

RESEARCH ARTICLE

Agronomy and Plant Nutrition

Distribution of phosphorus and potassium in selected rice cultivated soils and their accumulation in rice grains under farmer-managed field conditions in Sri Lanka

LDB Suriyagoda*, NASA Neththasinghe, EDCT Chandrasekara, EMS Ekanayake, DMSB Dissanayaka, M Ariyaratne and B Marambe

Department of Crop Science, Faculty of Agriculture, University of Peradeniya, Peradeniya, Sri Lanka.

Submitted: 06 September 2022; Revised: 18 March 2023; Accepted: 26 May 2023


Abstract: Rice (*Oryza sativa* L.) is the staple food in Sri Lanka and phosphorus (P) and potassium (K) are major nutrients for the rice plant. However, the variation of P and K contents (mg kg^{-1}) in rice soils and rice grains as affected by agro-climatic zones (ACZs), water source used (*i.e.*, major irrigation, minor irrigation and rain-fed) and cropping systems adopted (*i.e.*, fallow, vegetable, perennials, other field crops) by Sri Lankan farmers are not well elucidated, and are thus investigated in the present study. A total of 200 rice soil and 230 rice grain samples across the country were collected from farmer fields, representing different ACZs, water sources used, and cropping systems adopted using a stratified random sampling approach. The total and available P and K contents in rice soil, and the P and K contents in rice grains were determined. The plant-available P contents in soil were similar among ACZs, water sources, and rice-based cropping systems. Exchangeable K content was higher in rice fields where vegetables were cultivated in the previous season. Grain P and K contents were similar among the water sources used and rice-based cropping systems. Grain P contents was the lowest in the Low country Wet zone. Soil available-P and total-P contents ($r = 0.29$, $p < 0.0001$), and grain P and K contents were positively correlated ($r = 0.51$, $p < 0.0001$). The knowledge generated in the present study is important in P and K nutrient management in rice cultivation in the country.

Keywords: Agro-climatic zones, cropping systems, irrigation methods, P and K contents, rice soils and grains.

INTRODUCTION

Rice (*Oryza sativa* L.) is the staple food crop for about half of the world's population (Priya *et al.*, 2019). In addition, rice is a vital source of minerals and vitamins. About 40% of total calorie intake and 45% of total protein requirement of a Sri Lankan adult is fulfilled by rice (Liyaarachchi *et al.*, 2020). Moreover, more than 1.8 million farm families in Sri Lanka rely on the cultivation of rice as their livelihood and therefore, rice has become the most important cereal crop in the country (Hettiarachchi *et al.*, 2016). In Sri Lanka, rice is grown under a wide range of environments in different elevations, soil types, and hydrological regimes (FAO, 2000).

Phosphorus (P) and potassium (K) are two major essential mineral elements required by plants and thus determine the growth and yield of crops (Moe *et al.*, 2019; Ma *et al.*, 2020). Application of P and K containing fertilizers and manures is recommended to increase the grain yield of rice by ensuring soil fertility (Ma *et al.*, 2020; Suriyagoda, 2022). In rice, P fertilizer-use efficiency for the production of above-ground biomass is approximately 25% (Vinod & Heuer, 2012; Suriyagoda, 2022). Malpractices in nutrient management have led to deficiencies and toxicities of nutrients for crop growth, thereby negatively affecting the crop productivity (Masni & Wasil 2019; Moe *et al.*, 2019). Moreover, improper fertilization has been a serious issue in agricultural fields contributing to the degradation of soil, eutrophication of water bodies, pollution of groundwater and emission of toxic gases (Ju *et al.*, 2009; Ye *et al.*, 2015; Sirisena & Suriyagoda, 2018).

* Corresponding author (lalith.suriyagoda@agri.pdn.ac.lk;  <https://orcid.org/0000-0002-5253-2717>)



This article is published under the Creative Commons CC-BY-ND License (<http://creativecommons.org/licenses/by-nd/4.0/>). This license permits use, distribution and reproduction, commercial and non-commercial, provided that the original work is properly cited and is not changed in anyway.

When considering elevation, areas located below 300 m, between 300-900 m and above 900 m of sea level in Sri Lanka are identified as Low-, Mid-, and Up-Country regions, respectively (Punyawardane, 2008). Based on the rainfall pattern, areas receiving mean annual rainfall less than 1750 mm and having a relatively dry period from June to September are considered as the Dry zone. The areas receiving a mean annual rainfall greater than 2500 mm and without any dry period throughout the year are considered as the Wet zone, while the Intermediate zone has characteristics in between with respect to the amount and distribution of annual rainfall. Considering both mean annual rainfall and elevation, Sri Lanka is divided into seven agro-climatic zones (ACZs). Out of those, five ACZs are considered as main rice growing zones in the country, *i.e.*, Low country Dry zone (DL), Low country Intermediate zone (IL), Up country Intermediate zone (IU), Mid country Intermediate zone (IM) and Low country Wet zone (WL) (DOA, 2021). Phosphorus and K fertility of rice cultivated soils in these ACZs would vary due to the differences in soil forming parent materials, climate, and agronomic practices adopted. Therefore, it is important to understand the variability of soil P and K contents (mg kg^{-1}) among ACZs and their relationships to grain accumulation.

Based on the major water source used, rice cultivation in Sri Lanka is divided into three categories, namely major irrigation, minor irrigation and rainfed (Navarathna *et al.*, 2021). Reservoirs in major irrigation schemes have more than 80 ha of command area (irrigated land) while the minor irrigation schemes are comprised less than 80 ha of command area (Imbulana *et al.*, 2006). Rice cultivation in DL and IL of Sri Lanka largely depends on the well-distributed cascade irrigation network covering both major and minor irrigation schemes. Rice cultivation in other regions largely depends on rainfall. This variation in water source may contribute to spatial variation of P and K availability in rice soils and their accumulation in rice grains.

Rice cultivation in Sri Lanka is generally practised in two seasons, *i.e.*, *Yala* (minor season; March-September) and *Maha* (main season; October-February in the following year). In order to obtain the best returns from resources used such as land and water, economically valuable non-rice crops are cultivated in rotation with rice, mainly in the water-limited *Yala* season (Dimantha, 1987; Panabokke, 1989). Considering this, rice-based cropping systems can be recognised either as rice-rice, rice-fallow, rice-other field crops (OFC) or rice-vegetables cropping systems (Bandara *et al.*, 2003). However, the impacts of crop rotation in rice-based cropping systems on soil P and K availability and rice grain P and K status are not known. Therefore, the objectives of the present study were to determine the, (i) total and plant-available P and K contents in selected rice soils, (ii) P and K contents in rice grains, and (iii) relationships between soil and grain P and K contents as affected by the ACZ, water source used, and rice-based cropping systems adopted in rice lands.

