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Mathematical modeling of cations from non-edible food waste for the reclamation of sodic and saline soils

Md. Rezwanul Islam [a,b,*], Qingyue Wang [a,*], Sumaya Sharmin [a,b], Weiqian Wang [a], Christian Ebere Enyoh [a]

[a] Graduate School of Science and Engineering, Saitama University, 255 Shimo-Okubo, Sakura-ku, Saitama 338-8570, Japan

[b] Department of Agricultural Extension, Khamarbari, Dhaka 1215, Bangladesh

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Author(s)

M.R.Islam *

Q.Wang *

S.Sharmin

W.Wang

C.E.Enyoh

* Corresponding author

Abstract

Nutritional disparity is a crucial impediment to agricultural productivity that interferes with soil structural stability and plant growth since more than one-fourth of the total land area is affected, especially by sodicity globally. This study assesses the mathematical models of non-edible food waste, including brinjal waste, potato peel, banana peel, orange peel, eggshell, cow bone, chicken bone, and fish bone. After consumption of the food, the resulting non-edible food waste was cleaned, dried, crushed, and stored separately in aluminum zipper bags. Cation concentrations of the considered waste materials were measured using ion chromatography systems. Then the mathematical models such as Exchangeable Sodium Percentage (ESP), Exchangeable Potassium Percentage (EPP), Sodium Adsorption Ratio (SAR), Potassium Adsorption Ratio (PAR), and Cation Ratio of Soil Structural Stability (CROSS) were assessed considering cation concentrations. The results revealed that Na^+ concentrations ranged from 0.17±0.001 mg/kg in orange peel to 5.21±0.005 mg/kg in chicken bone; K^+ ranged from 0.28±0.003 mg/kg in eggshell to 56.50±0.216 mg/kg in banana peel; Ca^{2+} ranged from 0.30±0.004 mg/kg in potato peel to 1.37±0.049 mg/kg in eggshell; and Mg^{2+} ranged from 0.06±0.004 mg/kg in eggshell to 1.12±0.006 mg/kg in banana peel. The overall concentration sequence was $K^+>Na^+>Ca^{2+}>Mg^{2+}$. In addition, animal waste biomass had comparatively high ESP and EPP values for the studied waste biomasses. SAR, PAR, and CROSS models for all studied wastes are suitable for application to sodic and saline soils. In conclusion, non-edible food waste biomass might be a reliable source of cations that is important for soil structural stability and ultimately for plant growth and could be utilized in sodic and saline soils based on the analysis of cationic parameters and mathematical models.

Keywords: Cationic parameters, food waste, soil structural stability, plant growth.

Introduction

Cations (K^+, Na^+, Mg^{2+}, Ca^{2+}, etc.) are critical for agroecosystems as they significantly impact the physico-chemical properties of soil (Qadir et al., 2007), nutrient availability, plant growth, and crop yield (Filho et al., 2020). Specifically, these cations contribute to global soil salinity and sodicity problems, which hinder crop production due to ionic imbalance. Approximately 33% of irrigated land and 20% of total land worldwide are affected by salinity (Machado and Serralheiro, 2017). Additionally, nearly 424 million hectares of topsoil (0–30 cm) and 833 million hectares of subsoil (30–100 cm) have been affected by salt, covering 118 countries (FAO, 2021). The affected topsoil consists of 85% saline soil, 10% sodic soil, and 5% saline-sodic soil, whereas the subsoil comprises 62% saline soil, 24% sodic soil, and 14% saline-sodic soil (FAO, 2021). Salinization is rapidly spreading, affecting 1-2 million hectares of land annually, posing a significant threat to food security

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(Hopmans et al., 2021). Soil salinization and sodification are major obstacles to crop production, particularly in drylands (Filho et al., 2020; Stavi et al., 2021). It is predicted that about 50% of the world's crop fields will be affected by salt by 2050 (Jamil et al., 2011).

Plants require 17 essential nutrients for their growth and development (Fageria, 2009), including K^+, Na^+, Mg^{2+}, and Ca^{2+}. Sodium (Na) has also been found beneficial for many C4 plants, such as *Atriplex tricolor* and *Panicum miliaceum* (Arnon and Stout, 1939). Without these essential elements, plants cannot complete their life cycle. Conversely, an excess of these elements causes ionic toxicity. Therefore, balanced nutrient levels promote plant growth, while imbalanced nutrition impedes agricultural production.

