Cations ratio and its relationship with other soil nutrients of Java intensified lowland rice

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Abstract. The soil cation ratio is the result of the interaction of various factors, including soil acidity, organic C content, clay minerals, and cultivation management. This paper aims to study the cation ratio in lowland rice in Java and its relationship with the other nutrients. Soil chemical data were collected from survey for soil maps, soil nutrient status maps, and previously published data. The results showed that the average of cation saturation ratio in lowland rice in Java was 70.8:24.5:1.5 for Ca:Mg:K. The Ca, Mg, K, and Na nutrient contents vary by provinces, and there is a high content of Ca, especially in those soils derived from the calcareous parent materials. This high Ca of >50.0 cmol(+)/kg has noticed in Grobogan, Bojonegoro, and Gunung Kidul regencies. The domination of Ca cations in the soil can be seen when the Ca saturation >70%, spreading in 36 districts. Ca saturation is positively correlated with pH, P-Bray, and CEC, and negatively correlated with organic C, N-total, Mg, K, and Na saturation. Based on the regression there is a significant negative relationship between Ca and Mg saturations with R² = 0.92 and a weak negative relationship between K and Na saturations.

1. Introduction

In 2020 the total rice field in Indonesia was 7.46 million ha, and the harvest area was 11.38 million ha, with the cropping index as 1.53 [1]. Meanwhile, Java covers 46.55% of the national rice field area, and contributes 59.20 million tonnes or 50.0% of the national total production. Most of the lowland rice productivity had been leveling off, the organic C content was <2% [2,3], and rice plants were very responsive to N fertilization [4-6]. The existence of cations in the soil was variated, and the quantity of Ca>Mg>K>Na, Al, and H cations were generally low.

Inundation of upland used for lowland rice can increase soil pH, availability of P, Ca, Mg, K, Si, Fe, Mn, and Mo nutrients [7]. Cations in the soil are strongly influenced by the soil type, especially soil texture, soil acidity, and organic C content of the soil. There is a strong relationship between soil pH and base saturation in acidic and neutral soils, but not in alkaline soils [8]. The results of correlation for neutral to alkaline Inceptisols showed that exchangeable Ca has a positive correlation with organic C and exchangeable Mg, and negatively correlates with exchangeable Al, but for Vertisols showed that Ca has a positive correlation with pH and clay. While Alfisols showed that Ca has a positive correlation with pH, but negatively correlated with P-Olsen and P-Bray [9].

Most rice fields in Java are affected by volcanic materials from active volcanoes which lie from east to west. Rice fields affected by volcanic materials in Pati-Central Java, Ngawi-East Java, and Klaten-Central Java have smectite clay minerals [10]. Their exchangeable cations are dominated by Ca cations, followed by Mg, Na and K. Ca/Mg ratios range from 7:1-12:1, 5:1-11:1 and 2:1 in Pati,
Exchangeable cations in Vertisols dominated by Ca of 23.38 cmol(+)/kg. Ratio values of Ca/Mg, Ca/K, and Mg/K are 1.95, 70.85, and 36.39, respectively, and base saturation of 100% [11]. Previous result showed that the ratio of Ca/Mg in rice fields in Ebonyi Central-Nigeria ranges from 1.27-15.94, and the ratio of K/Mg ranges from 0.02-0.33 [12]. The ratio of Ca/Mg in farmer’s rice fields in Yola Metropolis, Adamawa State, Nigeria, ranged from 2.14 to 2.78 [13]. Ca saturation in Ultisols correlates negatively with the saturation of K, Na, Al, and H cations, while in Vertisols, Ca saturation negatively correlated with the saturation of Mg, K, and Na cations [14]. The optimum dry weight of maize was achieved at the K/Ca ratio values of 0.027 and 0.029 in Ultisols and Vertisols respectively, and the critical limit of K was increased with the addition of Ca [15].