MATERIALS AND METHODS

A total of 200 soil samples and 230 rice grain samples collected from farmer fields were used for the study. These samples were collected from five ACZs (except Up and Mid Country Wet zones), three major water sources used for rice cultivation (*i.e.*, major irrigation, minor irrigation and rain-fed), and four major rice-based cropping systems (*i.e.*, rice-rice, rice-vegetable, rice-other field crops and rice-fallow) adopted. A structured and pre-tested questionnaire was used to collect the information on the major water source used, and rice-based cropping system adopted. The number of soil and grain samples used for the analysis of P and K contents from different ACZs, rice-based cropping systems, and water sources is summarized in Tables 1 and 2.

Table 1: Number of soil samples used for the analysis of total and available P and K contents in rice soils

Agro-climatic zone	No.	Rice-based cropping system adopted	No.	Major water source used	No.
Dry zone Low country	128	Rice-Rice	113	Major irrigation	89
Intermediate zone Low country	28	Rice-Fallow	40	Minor irrigation	55
Intermediate zone Mid country	13	Rice-OFC	11	Rain-fed	38
Intermediate zone Upcountry	12	Rice-Vegetable	13		
Wet zone Low country	19				
Total	200		177		182

Table 2: Number of rice grain samples used for the analysis of total and available P and K contents in rice grains.

Agro-climatic zone	No.	Rice-based cropping system adopted	No.	Major water source used	No.
Dry zone Low country	138	Rice-Rice	113	Major irrigation	89
Intermediate zone Low country	33	Rice-Fallow	40	Minor irrigation	55
Intermediate zone Mid country	18	Rice-OFC	11	Rain-fed	38
Intermediate zone Upcountry	17	Rice-Vegetable	13		
Wet zone Low country	24				
Total	230		177		182

One soil sample was a composite of four to six samples collected from a rice track (*Yaya*) considering field level soil heterogeneity. Each sample was collected from top 0-15 cm soil layer using a soil auger. For grain collection, the same rice fields used to collect soil samples were considered. In addition, 30 rice fields selected randomly from other locations were also used. Twenty-five panicles were collected from the selected *Yaya* to represent the mainly cultivated rice variety of that *Yaya*. Soil and grain samples were collected using a stratified random sampling approach as described in Kadupitiya *et al.* (2021) before (*i.e.*, September and October, 2019) and at the end of the *Maha* 2019/20 season (*i.e.*, February and March, 2020), respectively.

Soil samples were air dried, gravel and plant parts were removed, the samples were homogenized, and then sieved using a 2 mm sieve. The samples were stored at room temperature, in a dry and dark room until used for analysis. The total K content of soil was determined using the Niton XL5 XRF analyzer (Thermo Fisher, USA). An air dried, ground soil sample was filled into a plastic ring and sealed with a polythene membrane. The packed ring was placed in the safety box of the X-ray shutter. Data of total soil-K content was recorded through a laptop installed with a Niton Connect ZRF analyzer (Thermo Fisher, USA) and expressed as mg K kg⁻¹ soil. For exchangeable soil K determination, about 2.5 g of dried, ground soil samples were treated with 50 mL of 1 M NH₄OAc solution. The pH of the sample was buffered at 7 and shaken for 2 h using an orbital shaker at room temperature. Then, the solution was filtered using Whatman[®] filter papers (No. 40; D = 110 mm). The exchangeable K content of soil was measured using a flame photometer at 766.5 nm wavelength and expressed as mg K kg⁻¹ soil.

For the determination of soil total P, two grams of soil was measured into a 250 mL Erlenmeyer flask. About 25 mL of 70% HClO₄ was added and the mixture allowed to digest at 80-120 °C until the dark color of the organic matter disappeared. After cooling, the digested samples were transferred into 250 mL volumetric flasks and the volume adjusted to the mark with distilled water. Samples were homogenized and the solid particles allowed to settle down. Then, 2 mL from the sample was pipetted out in to a test tube and mixed with 2 mL of colour development reagent and 6 mL of distilled water (Van Ranst *et al.*, 1999). After 10 min of standing, the optical density was measured using a spectrophotometer (A & E, AE-S70-2U, England) at 430 nm and the P concentration expressed as mg P kg⁻¹ soil. The colour development reagent was prepared by combining two solutions. One solution was made by dissolving 25 g of ammonium molybdate (Fisher Scientific, UK) in 400 mL of hot distilled water. In order to prepare other solution, 1.25 g of ammonium metavanadate (Fisher Scientific, UK) was dissolved in 300 mL of hot distilled water. After that, about 250 mL of concentrated HNO₃ was added. The two solutions were mixed in 1 L volumetric flask and the volume adjusted to 1 L (Van Ranst *et al.*, 1999).

The available P content in soil samples was determined using the Olsen method (Olsen, 1954). Dried, homogenized, and sieved soil samples of 2.5 g were measured into clean and dry conical flask of 250 mL. Then soil samples were treated with 50 mL of 0.5 M sodium bicarbonate (NaHCO₃) and allowed to shake for one hr on an orbital shaker at room temperature. Then the solution was filtered using Whatman[®] filter papers (No. 40; D = 110 mm). Next, 5 mL of the extract and 5 mL of colour developing reagent were pipetted out into a 25 mL volumetric flask, volume up to 25 mL using distilled water and mixed. The solution was kept for 20 min for colour development. The available P content was determined using a spectrophotometer at 880 nm and expressed as mg P kg⁻¹ soil (Van Ranst *et al.*, 1999).

The colour developing reagent was prepared by adding 0.739 g of ascorbic acid to 140 mL of mixed reagent. The mixed reagent was made by mixing two solutions. The first solution was prepared by dissolving 12 g of ammonium molybdate (Fisher Scientific, UK) in 250 mL distilled water. To prepare the second reagent, 0.29 g of antimony potassium tartrate (Fisher Scientific, UK) was dissolved in 1 L of 5 M sulfuric acid. The two solutions were dissolved together and made up to 2 L with distilled water (Van Ranst *et al.*, 1999).

The phosphorus standard graph was prepared as described in Van Ranst *et al.* (1999). Here, 0, 0.5, 1.0, 1.5, 2.0 and 2.5 mL of 5 mg P L⁻¹ of standard solution were separately pipetted out into different labelled conical flasks. Then 5 mL of 0.5 M NaHCO₃ solution and 5 mL of mixed reagent were added and mixed. Distilled water was added to each flask to reach the 25 mL level and the solutions allowed to stand for 15 min for colour development. Absorbance levels for the known available P contents (*i.e.*, 0, 0.1, 0.2, 0.3, 0.4, and 0.5) were determined using a spectrophotometer at 880 nm and calibration graph was drawn by plotting absorbance value and available P content. The available P content of a sample was determined using the following calculation:

$$\text{Available soil P content (mg kg}^{-1}\text{)} = (X \times 25 \times 50) / 5 \times W \text{ (Van Ranst } et al., 1999)$$

where X is the graph reading and W is the weight of the soil sample.