Improper waste management, particularly of non-edible food waste, poses a serious problem in developing and underdeveloped countries. Non-edible food waste such as brinjal waste (Quamruzzaman et al., 2020), potato peel (Jekayinfa et al., 2015), banana peel (Pyar and Peh, 2018), orange peel (Abdelazem et al., 2021), eggshell (Ajala et al., 2018), cow bone (Nwankwo et al., 2018), chicken bone (Khalil, 2018), and fish bone (Hooi et al., 2021) have been identified as sources of mineral nutrients. Previous studies of the authors have reported the presence of 17 essential minerals, including cationic nutrients (K, Mg, and Ca), in these plant and animal wastes (Islam et al., 2023).

Thus, these wastes can be potential sources of nutrients, including cations, depending on the soil's nutritional conditions. Additionally, they can add organic matter beneficial for amending sodic and saline soils (Aboelsoud et al., 2020). Achieving a clean environment is crucial for all countries to meet the Sustainable Development Goals (SDGs) established by the UN (UN, 2015). However, there has been no comprehensive assessment of non-edible food waste for improving soil conditions and plant growth. That is why, this study aims to evaluate the potential of non-edible food wastes for enhancing soil health and stability in problematic sodic and saline soils through mathematical modeling of cation dynamics. Therefore, Na^+, K^+, Mg^{2+}, and Ca^{2+} ions were determined using ion chromatography of the mentioned wastes. Then, the mathematical models ESP, EPP, SAR, PAR, and CROSS were calculated considering the ionic concentrations of K^+, Na^+, Mg^{2+}, and Ca^{2+} to assess the potential of non-edible food waste for maintaining soil structural stability and promoting plant growth based on mathematical modeling.

Material and Methods

Sample preparation

Eight non-edible food wastes, namely brinjal waste, potato peel, banana peel, orange peel, eggshell, cow bone, chicken bone, and fish bone, were collected from households at International House-2, Saitama University, Japan. The waste samples were thereafter washed. Then the sample was dried under sunlight to remove the moisture. After being dried, the samples were ground using a standard laboratory grinder (IKA® Japan K.K., Osaka, Japan) and crusher (WB-1, 700 W, Osaka Chemical Co. Ltd., Japan). Then, the samples were kept in a sealed aluminum foil bag temporarily for analysis.

Cation determination

50 mg of each waste biomass were taken in a plastic bottle for ion determination. 10 mL of Ultrapure (Type1) water (Direct-Q® 3 UV Water Purification System) was added. Then the sample solution was subjected to ultrasonic extraction for 30 minutes. After that, the solution was centrifuged for 30 minutes. Then the centrifuged solution was filtered (0.25μm). Then the sample was stored temporarily for analysis. By this time, eluent had been prepared using Na_2CO_3, $NaHCO_3$, and methane sulfonic acid for their ability to effectively elute the targeted cations. The extractant was then placed for analysis. A standard solution was prepared and analyzed. The ionic concentration (mg/kg) of four cations, namely Na^+, K^+, Mg^{2+}, and Ca^{2+}, having three replications, was measured using an ion chromatography system (Dionex ICS-1600, Diotec Tokyo Co., Ltd., Japan).

Mathematical models

Exchangeable Sodium Percentage (ESP)

The ESP was computed as the ratio of Na to the summation of all cations expressed in percentage. The equation is followed in (1) (Richards, 1954).

$$\mathrm{ESP} = \frac{\mathrm{Na}^+}{\mathrm{Na}^+ + \mathrm{K}^+ + \mathrm{Mg}^{2+} + \mathrm{Ca}^{2+}} \times 100 \quad (1)$$

Exchangeable Potassium Percentage (EPP)

The EPP was computed as the ratio of K to the summation of all cations expressed in percentage. The equation is as follows in (2) (Richards, 1954)

$$EPP = \frac{K^+}{Na^+ + K^+ + Mg^{2+} + Ca^{2+}} \times 100 \quad (2)$$

Sodium Adsorption Ratio (SAR)

SAR addresses the effects of sodium on the stability of soil aggregates. SAR was calculated using the mathematical equation (3) (Richards, 1954)

$$SAR = \frac{Na^+}{\sqrt{\frac{(Ca^{2+} + Mg^{2+})}{2}}} \quad (3)$$

Potassium Adsorption Ratio (PAR)