The ideal ratio of cations saturation is the saturation of Ca, Mg, and K which gives the highest crop yields, but it also depends very much on soil type, cropping management, and cultivated plants. The content of Al(III) and H+ in the soil of lowland rice is very low and does not affect the cation ratio. The highest ryegrass yield was achieved at Ca, Mg, and K saturations of 50-60, 8-12, and 4-5% respectively. Furthermore, it was also stated that the decrease of K saturation to <4% had caused the ryegrass yield drastically decreased [16]. The optimum yield of maize in Ultisols was achieved at Ca, Mg, K, and Al saturations of 62, 7.2, 3.3, and 16% respectively, while in Vertisols it was achieved at Ca, Mg, and K saturation values of 77, 20, and 0.6-0.7% respectively [14]. The concept of maximum plant growth will be achieved if there is under ideal saturation values of 65, 10, and 5% for Ca, Mg, and K nutrients, while the ratio values of Ca/Mg, Ca/K, Ca/H, and Mg/K of 6.5:1, 13:1, 3.25:1, and 2:1 [17].

This paper aims were to study the ratio of cation and their effects on other nutrients in the intensification of rice cultivation in Java.

2. Materials and methods
This study was started by collecting soil chemical analysis data from 1990 to 2019. The chemical analysis data were collected from the soil surveys, surveys to create maps of P and K nutrient status, and previously published data. Collected data included the analysis results of pH (H2O, 1:5), organic C (Kurmis), N (Kjeldhal), P2O5, and K2O (extracted HCl 25%), Ca, Mg, K, Na, CEC (extracted NH4OAc 1N pH 7), base saturation, Al(III), and H+ (extracted KCl 1N).

Soil samples from the soil survey were taken from the analysis of the topsoil profile. Soil samples were taken from the tillage layer of each soil profile. This study considered both the depth of the cultivating/tillage layer and the use of ameliorant materials. The depths of the cultivated layer on conventional, semi-organic, and organic paddy soils are about 20-25, 30-45, and 40-50 cm [18]. The depths of alluvial lowland tillage in Indramayu West Java, North Lampung, Pametikarta East Sumba, Klaten Central Java and in Sangata East Kalimantan are 13, 20, 22, 17, 5 cm respectively [19].

Soil sampling in soil survey for making a map of the P and K nutrient status of the paddy soil was using a composite method. The sampling point is determined by a grid system but with some modification according to field conditions, especially the ease of sample taking. Soil samples were taken in 20 cm depth using a lowland/rice-field drill. One soil sample consists of 10 sub-samples, then they put together, stirred until homogeneous, and taken ±1 kg.

Soil samples from the study were taken compositely before being treated. Samples were taken 3 to 4 samples using a rice-field drill from each replication, and there were 9 to 12 samples in one experimental unit, then they were put together, stirred until homogeneous, and then taken ±1 kg.

The results of the soil samples analysis were collected by the district. The amount of analyzed soil sample data per district depended on the available data. The average data of the district was presented, and then generated the saturation of Ca, Mg, K, and Na, as well as the ratio of Ca/Mg, Ca/K, and Mg/K. Based on the Ca saturation, data were grouped into 5 groups. The five groups of Ca saturation values were <60, 60 to 70, 70 to 80, 80 to 90, and >90%. Al and H contents in paddy
soil were very low so that they did not affect the calculation results of cation saturation. The calculation of the saturation of Ca, Mg, and K was using the following formula:

\[
\text{Ca saturation ratio} = \frac{\text{Ca}}{\text{Ca} + \text{Mg} + \text{K} + \text{Na} + \text{Al} + \text{H}} \times 100\% 
\]

(1)

\[
\text{Mg saturation ratio} = \frac{\text{Mg}}{\text{Ca} + \text{Mg} + \text{K} + \text{Na} + \text{Al} + \text{H}} \times 100\% 
\]

(2)

\[
\text{K saturation ratio} = \frac{\text{K}}{\text{Ca} + \text{Mg} + \text{K} + \text{Na} + \text{Al} + \text{H}} \times 100\% 
\]

(3)

To determine the relationship between the saturation of Ca, Mg, and K nutrients with the others, a correlation test was made. A correlation test was performed using SPSS version 25. The results of the correlation showed that there was a strong and significant and very significant relationships if Sig. (2-tailed) values were <0.05, and <0.01. To determine the saturation relationships among Ca, Mg and K nutrients, a regression analysis was performed.