For the determination of grain P and K contents (mg kg⁻¹), one gram of de-husked grain sample was burnt in a muffle furnace for 2 h until converted to ash. The temperature was set to 200 °C in the 1st hour and 450 °C in the 2nd hour. After cooling the sample, 5 mL of 6 M nitric acid was added into the crucible and thoroughly mixed by using a glass rod. Then, the sample was put into a 100 mL beaker, and the crucible and glass rod were washed with 1% nitric acid and placed in the beaker. The sample was then boiled for about 15 min, and 5 mL of 3 M nitric acid were added during boiling. Thereafter, the sample was kept outside for cooling. The beaker solution was filtered into a 50 mL volumetric flask and the volume adjusted to 50 mL using distilled water. The grain P content in the solution was measured using a spectrophotometer at 430 nm wavelength and expressed as mg P g⁻¹ grains. Two mL of the previous solution was pipetted out into a test tube. Six milliliters of distilled water and 2 mL of nitro-vanadomolybdate was added and mixed properly. The grain K content in the solution was measured by using a flame photometer (Jenway, Sussex, England) at 766.5 nm wave length and expressed as mg kg⁻¹ grains.

Data were statistically analysed using SAS 9.1 software. Element contents in soil and grain samples collected from different sources (*i.e.*, ACZ, water sources and cropping systems) were analysed using analysis of variance (Proc GLM) and mean separation was done through Duncan's New Multiple Range Test (DNMRT). Strengths of the relationships between elements (paired comparisons) were determined using Pearson's linear correlation coefficient (*r*). Statistical significances were expressed at $\alpha = 0.05$.

RESULTS AND DISCUSSION

P and K contents in rice soils

The available P content in rice soil samples ranged between 5.4 and 220.1 mg kg⁻¹ with a mean content of 22.1 mg kg⁻¹ (Figure 1). The critical soil available P content causing P deficiency symptoms in Sri Lankan rice is generally considered as 10 mg kg⁻¹ (Sims, 2000). It has also been reported that the critical available P content would vary from 10 to 40 mg kg⁻¹ based on the geographical region, crop type, and soil type, including soil structure, pH, soil depth, and organic matter content (Bai *et al.*, 2013). When considering the soil pH, critical available P content recorded for acidic soil is 5 mg kg⁻¹ and it is more than 25 mg kg⁻¹ in calcareous soils (Dobermann & Fairhurst 2000).

Over 70% of rice soil samples recorded available P contents less than 30 mg kg⁻¹ and 23% of soil samples had available P contents less than 10 mg kg⁻¹. Total P content of rice soil samples ranged between 24 and 4,929 mg kg⁻¹ (Figure 1). According to Sirisena and Suriyagoda (2018), the mean available P content of continuously rice-cultivated soils in Sri Lanka was around 13 mg kg⁻¹, and 44% of rice growing soils in the country recorded an available P contents less than 10 mg kg⁻¹. Farmers have applied P fertilizers as a routine practice without considering the 2013 fertilizer recommendation in the Department of Agriculture. This might have caused an

increase in the mean available P content in selected rice tracts in the present study compared to that reported by Sirisena and Suriyagoda (2018).

The mean exchangeable K content in rice soil was 257.8 mg kg⁻¹, and it ranged from 26.4 to 1,372.8 mg kg⁻¹ (Figure 1). The total K content in rice soil samples was in the range of 316 - 31,153 mg kg⁻¹ (Figure 1). Bandara *et al.* (2003) reported that soil critical exchangeable K content for rice is 78 mg kg⁻¹. According to the Department of Agriculture recommendation, the optimum exchangeable K content for rice cultivation in Sri Lanka is considered as 80 – 160 mg kg⁻¹ (Rathnayake *et al.*, 2015). However, according to Dobermann and Fairhurst (2000), soil exchangeable K contents less than 60 mg kg⁻¹, between 60 mg kg⁻¹ and 175 mg kg⁻¹, more than 175 mg kg⁻¹ are considered as deficient, optimal, and excess exchangeable K contents for rice, respectively. Accordingly, out of the total samples used in the present study, 4.0%, 39.5% and 56.5% of soil samples had exchangeable K contents less than 60 mg kg⁻¹, between 60 and 175 mg kg⁻¹ and greater than 175 mg kg⁻¹ contents, respectively. However, the critical exchangeable K content may vary from 40 to 156 mg kg⁻¹ depending on soil texture, clay mineralogy, rainfall variation, and K inputs, especially from the natural resources (Bandara *et al.*, 2003; Rathnayake *et al.*, 2015).

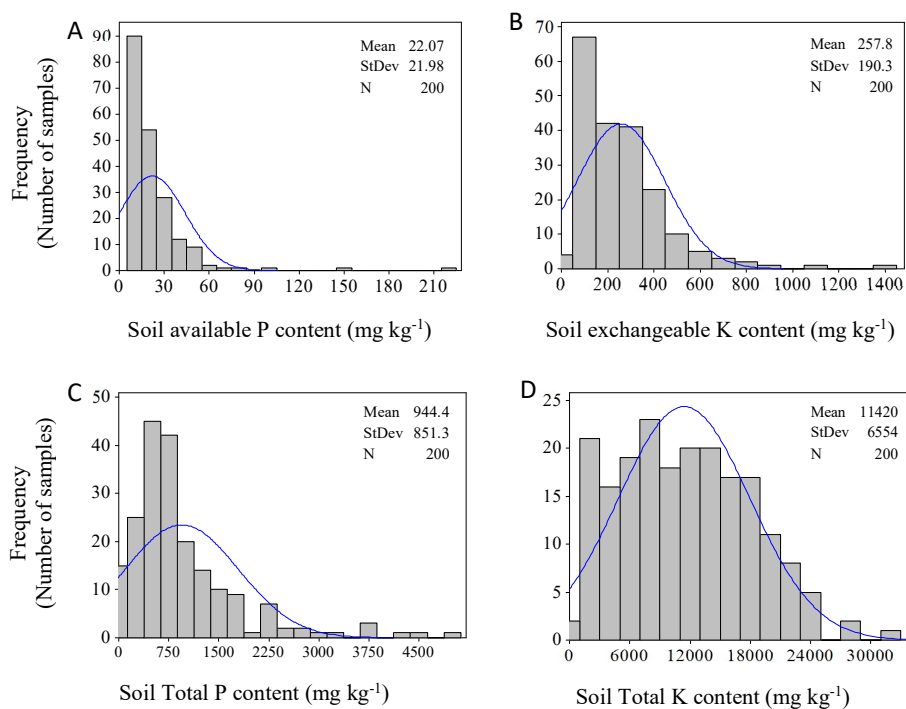


Figure 1: Distribution of (A) available phosphorus (P); (B) exchangeable potassium (K); (C) total P and (D) total K content of the rice soil samples collected from Sri Lanka.