PAR addresses the effects of potassium on the stability of soil aggregates. PAR was calculated using the mathematical equation (4) (Chen et al., 1983)

$$PAR = \frac{K^+}{\sqrt{\frac{(Ca^{2+} + Mg^{2+})}{2}}} \quad (4)$$

Cation Ratio of Structural stability (CROSS)

CROSS considers the effects of all cations on the stability of soil aggregates. It includes the potential negative effects of high sodium (Na), potassium (K), and magnesium (Mg) concentrations. CROSS was estimated using the mathematical equation in (5).

$$CROSS = \frac{Na^+ + 0.56K^+}{\sqrt{\frac{(Ca^{2+} + 0.6Mg^{2+})}{2}}} \quad (5)$$

Statistical analysis

IBM SPSS Statistics 20 and Microsoft office Excel 2013 (Microsoft, Inc, USA) were used for calculation and data analysis. Analysis of variance (ANOVA) was conducted to determine significant differences among treatment groups.

Results and Discussion

Concentration of mono and divalent cations in different non-edible food waste

This study found that non-edible food waste contains a significant amount of monovalent and divalent cations like Na^+, K^+, Ca^{2+}, and Mg^{2+} (Table 1). Sodium ions were the highest in animal-derived wastes (2.24±0.002–5.21±0.005), excluding eggshell, while plant-derived wastes exhibited the lowest concentrations (0.30±0.001), with the exception of potato peel (1.74±0.003). Potassium ions (7.11±0.017–56.50±0.216) and magnesium ions (0.38±0.002–1.12±0.006) were highest in plant-derived wastes, particularly in banana peel, with eggshell showing the lowest values for both elements. Calcium ions were notably high in eggshell (1.37±0.049) and banana peel (1.17±0.003), whereas potato peel had the lowest calcium content (0.30±0.004).

Table 1. Ionic concentration of mono and divalent cations in waste materials

Waste materials	Ion concentration (mg/kg)			
	Na^+	K^+	Ca^{2+}	Mg^{2+}
Brinjal waste	0.30^e ± 0.001	29.57^b ± 0.025	0.52^e ± 0.005	0.84^b ± 0.001
Potato peel	1.74^d ± 0.003	26.69^c ± 0.045	0.30^g ± 0.004	0.79^c ± 0.002
Banana peel	0.19^g ± 0.001	56.50^a ± 0.216	1.17^b ± 0.003	1.12^a ± 0.006
Orange peel	0.17^h ± 0.001	7.11^d ± 0.017	1.01^c ± 0.047	0.38^d ± 0.002
Eggshell	0.25^f ± 0.001	0.28^h ± 0.003	1.37^a ± 0.049	0.06^g ± 0.004
Cow bone	2.24^c ± 0.002	1.09^g ± 0.008	0.46^f ± 0.041	0.16^f ± 0.005
Chicken bone	5.21^a ± 0.005	2.91^e ± 0.017	1.02^c ± 0.018	0.21^e ± 0.008
Fish bone	3.06^b ± 0.003	1.84^f ± 0.003	0.68^d ± 0.007	0.16^f ± 0.001

Mean values in the column with uncommon superscript letters differ significantly ($p < 0.05$)

The overall trend of cationic distribution followed the following sequence: $K^+>Na^+>Ca^{2+}>Mg^{2+}$. K^+ is higher in plant and animal wastes because it is an essential nutrient for both. Since plants and animals require large amounts of potassium for various biological processes, it accumulates in their tissues and, consequently, in their waste. Na^+ concentrations are lower in both plant and animal wastes compared to K^+. But animal bone contained higher Na^+ compared to non-edible plant waste biomasses because animal bone acts as a reservoir of different minerals including Na^+ and Na^+ is integrated into the mineral matrix of the bone, contributing its stability. The findings regarding the high potassium content in banana peel are consistent with those reported by Jekayinfa et al. (2015), suggesting that these wastes have high potential for use as potassium supplements in deficient soils. In addition, eggshell, chicken bone, fruit peel biomasses contained a higher amount of Ca^{2+} than others mentioned in Table 1 might be used in Ca deficient soils. The result is similar to the findings of Al-awwal and Ali (2015) for eggshell. Calcium is higher in eggshell because it is primarily composed of calcium carbonate ($CaCO_3$). Mg^{2+} was recorded as having the highest concentration in banana peels and comparatively higher in plant waste biomasses. The present study concurs with the findings in brinjal waste, potato peel, banana peel, orange peel, and eggshell reported by Quamruzzaman et al. (2015), Jekayinfa et al. (2015), Pyar and Peh (2018), Abdelazem et al. (2021), Ajala et al. (2018), respectively. As salinity and sodicity are affected mainly by the presence of Na^+ (Rath et al., 2019), non-edible plant waste with lower Na^+ might be suitable for maintaining soil health and supplying essential plant nutrients.

