordingly, soil P fertility status has reduced from the observations made before; however, rice crops still do not show P deficiency symptoms (Bandara, 2006; Sirisena et al., 2013; Somaweera et al., 2017).

P response studies

Experiments conducted in 83 fields representing six soil types through seven seasons showed an increase in the rice yield with increased P supply only at 26 locations (Rezania et al., 1992). Another P response study conducted for five consecutive seasons revealed that application of 50 kg P_2O_5/ha reduced the grain yield only in two seasons, and the rice crop did not respond to P fertilizer applications over 75 kg P_2O_5/ha (Kendaragama et al., 2003). Moreover, it has been found that soil P availability and grain yield were maintained at a constant level when P was applied at a rate of 30–75 kg P_2O_5/ha (Sirisena et al., 2002; Bandara, 2006). Any differences in the P application rates from the above could have been due to differences in the P buffer capacity of those soils and the yield potential associated with the climate in those regions.

With the current rate of P fertilizer application, plant available P concentration in lowland soils did not reduce to the extent of showing P deficiency symptoms in the rice plants and only in a few instances were P deficiency symptoms observed (Senevirathna Banda et al., 2002; Bandara, 2006). As most of the experiments were conducted at different locations, seasons and the use of different varieties did not indicate a P deficiency or positive response to P application, Sirisena et al. (2013) conducted a field experiments at 21 locations in four districts for three consecutive seasons with the application of P fertilizer at a reduced rate of 45 kg P_2O_5/ha in alternate seasons. They found that the grain yield obtained under alternate P applications was similar to that obtained with P application every season at a rate of 45 kg P_2O_5/ha. Kendaragama et al. (2003) also found that application of P at a rate of 75 kg P_2O_5/ha in the irrigated dry season possibly supplied P for the subsequent rain fed rice crop through residual P. However, if an alternate P fertilizer application is recommended, careful monitoring of crop growth throughout the season and in different agro-climatic regions is required as soils may deplete their inherent P status and begin to show P deficiency symptoms and yield reductions (Somaweera et al., 2017). Moreover, the time taken to show P deficiency symptoms could vary depending on the total P reserves in the soil, the P mineralization rate, the P buffer capacity, the amount and type of P fertilizers and organic manures applied and the cropping intensity. It has also been reported that physiological responses of rice plants are more prominent than morphological responses, and the tillering stage is the most sensitive stage in the rice crop life cycle to declining soil P (Somaweera et al., 2017). The overall results from the above studies for a broad range of soils, agro-climatic conditions, seasons and P fertilizer management strategies indicate that most of the rice growing soils in the country are not deficient in P. Moreover, the amount of P already retained in those soils is adequate to supply the required amounts of P to the rice crop for several seasons depending on the buffer capacity of those soils, and P fertilization and cultivation history.

Impact on the environment and human health

A high phosphate concentration in surface waters indicates fertilizer runoff, domestic waste water discharge or the presence of industrial effluents or detergents (Pathirana et al., 2004; Jayatissa et al., 2006). Phosphate is carried along with silt particles and settles down in water bodies. Therefore, reservoir sediments serve as a phosphate sink. According to the classification of Ayers and Westcot (1994), irrigation water with a phosphate-P concentration in the range 0–2 mg/L can be categorized as normal. However, the available phosphate P concentration in Parakarama Samudraya, a major reservoir located at the centre of intensively rice cultivated region, was in the range 19–34 mg/L (Pathirana et al., 2004). If the current rate of P fertilizer application continues, the risk of increasing P concentration in reservoir waters will be high, and therefore, approaches for sustainable P management are urgently required.