3. Results and discussions

3.1. Soil chemical characteristics of lowland rice

Rice fields in Java spread out from Banten to East Java, especially on the north and partly on the south coasts. However, there are also rice fields on the highlands in the central part of Java. Those rice fields have an averagely 40% clay content with clay, silty clay, and sandy clay textural classes (table 1). There were 6 representative pedons taken from the alluvial rice fields of the Solok rice center, having 36 to 48% clay fraction [20]. Clay content influences water loss and water efficiency in rice fields [21].

| Province     | n  | Clay (%) | pH     | C-organic (%) | N-total | P₂O₅-Pot* (mg 100 g⁻¹) | K₂O-Pot* (cmol(+), kg⁻¹) | CEC (cmol(+), kg⁻¹) | BS (%) |
|--------------|----|----------|--------|---------------|---------|-----------------------|--------------------------|------------------------|--------|
| Banten       | 57 | 41.2±15.7| 5.3±0.7| 1.59±0.66     | 0.15±0.07| 40±33                 | 18±16                    | 21.7±9.9              | 75±20  |
| West Java    | 182| 51.7±15.6| 5.8±0.6| 1.92±0.69     | 0.18±0.06| 122±92               | 34±32                    | 28.6±12.8             | 72±22  |
| Yogyakarta   | 24 | 47.3±19.6| 6.2±0.7| 2.84±2.01     | 0.14±0.04| 74±53               | 30±23                    | 27.9±11.5             | 72±26  |
| Central Java | 396| 47.4±19.9| 6.7±0.6| 1.74±1.09     | 0.15±0.08| 102±59              | 46±43                    | 33.8±16.2             | 71±20  |
| East Java    | 200| 42.5±22.1| 6.7±0.6| 1.24±0.49     | 0.11±0.04| 88±128             | 44±39                    | 35.5±18.1             | 86±15  |

Notes: * = P₂O₅ and K₂O potential extracted HCl 25%, n = number of samples, CEC = Cation Exchangeable Capacity, BS = Base Saturation.

The soil reactions of the rice field usually close to the acidity of the irrigation water used. The pH of irrigation water in Karanganyar, Central Java, ranges from 6.50 to 8.50 [22] and the average of soil pH-H₂O (1:5) of rice fields is >5.5. It seems that the soil pH of the rice field in Banten province to East Java slight increased from 5.3 in Banten to 6.7 in East Java. Generally, the organic C content of rice fields in Java is low [2] and so is in Serdang Bedagai, North Sumatera [3]. Slightly high organic C content occurs in Yogyakarta, especially in the highlands of the Sleman region.

The N nutrient content in the soil of the lowland rice field ranged from 0.11 to 0.18%, and was considered low. There was a gradation value from Banten, West Java, that was getting lower towards East Java. The higher N content occurred in West Java, although the values were still at the same low range. The N nutrient content of rainfed lowland rice fields was also low [5, 6]. The N contents in the technical irrigated rice fields in Karawang, Sragen and Madiun were 0.19, 0.12, and 0.13% respectively and were categorized as low [23].

Almost all provinces had high levels of P and K nutrients (extracted with HCl 25%). The levels of P and K tended to increase from West to East Java. Soil CEC ranged from 21.7 to 35.5 cmol(c)
kg\(^{-1}\) and tended to increase from the West to the East. Base saturations in all provinces were >70%. The higher values of soil base saturation mean the lower content of acidic soil nutrients.