Note: blue line in each sub-figure indicates the fitted frequency distribution, N = Sample Size

The total and available P content in soil samples were similar among ACZs ($p > 0.05$) (Table 3). However, the total soil K content was the lowest in WL and exchangeable K content was the highest in IM ($p < 0.05$) (Table 3).

The comparatively higher exchangeable K content observed in IM could be due to the presence of Immature Brown Loam (IBL) soil in this region (Bandara *et al.*, 2003; Wickramasinghe *et al.*, 2003). The amount of K taken up and tissue K content in rice were the highest when grown in IBL soil due to the higher initial exchangeable K content and the higher negative K balance in IBL soil (Mapa, 1992; Bandara *et al.*, 2003; Wickramasinghe *et al.*, 2003). Rezanía (1993) reported that almost 50% of the rice growing soils in WL have exchangeable K content less than 58 mg kg⁻¹, which is lower than that reported in the present study. However, consistent with the present study, Rubasinghe *et al.* (2021) also observed similar exchangeable K content in WZ and DZ soils. In the WZ, K

could be lost due to leaching as a result of higher mean annual rainfall than in DZ and IMZ (Wickramasinghe *et al.*, 2003).

Table 3: Phosphorus (P) and potassium (K) contents (mg kg⁻¹) in samples from rice cultivated soils collected from different agro-climatic zones.

Element	Agro-climatic zone				
	DL	IL	WL	IM	IU
Total P	934 ± 75 ^a	879 ± 110 ^a	920 ± 192 ^a	1,705 ± 139 ^a	1,046 ± 243 ^a
Total K	12,270 ± 534 ^a	11,402 ± 1,144 ^{ab}	3,317 ± 421 ^b	10,739 ± 399 ^{ab}	15,488 ± 740 ^a
Available P	24 ± 2 ^a	19 ± 2 ^a	15 ± 2 ^a	27 ± 2 ^a	26 ± 5 ^a
Exchangeable K	265 ± 17 ^b	224 ± 30 ^b	230 ± 26 ^b	603 ± 57 ^a	166 ± 43 ^b

Note: means followed by the same letter within a row are not significantly different at $\alpha = 0.05$. Values represent the mean ± SE (DL = Dry zone Low country, IL = Intermediate zone Low country, WL = Wet zone Low country, IM = Intermediate zone Mid country, IU = Intermediate zone Upcountry)

The total P, total K, and available P contents in soils from different rice-based cropping systems were similar ($p > 0.05$) (Table 4). However, the exchangeable K contents in soils collected from the rice-vegetable cropping system was higher than those of other rice-based cropping systems ($p < 0.05$). Vegetables demand a frequent and steady supply of nutrients due to the presence of a shallow root system and fast growth rate (Suriyagoda *et al.*, 2012; Upekshani *et al.*, 2018). Therefore, frequent application of inorganic fertilizers in combination with organic manures such as cattle and poultry manure, during the period of vegetable cultivation in the rice-vegetable cropping system is essential (Maraikar *et al.*, 1997; Wickramasinghe *et al.*, 2003; Sirisena and Suriyagoda, 2018; Suriyagoda *et al.*, 2022). It is also reported that the fertilizer use in upcountry vegetable cultivating systems was higher than the recommended rates (Upekshani *et al.*, 2018; Suriyagoda *et al.*, 2022), e.g., 30% to 50% of the upcountry vegetable farmers have applied more than the recommended rate of muriate of potash for K when cultivating carrot, leeks, and cabbage in Nuwara Eliya and tomato, snake gourd, and bitter gourd in the Marassana area (Upekshani *et al.*, 2018). In general, the organic fertilizer application rates for vegetable cultivation in this region varied from 10 to 15 t ha⁻¹ yr⁻¹ of poultry manure and 20 to 30 t ha⁻¹ yr⁻¹ of cattle manure (Suriyagoda *et al.*, 2012). Vegetables such as pole bean take up low amounts of K whereas cabbage acquires a high amount of K, indicating that soil K content is also influenced by the type of vegetable cultivated in the cropping system (Maraikar *et al.*, 1997). Overall results suggest that the higher rates and frequencies of K fertilizer application have contributed to an increase in exchangeable K content in rice-vegetable cropping systems than other rice-based cropping systems tested in the study.

The available P content reported in rice-vegetable cropping systems was around 26 mg P kg⁻¹ soil (Table 4). In contrast, Sirisena and Suriyagoda (2018) reported an available P content of 85 mg P kg⁻¹ in rice-vegetable cropping systems. Comparatively lower available soil P content observed in the present study in comparison to the previous report would be due to the reduced rate in the recommendation of P fertilizers, P fixation in soil, removal of P with the harvest of vegetable crops, leaching and runoff. Phosphorus removal through harvesting of rice may also contribute to the decline in soil P availability. For example, 20 kg of P is removed with the harvest of 6 t ha⁻¹ of rice grains (Sirisena & Suriyagoda, 2018). Moreover, unlike K, most of the P taken up by rice plants is stored in rice grains; thereby a considerable amount of P is removed from soil with the harvest of rice grains (Somaweera *et al.*, 2017).

Table 4: Phosphorus (P) and potassium (K) contents in soil samples collected from different rice-based cropping systems.

Element	Rice-based cropping systems			
	Rice-rice	Rice-fallow	Rice-vegetables*	Rice-other field crops
Total P (mg g ⁻¹)	0.9 ± 0.09 ^a	1.1 ± 0.19 ^a	1.7 ± 0.14 ^a	1.5 ± 0.2 ^a
Total K (mg g ⁻¹)	11.0 ± 0.86 ^a	10.1 ± 1.2 ^a	10.7 ± 0.40 ^a	13.4 ± 1.99 ^a
Available P (mg kg ⁻¹)	18.2 ± 1.5 ^a	29.4 ± 8.4 ^a	26.9 ± 2.2 ^a	25.6 ± 4.4 ^a
Exchangeable K (mg kg ⁻¹)	203.1 ± 13.1 ^b	274.6 ± 27.7 ^b	603.4 ± 56.5 ^a	337.5 ± 80.8 ^b

Note: means followed by the same letter within a row are not significantly different at $\alpha = 0.05$. Values represent the mean ± SE