Even though chemical fertilizers available in the market are expected to contain trace amounts of heavy metals, high concentrations of arsenic (As) and cadmium (Cd) have been found in P fertilizers (Dissanayake and Chandrajith, 2009; Roberts, 2014; Jayasumana et al., 2015a). The maximum acceptable levels of Cd, lead (Pb), and As in phosphate fertilizer are 4 μg/g, 20 μg/g and 2 μg/g, respectively (Bandara et al., 2010; Jayatilake et al., 2013). However, the maximum levels of Cd, Pb and As detected in phosphate fertilizer were 30.8 μg/g, 823.4 μg/g and 0.19 μg/g, respectively (Jayatilake et al., 2013), indicating that at least some of the phosphate fertilizers available in the market are contaminated with Cd and Pb. Similar results were reported by Dissanayake and Chandrajith (2009) and Jayasumana et al. (2015a). A continuous application of overdoses of contaminated fertilizers may have contributed to the increase in heavy metals in the soil and groundwater aquifers. To date, there are no permissible levels of heavy metals identified for Sri Lankan rice soils. However, the permissible levels of Cd, Pb and inorganic As in rice grains are; 0.4 mg/kg rice grain, 0.2 mg/kg rice grain and 0.2 mg/kg rice grain, respectively (World Health Organization, 2011, 2016). Rice grains produced in Sri Lanka contained 0.12 mg As/kg (n = 154) and the range was 0.012–0.54 mg As/kg indicating that certain rice samples contained As concentrations over the permissible level (Rowell et al., 2014; Jayasumana et al., 2015b; Suriyagoda et al., 2018). Chronic exposure of people to low concentrations of heavy metals such as As and Cd through the food chain may cause health problems (Williams et al., 2009; Roberts, 2014). In the last two decades, escalating numbers of patients with kidney disease have been reported in Sri Lanka where rice is continuously grown and P fertilizers are continuously applied (Jayasumana et al., 2013; Wimalawansa, 2014). The Ministry of Health (2009) in Sri Lanka has labelled this as chronic kidney disease of unknown etiology (CKDu). Due to these reasons scientists suspect that one of the potential reasons for the escalation of CKDu is due to the contamination of rice growing soils with heavy metals added through P fertilizers (Jayasumana et al., 2015a; b). It has also been found that the concentration of heavy metals is very low in the organic manures widely used in Sri Lanka (Jayasumana et al., 2015a). Therefore, incorporation of organic manures to soils contaminated with heavy metals would be one strategy to reduce the heavy metal loading and bio-availability through fixation and bioremediation. Even though the rate of phosphate fertilizer application in intensive vegetable-cultivated areas is higher than that found in rice-based cropping systems, the occurrence of CKDu in vegetable-cultivating regions is not prevalent. Therefore, the occurrence of CKDu only in certain areas in the country is also expected to be linked with the soil parent material, water hardness and the distribution of irrigation water in a cascade system apart from the use of phosphate fertilizers contaminated with heavy metals. However, detailed fact finding is needed to improve the quality of life of people in any region where CKDu is prevalent, and to reduce the negative impacts of P fertilizers on the environment and human health.

As a result of the gradual development of the knowledge base with respect to environment and health concerns, the government and the Department of Agriculture in Sri Lanka have taken several steps to ensure sustainable P management in agriculture. Among many others key steps included are: the introduction of an act to regulate fertilizer use inclusive of P; policy measures to control fertilizer adulteration; the establishment of the National Fertilizer Secretariat and its functions to ensure sustainable P management; the establishment of the Fertilizer Advisory Committee; promotion of straight fertilizer use; introduction of soil testing-based fertilizer recommendations; periodic revision of P fertilizer recommendations; research attempts to replace TSP by ERP for all possible crops; and the introduction of P application in alternate seasons at a pilot scale for rice (Wijewardena, 2006; Sirisena et al., 2013). Despite all these steps being taken, farmers have not adopted them at the field scale and continue to apply high rates of P than recommended (Kendaragama et al., 2001; Sirisena et al., 2013). Therefore, farmers need to be empowered with updated knowledge and assisted in their decision making process.

Shepherd et al. (2016) suggested a conceptual framework to optimize P utilization at plant, farm, regional and global scales aimed at enhancing the sustainability of agriculture with respect to P nutrition. Among many others key efforts they included: regulating P available in the market; inter-institution collaboration (both in private and public sector enterprises); strengthening agriculture extension services to empower farmers; mapping soil P dynamics both in spatial and temporal scales; revised P application plans; and strengthening research and development. The implementation of these practices is expected to improve the sustainability of P management in rice- and vegetable-cultivating systems in Sri Lanka.

Conflict of interest

The authors declare no conflict of interest.

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