The cation contents in lowland rice in Java are dominated by Ca, followed by Mg, Na, and K cations (table 2). Meanwhile, there were very small numbers of Al and H cations in the rice fields. By flooding the dry land to be converted into a rice field system, the soil pH will approach the pH of the irrigation water used. So that it had no significant effect on the calculation results if Al and H were excluded.

| Province      | n   | Exchangeable cation (cmol\(_{(+)}\) kg\(^{-1}\)) |
|---------------|-----|-----------------------------------------------|
|               |     | Ca     | Mg    | K     | Na    | Al    | H     |
| Banten        | 57  | 11.18  | 4.21  | 0.24  | 0.52  | 0.54  | 0.19  |
| West Java     | 182 | 15.99  | 7.21  | 0.35  | 0.62  | 0.31  | 0.09  |
| Yogyakarta    | 24  | 16.42  | 6.37  | 0.33  | 1.90  | 0.03  | 0.09  |
| Central Java  | 396 | 22.78  | 5.79  | 0.38  | 0.68  | 0.12  | 0.05  |
| East Java     | 200 | 26.14  | 7.65  | 0.37  | 0.60  | 0.01  | 0.01  |

The Ca, Mg, K, and Na saturations of rice fields in Java were around 54.57 to 72.51, 23.07 to 33.23, 1.49 to 1.95, and 1.93 to 10.25% (table 3). Meanwhile, Al and H saturations were <5%, and considered very low. The Ca/Mg ratio was around 2.73 to 4.95, and the lowest values occurred in Banten and West Java. The ratio of Ca/K cations was around 52.67 to 117.19 and the highest and lowest values occurred in Yogyakarta and occurred in Banten. The Mg/K ratio was around 18.54 to 34.52, and the highest and the lowest values occurred in Yogyakarta and Banten.

| Province      | n   | Cation saturation ratio (%) | Cation ratio |
|---------------|-----|----------------------------|--------------|
|               |     | Ca-sat* | Mg-sat | K-sat | Na-sat | Al-sat | H-sat | Ca/Mg | Ca/K | Mg/K |
| Banten        | 57  | 69.93   | 24.88  | 1.64 | 3.55 | 3.43 | 1.08 | 2.96  | 52.67 | 18.54 |
| West Java     | 182 | 66.14   | 29.54  | 1.84 | 2.48 | 2.05 | 0.52 | 2.73  | 64.42 | 26.76 |
| Yogyakarta    | 24  | 54.57   | 33.23  | 1.95 | 10.25 | 0.11 | 0.22 | 4.13  | 117.19 | 34.52 |
| Central Java  | 396 | 72.51   | 23.07  | 1.73 | 2.69 | 0.55 | 0.22 | 4.95  | 84.00 | 21.92 |
| East Java     | 200 | 72.19   | 24.39  | 1.49 | 1.93 | 0.03 | 0.02 | 3.89  | 92.27 | 27.32 |

Note: * sat = saturation.

### 3.2. The relation between cation saturation ratio with the other soil chemical characteristic

The increasing Ca saturation from 60 to 90% had increased the soil pH, CEC, and base saturation (figure 1) from 5.65 to 7.19 (or by 1.54), 23.25 to 47.26 (or as much as 24.01) cmol\(_{(+)}\) kg\(^{-1}\) and 68.94 to 92.18 (or by 23.24%). At the pH of around 7.0, Ca and base saturations, and CEC values were >80 and approached 90%, approached 50 cmol\(_{(+)}\) kg\(^{-1}\) respectively. Cations contents in Vertisols soil with pH around 7.0 in Ungaran Central Java, Madiun East Java and Lewa Sumba were dominated by Ca cation with saturation values of 84.8, 73.0, and 94.7% respectively [24]. Although the soil had a high content of exchangeable Mg and K, their saturations were only 2.2-13.2, and 0.39-1.08%. Looking at, the K and Mg saturations, their values were lower than the ideal saturation (20 and 5%).

The higher Ca saturation from 60 to 90% caused exchangeable Mg and Al, and saturations of Mg, K, Na, Al, and H to be lower (table 4). Meanwhile, the ratio of Ca/Mg and Ca/K increased along with increasing Ca saturation and exchangeable. There was a mutually suppressive relationship between Ca and Mg, which both elements are having two valences. The high content of Mg and Na in the soil inhibited the uptake of K and Ca, and the quality of pomelo fruit to be better in the treatments with K/Ca, K/Mg, and Ca/Mg ratios between 0.24 to 0.44, 0.31 to 0.44, and 0.89 to 1.29 respectively [25].
In soils with Ca and Mg saturations are <60 and around 37.76%, the addition of Ca nutrient is required in this soil. On soil with Ca and Mg saturations are >80 and around 6.13 to 13.17% where Mg is still below the ideal limit, so it is necessary to add Mg nutrients.