* values presented in this column are similar to that in IM column of Table 3 as rice-vegetable farmers were found only in IM

The total P and K content in soil samples collected from rain-fed fields were lower than the soil samples collected from major and minor irrigated fields ($p < 0.05$) (Table 5). However, the available P and exchangeable K content in soils were similar among major water sources used for rice cultivation ($p > 0.05$) (Table 5). The wet zone receives higher total annual rainfall than DZ and IZ (DOA, 2021), which could cause a higher loss of nutrients from soil through leaching and runoff (Wickramasinghe 1991; Kumaragamage & Indraratne, 2011; Rubasinghe *et al.*, 2021). Moreover, rivers originating from Up country WZ carry nutrients to lowlands in the DZ where rice is extensively cultivated (Kumaragamage & Indraratne, 2011). Therefore, the irrigation water distributed through both major and minor irrigation schemes have become a major source of K supply for rice cultivation in the DZ and IZ (Kulasinghe *et al.*, 2020). Irrigation water contributes 43-57% of the recommended amount of nutrients in major and minor irrigation schemes (Wickramasinghe, 1991). Moreover, K content in surface waters in the DZ of Sri Lanka was $2-8 \text{ mg L}^{-1}$, which is higher than the permissible level (2 mg L^{-1}) of the World Health Organization (Wijesundara *et al.*, 2012). Therefore, the heterogeneous nature of the supply of irrigation water has an influence on the variability of soil total K content in Sri Lankan rice fields. Irrigation water is not considered as a source of P as it contains negligible amounts of P for rice cultivation (Buresh *et al.* 2010; Somaweera *et al.*, 2017). Therefore, accumulation of runoff-K in rivers and tanks has resulted in a higher K content in rice fields in the DZ and IZ of Sri Lanka. Soils in DZ have originated from basic cation-rich parent materials with less weathering capacity, due to the low rainfall (Indraratne, 2020). In addition, compared to WZ, DZ and IZ have high temperature and high evaporation (Kumaragamage & Kendaragama, 2010). These conditions have created high base saturation in DZ and IZ soils, recording high K content (Kumaragamage and Kendaragama, 2010; Wickramasinghe 2010). In contrast, Ultisols is the model soil of WZ and potassium feldspars are the primary mineral found in Ultisols (Indraratne, 2020). The highly weathered nature of Ultisols resulting from high rainfall may have leached K out from potassium feldspars and transported it to DZ and IZ soils through rivers (Kumaragamage & Indraratne, 2011).

Table 5: Phosphorus (P) and potassium (K) contents in soil samples receiving water from different sources for rice cultivation.

Element	Major water sources		
	Major irrigation	Minor irrigation	Rain-fed
Total P (mg g^{-1})	1.1 ± 0.11^a	1.1 ± 0.14^a	0.68 ± 0.09^b
Total K (mg g^{-1})	13.5 ± 0.85^a	11.5 ± 1.05^a	6.9 ± 1.05^b
Available P (mg kg^{-1})	27.7 ± 5.4^a	20.5 ± 2.0^a	16.7 ± 2.2^a
Exchangeable K (mg kg^{-1})	252.4 ± 30.5^a	256.3 ± 26.2^a	238.0 ± 27.6^a

Note: means followed by the same letter within a row are not significantly different at $\alpha = 0.05$. Values represent the mean \pm SE

P and K content in rice grains

The grain P content was in the range of $0.10 - 1.76 \text{ mg g}^{-1}$ with a mean of 1.17 mg g^{-1} while grain K content was in the range of $1.61 - 4.65 \text{ mg g}^{-1}$ with a mean of 2.81 mg g^{-1} (Figure 2). The results of the present study further revealed that 20% of selected grain samples had P content less than 1 mg g^{-1} . When over 50 recommended rice varieties were tested under experimental field conditions at the Rice Research and Development Institute at Batalagoda in Sri Lanka, the grain P and K contents were in the ranges of $1.5 - 2.9 \text{ mg P g}^{-1}$ and $1.6 - 2.1 \text{ mg K g}^{-1}$, respectively (Kekulandara *et al.*, 2019). The difference of grain P content observed between the present study and previous studies indicates that the accumulation of grain P in actual farmer field conditions is less than that observed under experimental field conditions at research stations. Moreover, a wide range of rice varieties was included in the present study; e.g., At308, At362, Bg300, Bg357, Bg358, Bg359, Bg360, Bg367, Bg379/2, Bg403, Bw367, Ld365 and Ld368. However, the differences in grain P content observed between studies may not be due to the differences of varieties tested, but may be due to the difference in soil fertility between farmer field conditions and experimental fields at research stations.

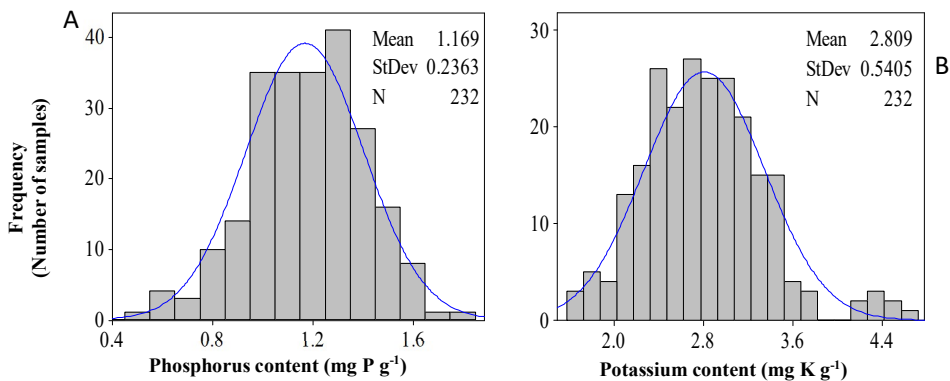


Figure 2: Distribution of (A) phosphorus (P) and (B) potassium (K) content of rice grain samples collected from rice fields in Sri Lanka.
 Note: the blue line in each sub-figure indicates the fitted frequency distribution

Grain K content was similar among different ACZs ($p > 0.05$) (Table 6). However, grain P content was the lowest in WL ($p < 0.05$) which could be due to the lower P availability in WZ soils as a result of higher rainfall, lower soil pH and higher P fixation than other ACZs (Wickramasinghe, 1991; Ahn *et al.*, 2010; Sirisena and Suriyagoda, 2018).

Table 6: Phosphorus (P) and potassium (K) contents (mg g⁻¹) in rice grain samples collected from different agro-climatic zones.

Elements	Agro-climatic zone				
	DL	IL	WL	IM	IU
P	1.30 ± 0.03 ^{ab}	1.20 ± 0.06 ^{bc}	0.90 ± 0.05 ^c	1.30 ± 0.10 ^{ab}	1.60 ± 0.01 ^a
K	2.90 ± 0.08 ^a	2.70 ± 0.11 ^a	2.70 ± 0.20 ^a	2.30 ± 0.54 ^a	3.20 ± 0.26 ^a

Note: means followed by the same letter within a row are not significantly different at $\alpha = 0.05$. Values represent the mean ± SE (DL=Dry zone Low country, IL=Intermediate zone Low country, WL=Wet zone Low country, IM=Intermediate zone Mid country, IU=Intermediate zone Upcountry)

Nutrient accumulation in rice grains is affected by many factors such as climate, soil, crop management including fertilizer application, water management, and crop rotation (Johnson *et al.*, 2021; Suriyagoda, 2022). Therefore, environment and management practices largely affect the accumulation of nutrients in rice grains (Du *et al.*, 2013; Huang *et al.*, 2016; Johnson *et al.*, 2021; Suriyagoda, 2022). However, as observed in the present study, grain P and K content were similar ($p > 0.05$) among major water sources used for rice cultivation and rice-based cropping systems tested (Tables 7 and 8). Therefore, different water sources and rice-based cropping systems tested in the present study did not significantly contribute to P and K content of rice grains under the tested conditions.

Table 7: Phosphorus (P) and potassium (K) contents (mg g⁻¹) in rice grain samples collected from different rice-based cropping systems

Elements	Rice-based cropping systems			
	Rice-rice	Rice-fallow	Rice-vegetables	Rice-other field crops
P	1.30 ± 0.03 ^{ab}	1.20 ± 0.06 ^{bc}	0.90 ± 0.05 ^c	1.30 ± 0.10 ^{ab}
K	2.90 ± 0.08 ^a	2.70 ± 0.11 ^a	2.70 ± 0.20 ^a	2.30 ± 0.54 ^a

Note: means followed by the same letter within a row are not significantly different at $\alpha = 0.05$. Values represent the mean ± SE

Table 8: Phosphorus (P) and potassium (K) contents (mg g^{-1}) in rice grain samples collected from the areas receiving water from different sources for rice cultivation

Elements	Major water source		
	Major irrigation	Minor irrigation	Rain-fed
P	1.20 ± 0.02^a	1.20 ± 0.03^a	1.20 ± 0.04^a
K	2.70 ± 0.05^a	2.80 ± 0.07^a	2.90 ± 0.11^a

Note: means followed by the same letter within a row are not significantly different at $\alpha = 0.05$. Values represent the mean \pm SE

Strengths of the relationships between soil and grain P and K contents

There were positive correlations between soil available P and soil total P contents, and grain P and grain K contents (Table 9). These results revealed that the soils with higher total P content make more P available for plant uptake. According to Lee *et al.* (2004), the available P fraction is correlated with total soil P due to the long-term P fertilizer application. Moreover, the significant correlation observed between grain K and P contents would be due to the presence of P in the form of K-Mg salt in phytic acid (Pinson *et al.*, 2014). Irrespective of the weak soil P and K relationships, the strong grain P and K relationship also reveal that the rice plant has the ability to take up P and K selectively to optimize the growth and grain P and K nutrition.

Table 9: Correlations between the soil and grain phosphorus (P) and potassium (K) contents.

	Soil total P	Soil exchangeable K	Soil total K	Grain K	Grain P
Soil available P	0.2911	0.0986	0.2046	0.1426	0.1176
	<0.0001	0.1649	0.0037	0.1776	0.2669
Soil total P		0.2271	0.1437	0.0452	-0.0498
		0.0012	0.0423	0.6705	0.6393
Soil exchangeable K			-0.0274	-0.0628	0.1661
			0.7006	0.5542	0.1156
Soil total K				-0.0017	0.2193
				0.9869	0.0368
Grain K					0.5141
					<0.0001

Note: upper and lower values in each pair represent the correlation coefficient and the corresponding probability (P) level, respectively.

CONCLUSION

Soil available and total P and K contents are adequate for rice cultivation in most of the rice fields in the country. Rice lands used for vegetable-rice rotation recorded significantly higher soil exchangeable K content than other rice-based cropping systems. Rice grain P and K contents were similar among different water sources used for rice cultivation and rice-based cropping systems adopted. Grain P contents was lower in WL than that in other ACZs. There was a positive correlation between grain P and K contents. The results of the present study provide important information for sustainable soil P and K management in selected rice-based cropping systems using different water sources.

Acknowledgment

Financial assistance from the World Bank, under the Accelerating Higher Education Expansion and Development (AHEAD) (Grant No AHEAD/RA3/DOR/AGRI/PERA-No16) is acknowledged.