Ca saturation was positively correlated with pH, exchangeable Ca, CEC, and base saturation, and negatively correlated with organic C, exchangeable Mg, and the saturation of Mg, K, and Na (table 5). Mg saturation had a positive correlation with K saturation, and negatively correlated with pH, exchangeable Ca, CEC, and Ca saturation. K saturation had a positive correlation with organic C, total-N, potential P and K, and Mg saturation, and negatively correlated with exchangeable Ca, CEC, and Ca saturation.

**Table 4.** The exchangeable, saturation and ratio of Ca, Mg, K, Na, Al$^{3+}$, and H$^+$ cations of lowland rice in Java.

| Ca saturation (%) | Exchangeable cation (cmol$^{+}$ kg$^{-1}$) | Saturation cation ratio (%) | Cation ratio |
|-------------------|------------------------------------------|-----------------------------|--------------|
|                   | Ca  | Mg  | K   | Na  | Al  | H   | Ca  | Mg  | K   | Na  | Al  | H   | Ca/Mg | Ca/K | Mg/K  |
| <60               | 10.02 | 6.84 | 0.34 | 0.57 | 0.34 | 0.08 | 54.94 | 37.76 | 1.90 | 3.47 | 1.86 | 0.43 | 1.49   | 31.22 | 21.82 |
| 60 to 70          | 15.99 | 7.52 | 0.40 | 0.61 | 0.12 | 0.05 | 64.98 | 29.98 | 1.71 | 2.79 | 0.59 | 0.25 | 2.21   | 46.75 | 22.23 |
| 70 to 80          | 20.30 | 5.68 | 0.34 | 0.66 | 0.12 | 0.04 | 74.54 | 20.93 | 1.37 | 2.35 | 0.55 | 0.18 | 3.64   | 69.41 | 19.74 |
| 80 to 90          | 36.25 | 5.57 | 0.32 | 0.65 | 0.03 | 0.02 | 84.21 | 13.17 | 0.80 | 2.37 | 0.08 | 0.07 | 6.79   | 117.02 | 19.02 |
| >90               | 53.12 | 3.56 | 0.48 | 0.62 | 0.02 | 0.04 | 91.84 | 6.13  | 0.83 | 1.01 | 0.03 | 0.08 | 15.12  | 244.76 | 17.12 |
The high Ca saturation and exchangeable dominated the cation exchange complex in the soil. It could suppress the saturation of Mg, K, and Na, or made them act antagonistically to each other. Strongest antagonists occurred between Ca and Mg, followed by Ca and K, and then between Ca and Na.

Table 5. Correlation between cation saturation with other nutrients in the lowland rice in Java.