REFERENCES

- Ahn D.J., Won J.G., Rico C.M. & Lee S.C. (2010). Influence of variety, location, growing year, and storage on the total phosphorus, phytate-phosphorus, and phytate-phosphorus to total phosphorus ratio in rice. *Journal of Agricultural and Food Chemistry* **58**: 3008–3011.
DOI: <https://doi.org/10.1021/jf1001167>
- Bai Z., Li H., Yang X., Zhou B., Shi X., Wang B. & Zhang F. (2013). The critical soil P levels for crop yield, soil fertility and environmental safety in different soil types. *Plant and Soil* **372**: 27–37.
- Bandara W.M.J., Wickramasinghe W.M.A.D.B. & Sirisena D.N. (2003). Potassium fertilization of paddy in Sri Lanka. In: *Importance of Potash Fertilizers for Sustainable Production of Plantation and Food Crops in Sri Lanka* (Eds. V.V. Nossov & J.D.H. Wijewardena). pp. 143–160. International Potash Institute, Horgen, Switzerland.
- Buresh R.J., Pampolino M.F. & Witt C. (2010). Field-specific potassium and phosphorus balances and fertilizer requirements for irrigated rice-based cropping systems. *Plant and Soil* **335**: 35–64.
DOI: <https://doi.org/10.1007/s11104-010-0441-z>
- Dimantha S. (1987). *Irrigation Management for Crop Diversification in Sri Lanka*, pp. 135–150. International Water Management Institute, Colombo, Sri Lanka.
- DOA (Department of Agriculture) (2021). *Rice Research and Development Institute Bathalagoda (RRDI)*. Available at https://doa.gov.lk/rrdi_climate/, Accessed 31 January 2022.
- Dobermann A. & Fairhurst T. (2000). *Rice Nutrient Disorders and Nutrient Management*, 1st edition, pp. 203. Potash and Phosphate Institute (PPI), Canada, International Rice Research Institute (IRRI), Laguna, Philippines.
- Du J., Zeng D., Wang B., Qian Q., Zheng S. & Ling H.Q. (2013). Environmental effects on mineral accumulation in rice grains and identification of ecological specific QTLs. *Environmental Geochemistry and Health* **35**: 161–170.
DOI: <https://doi.org/10.1007/s10653-012-9473-z>
- FAO (Food and Agriculture organization) 2020. *Crop Diversification In Sri Lanka*. Available at <https://www.fao.org/3/x6906e/x6906e0b.htm>, Accessed 31 January 2022.
- Hettiarachchi H.A.P.W., Ribeira S.P., Prasantha B.D.R. & Wickramasinghe H.A.M. (2016). Diversity of physical and cooking quality characters of selected traditional and improved rice varieties in Sri Lanka. *Sri Lankan Journal of Biology* **1**: 15–26.
- Huang Y., Tong C., Xu F., Chen Y., Zhang C. & Bao J. (2016). Variation in mineral elements in grains of 20 brown rice accessions in two environments. *Food Chemistry* **192**: 873–878.
DOI: <https://doi.org/10.1016/j.foodchem.2015.07.087>
- Imbulana L. (2006). Water allocation between agriculture and hydropower: A case study of Kalthota irrigation scheme, Sri Lanka. In: *Integrated Water Resources Management: Global Theory, Emerging Practice and Local Needs* (Eds. P.P. Mollinga, A. Dixit & K. Athukorala), pp. 219–248. Sage Publications, New Delhi, India.
- Indraratne S.P. (2020). Soil Mineralogy. In: *The Soils of Sri Lanka* (Ed. R. Mapa), pp.35–48. Springer Cham, Switzerland.
DOI: https://doi.org/10.1007/978-3-030-44144-9_4
- Johnson J.M., Silva A., Senthilkumar K., Shepherd K.D. & Saito K. (2021). Application of infrared spectroscopy for estimation of concentrations of macro-and micronutrients in rice in sub-Saharan Africa. *Field Crops Research* **270**: 108222.
DOI: <https://doi.org/10.1016/j.fcr.2021.108222>
- Ju X.T., Xing G.X., Chen X.P., Zhang S.L., Zhang L.J., Liu X.J., Cui Z.L., Yin B., Christie P., Zhu Z.L. & Zhang F.S. (2009). Reducing environmental risk by improving N management in intensive Chinese agricultural systems. *Journal of Agricultural Sciences* **106**(9): 3041–3046.
DOI: <https://doi.org/10.1073/pnas.0813417106>
- Kadupitiya H.K., Madushan R.N., Rathnayake U.K., Thilakasiri R., Dissanayaka S.B., Ariyaratne M. & Suriyagoda L. (2021). Use of smartphones for rapid location tracking in mega scale soil sampling. *Open Journal of Applied Sciences* **11**: 239–253.
DOI: <https://doi.org/10.4236/ojapps.2021.113017>
- Kekulandara D.S., Sirisena D.N., Bandaranayake P.C.G., Samarasinghe G., Wissuwa M. & Suriyagoda L.D.B. (2019). Variation in grain yield, and nitrogen, phosphorus and potassium nutrition of irrigated rice cultivars grown at fertile and low-fertile soils. *Plant and Soil* **434**: 107–123.
DOI: <https://doi.org/10.1007/s11104-018-3663-0>
- Kulasinghe H.P.G.T.N., Dharmakeerthi R.S., Sirisena D.N. & Rathnayake W.M.U.K. (2020). Exploring the yield response of paddy (*Oryza sativa* L.) under varying levels of soil nitrogen, phosphorus and potassium. *Tropical Agricultural Research* **31**: 1–12.
- Kumaragamage D. & Indraratne S.P. (2011). Systematic approach to diagnosing fertility problems in soils of Sri Lanka. *Communications in Soil Science and Plant Analysis* **42**: 2699–2715.
DOI: <https://doi.org/10.1080/00103624.2011.622818>
- Kumaragamage D. & Kendaragama K. M. A. (2010). Risk and limitations of dry zone soils. *Soils of the Dry Zone of Sri Lanka* (Eds. R.B. Mapa, S. Somasiri & A.R. Dassanayake), pp. 239–258. Soil Science Society of Sri Lanka, Peradeniya, Sri Lanka.
- Lee C.H., Park C.Y., Do Park K., Jeon W.T. & Kim P.J. (2004). Long-term effects of fertilization on the forms and availability of soil phosphorus in rice rice. *Chemosphere* **56**: 299–304.
DOI: <https://doi.org/10.1016/j.chemosphere.2004.02.027>
- Liyanaarachchi G.V.V., Mahanama K.R.R., Somasiri H.P.P.S., Punyasiri P.A.N. & Kottawa-Arachchi J.D. (2020). Total and free amino acid contents of popular rice varieties (*Oryza sativa* L.) consumed in the capital city of Sri Lanka. *Journal of the National Science Foundation of Sri Lanka* **48**: 199–211.