| Soil characteristics | Ca-sat | Mg-sat | K-sat | Na-sat | Al-sat | H-sat*** | CEC | BS |
|----------------------|--------|--------|--------|--------|--------|----------|-----|-----|
| pH                   | 0.499** | -0.415** | -0.268 | -0.121 | -0.495** | -0.414** | 0.375** | 0.686** |
| org C                | -0.297** | 0.194  | 0.356** | 0.310** | 0.226*  | 0.269*   | -0.090  | -0.374** |
| total-N              | -0.193  | 0.138  | 0.437** | -0.066 | 0.307** | 0.205    | -0.099  | -0.338** |
| P-HCl                | -0.102  | 0.081  | 0.324** | -0.104 | 0.120   | 0.135    | 0.033   | -0.401** |
| K-HCl                | 0.120   | -0.175 | 0.342** | 0.186  | -0.212  | -0.272*  | 0.422** | 0.189  |
| Ex.Ca                | 0.716** | -0.650** | -0.506** | -0.222* | -0.251* | -0.339   | 0.762** | 0.504** |
| Ex.Mg                | -0.428** | 0.536** | -0.194  | -0.019 | -0.148  | -0.249*  | 0.140   | 0.380** |
| Ex.K                 | -0.042  | -0.022 | 0.650** | 0.112  | -0.171  | -0.100   | 0.234*  | 0.240*  |
| Ex.Na                | -0.034  | -0.122 | 0.034  | 0.764** | -0.182  | -0.075   | 0.263*  | 0.144  |
| CEC                  | 0.544** | -0.511** | -0.343** | -0.121 | -0.196  | -0.373** | 1      | 0.066  |
| BS                   | 0.230*  | -0.159 | -0.210 | -0.173 | -0.302* | -0.179   | 0.066   | 1      |
| Ca-sat               | 0.961** | -0.961** | -0.431** | -0.306** | -0.246* | -0.254*  | 0.544** | 0.230*  |
| Mg-sat               | 0.961** | 0.961** | 0.315** | 0.119  | 0.113   | 0.100    | -0.511** | -0.159 |
| K-sat                | -0.431** | 0.315** | 0.119  | 0.214  | 0.041   | 0.216    | -0.343** | -0.210 |
| Na-sat               | -0.306** | 0.119  | 0.214  | 1      | -0.060  | 0.147    | -0.121  | -0.173 |

Notes: * = significant correlation at 5%, ** = significant correlation at 1%, *** = saturation.

Figure 2. Relationship between the saturation of Ca and Mg (a), Ca and K (b), and Ca and Na (c) in lowland rice in Java.
In line with the saturation correlations between Ca and the saturation of Mg, K, and Na cations, figure 2 shows the regression closeness between Ca and Mg saturations with \( R^2 = 0.923 \). Meanwhile, the regression between Ca and K and Ca and Na saturations resulted in \( R^2 = 0.185 \), and \( R^2 = 0.094 \). This shows that the high Ca content in the cation exchange complex depressed more to Mg nutrients than K and Na.

The Ca, Mg, and K saturations of the areas were >90, around 5.32 to 6.46, and around 0.16 to 1.47%. In the areas with Ca saturation between 80 to 90%, the Mg and K saturations were about 9.14 to 17.39 and 0.47 to 1.36%. This shows that at the Ca saturation of >80%, exchangeable Mg and K are in deficient conditions and not ideal for plant growth.

Those districts having Ca saturation <60, their Mg and K saturations were around 28.78 to 44.58 and 1.24 to 3.04%. This indicates that Mg nutrients contained in the soil are in a higher condition than the ideal one.

4. Conclusions
Ca saturation in the soil correlates positively with pH, exchangeable Ca, CEC, base saturation, and negatively correlates with organic C, exchangeable Mg, and the saturations of Mg, K, and Na. Ca saturation >80% occurs at pH 7.19, CEC 47.26 cmol(+)/kg and base saturation 92.18%. Ca saturation <60% occurs at pH 5.65, CEC 23.25 cmol(+)/kg and base saturation 68.93%.

Ca/Mg and Ca/K ratio values of >6.5 and >100 occurs at Ca saturation >80%, and Ca/Mg and Ca/K ratio values of <1.5 and <40 occur at Ca saturation of <60%. The ideal Ca saturation value is between 60 and 80%, and the higher and lower values of >80% and <60% will turn the Mg and K nutrients into an unideal saturation state for rice plant growth. In soils with Ca saturation >80%, the Mg content and saturation states are less than or below the ideal conditions. In soils with Ca saturation <60%, Mg content and saturation states are higher than or above the ideal condition.

The relatively ideal saturations of Ca, Mg, and K nutrients for rice fields in Java range from 60.07 to 79.49, 36.71 to 15.27, and 0.50 to 3.33% respectively.

It needs to consider adding Mg and K fertilizer in Java rice fields with Ca saturation >80% to obtain the highest land productivity and Ca fertilization in rice fields with Ca saturation <60%.

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