- DOI: <http://dx.doi.org/10.4038/jnsfsr.v48i2.9565>
- Ma L., Duan T. & Hu J. (2020). Application of a universal soil extractant for determining the available NPK: A case study of crop planting zones in central China. *Science of the Total Environment* **704**: 135253.
DOI: <https://doi.org/10.1016/j.scitotenv.2019.135253>
- Mapa R.B. (1992). Clay mineralogy of six Sri Lankan soils. *Journal of Geology Society of Sri Lanka* **4**: 45–47.
- Maraikar S., Wijewardena J.D.H. & Amarasiri S.L. (1997). Improving productivity of vegetable cultivation in ultisols of Sri Lanka. *Proceeding of the International Conference on Managing Soil Fertility for Intensive Vegetable Production Systems in Asia*. World Vegetable Centre, Tainan, Taiwan, pp. 270–282.
- Masni Z. & Wasli M.E. (2019). Yield performance and nutrient uptake of red rice variety (MRM 16) at different NPK fertilizer rates. *International Journal of Agronomy* **2019**.
DOI: <https://doi.org/10.1155/2019/5134358>
- Moe K., Htwe A.Z., Thu T.T.P., Kajihara Y. & Yamakawa T. (2019). Effects on NPK status, growth, dry matter and yield of rice (*Oryza sativa* L.) by organic fertilizers applied in field condition. *Agriculture* **9**: 109.
DOI: <https://doi.org/10.3390/agriculture9050109>
- Navarathna C., Pathiratne S., de Silva D.S.M., Rinklebe J., Mohan D. & Mlsna T. (2021). Intrusion of heavy metals/metalloids into rice (*Oryza sativa* L.) in relation to their status in two different agricultural management systems in Sri Lanka. *Groundwater for Sustainable Development* **14**: 100619.
DOI: <https://doi.org/10.1016/j.gsd.2021.100619>
- Olsen S.R., Cole C.V., Watanabe F.S. & Dean L.A. (1954): *Estimation of Available Phosphorus in Soils by Extraction with Sodium Bicarbonate*, 1st edition, pp. 19. Department of Agriculture, Washington D.C., USA.
- Panabokke C.R. (1989): *Irrigation Management for Crop Diversification in Sri Lanka: A Synthesis of Current Research*. International Irrigation Management Institute, Colombo, Sri Lanka. Available at https://pdf.usaid.gov/pdf_docs/pnabf279.pdf
- Pinson S.R., Tarpley L., Yan W., Yeater K., Lahner B., Yakubova E. & Salt D.E. (2014). Worldwide genetic diversity for mineral element concentrations in rice grain. *Crop Science* **55**: 294–311.
DOI: <https://doi.org/10.2135/cropsci2013.10.0656>
- Priya T.R., Nelson A.R.L.E., Ravichandran K. & Antony U. (2019). Nutritional and functional properties of coloured rice varieties of South India: A review. *Journal of Ethnic Foods* **6**: 1–11.
DOI: <https://doi.org/10.1186/s42779-019-0017-3>
- Punyawardane B.V.R. (2008). *Evolution of Climatic Zones in Sri Lanka, Agro-climatological Zones and Rainfall Pattern in Sri Lanka*. pp. 44–113. Department of Agriculture, Peradeniya, Sri Lanka.
- Rathnayake W.M.U.K., De Silva R.P. & Dayawansa N.D.K. (2015). Variability of some important soil chemical properties of rainfed low land paddy fields and its effect on land suitability for rice cultivation. *Tropical Agricultural Research* **26**: 506–516.
DOI: <http://doi.org/10.4038/tar.v26i3.8113>
- Rezania M. (1993). Preliminary investigations on nutrient management of subsidiary field crop cultivation in Sri Lanka. Food and Agriculture Organization. Rome, Italy.
- Rubasinghe R., Gunatilake S. & Chandrajith R. (2021). Climatic control of major and trace elements in rice soils from wet and dry regions of Sri Lanka. *Environmental Challenges* **5**: 100361.
DOI: <https://doi.org/10.1016/j.envc.2021.100361>
- Sims J.T. (2000): Soil test phosphorus: Olsen P. (2000). In: *Methods of Phosphorus Analysis For Soils, Sediments, Residuals, And Waters* (Pierzynski G.M. Eds), pp. 20-21. North Carolina State University, Raleigh, USA.
- Sirisena D. & Suriyagoda L.D. (2018). Toward sustainable phosphorus management in Sri Lankan rice and vegetable-based cropping systems: A review. *Agriculture and Natural Resources* **52**: 9–15.
DOI: <https://doi.org/10.1016/j.anres.2018.03.004>
- Somaweera K.A.T.N., Sirisena D.N., De Costa W.A.J.M. & Suriyagoda L.D.B. (2017). Age-related morphological and physiological responses of irrigated rice to declined soil phosphorus and potassium availability. *Paddy and Water Environment* **15**: 499–511.
DOI: <https://doi.org/10.1007/s11104-018-3663-0>
- Suriyagoda L.D.B. (2022). Rice production in nutrient-limited soils: Strategies for improving crop productivity and land sustainability. *Journal of the National Science Foundation of Sri Lanka* **50**: 521–539.
DOI: <https://jnsfsl.sljol.info/articles/abstract/10.4038/jnsfsr.v50i3.10601/>
- Suriyagoda L.D.B., Dissanayake O., Kodithuwakku V., Maduwanthi I., Dissanayaka N. & Chandrajith R. (2022). Accumulation of essential mineral and toxic trace elements in crops and soils of vegetable cropping systems in central highlands of Sri Lanka. *The Journal of Agricultural Science* **160**(1-2): 86–97.
DOI: <https://doi.org/10.1017/S0021859622000156>
- Suriyagoda L.D.B., Ranil R.H.G., Dissanayaka D.M.S.B. & Weerakkody W.A.P. (2012). The sustainability of intensive vegetable farming systems in Sri Lanka. International Society of Horticultural Science. *Chronica Horticulturae* **52**:14–17.
- Upekshani H.A.N., Dharmakeerthi R.S., Weerasinghe P. & Dandeniya W.S., (2018): Fertilizer usage and land productivity in intensively cultivated vegetable farming systems in Sri Lanka: an analysis based on a questionnaire survey. *Tropical Agricultural Research* **30**: 44–55.
DOI: <http://doi.org/10.4038/tar.v30i1.8277>
- Van Ranst E., Verloo M., Demeyer A. & Pauwels J.M. (1999). *Manual for the Soil Chemistry and Fertility Laboratory-Analytical Methods for Soils and Plants, Equipment, and Management of Consumables*, 1st edition, pp. 243. Ghent, Belgium.

- Vinod K.K. & Heuer S. (2012). Approaches towards nitrogen- and phosphorus-efficient rice. *AoB Plants* **2012**: 28.
DOI: <https://doi.org/10.1093/aobpla/pls028>
- Wickramasinghe L.A. (1991): Soil constraints on sustainable plant production in Sri Lanka. *Japan International Research Center for Agricultural Sciences* **24**: 12–29. Available at https://www.jircas.go.jp/sites/default/files/publication/tars/tars24_12-29.pdf
- Wickramasinghe W.M.A.D.B. 2010. Management of dry zone soils. *Soils of the Dry Zone of Sri Lanka* (eds. R.B. Mapa, S. Somasiri & A. R. Dassanayake), pp. 259–266. Soil Science Society of Sri Lanka. Peradeniya, Sri Lanka.
- Wickramasinghe W.M.A.D.B., Dasanayake A.R. & Sirisena D.N. (2003): Potassium status of rice growing soils in Sri Lanka. In: *Importance of Potash Fertilizers for Sustainable Production of Plantation and Food Crops in Sri Lanka* (Eds. V.V. Nossov & J.D.H. Wijewardena), pp. 35–41. International Potash Institute, Horgen, Switzerland.
DOI: https://doi.org/10.1007/978-981-15-3673-1_10
- Wijesundara W.M.G.D., Nandasena K.A. & Jayakody A.N. (2012). Spatial and temporal changes in nitrogen, phosphorus and potassium concentration in water in the thirappane tank cascade in dry zone of Sri Lanka. *Journal of Environmental Professionals Sri Lanka* **1**: 70–81.
DOI: <https://dx.doi.org/10.4038/jepsl.v1i1.5143/galley/4109/download/>
- Ye Y.S., Liang X.Q., Li L., Yuan J. & Zhu S. (2015): Effects of different water and nitrogen managements on phosphorus loss via runoff and leaching from paddy fields in Taihu L. Taihu Lake basin. *Acta Scientiac Circumstantiac* **35**(4): 1125–1135