Mathematical modeling of cation of non-edible food waste

Exchangeable sodium percentage (ESP), Exchangeable potassium percentage (EPP), sodium adsorption ratio (SAR), potassium adsorption ratio (SAR) and cationic ratio of structural stability (CROSS) are shown in Figure 1, 2, 3, 4 and 5.

Exchangeable Sodium Percentage (ESP)

The results for the exchangeable sodium percentage are presented in Figure 1. The results showed that the ESP of non-edible food waste ranged from 0.32±0.001 to 56.84±0.64. Cow bone had the highest ESP (56.84±0.64) followed by chicken bone, and fish bone that had ESPs greater than 15. Waste from vegetables and fruits has a lower value (0.32±0.0013-5.89±0.002) from the ESP model than animal waste (13.01±0.0013-56.84±0.64). The ESP value was statistically significant ($p<0.05$).

The ESP model is highly related to soil structure and sodicity. A higher ESP value indicates the presence of more Na^+ over monovalent and divalent cations, resulting in poor soil structure. ESP having ≤15 unlikely effects adversely, whereas >15 implies sodic soil-associated problems on soil structure (USDA, 2007). High ESP insists on soil particle dispersion and nutrient imbalances or deficiencies. Plants grow in a wide range of soils. Trapp et al. (2008), Prasad et al. (2007) and Kumar et al. (2006) described those plants exposed to higher ESP had reduced plant height, branches, leaves, flowers, and fruits. In addition, chlorophyll a and b and carotenoids in leaves decreased with increasing ESP. Anwar et al. (1996) found similar findings with the vetiver plant. Pea and lentil growth is affected even at ESP levels below 15, whereas rice and grass growth continue up to 15 and above 65, respectively. In addition, *A. majus* is more tolerant of sodic soil (ESP 57.4). Barley, linseed, mustard, sunflower, and wheat were supposed to be salt-tolerant crops (Chippa and Lal, 1995). Many halophyte plants can adapt to high-salty areas (Chen and Wang, 2024). Na can be used by glycophytic plants (turnips, beets, and spinach) as well, to such an extent that it can be an alternative to K (Marschner, 1971). It is also essential for Chenopodiaceae, Amaranthaceae, and Cyperaceae plants (Arnon and Stout, 1939). These C4 plants exhibited poor growth, visual deficiency indications such as chlorosis and necrosis, or failed to produce flowers in the absence of Na (Johnston at al., 1988). A recent field study revealed that Na fertilization increased beet yield (Barłóg et al., 2018). It has been reported that tomatoes respond to extra Na stress (Roșca et al., 2023) too. Therefore, cow bone, chicken bone, and fish bone can be added to the Na-deficient soil for the growth of C4 plant (tomato, etc.) that are beneficial for their growth. On the contrary, remaining waste materials can be applied to saline and sodic soil to improve its structure as well as plant growth.

Exchangeable Potassium Percentage (EPP)

The results for the EPP of the non-edible food waste are presented in Figure 2. It represents that the studied waste material possessed a higher EPP with a range of EPP (14.07±0.46 to 95.79±0.028). Vegetables, and fruits waste had a higher EPP value (81.96±0.487 to 95.79±0.028) than animal waste (14.065±0.46-32.07±0.014) with statistically differed ($p<0.05$). Animal waste had a low EPP value, but that is also higher than the critical value of 13. The EPP model is directly proportional to K^+ over monovalent and divalent cations. K^+ is very important for plants to maintain the proper functioning of cell membranes (Wei et al., 2003). It is also a macronutrient, essential for plant growth. A significant increase in crop yield was recorded with increasing EPP (Ravina and Markus, 1975). Clay dispersion has been linked to soils with high exchangeable K levels

(Farahani et al., 2018). According to Dexter and Czy (2000), clay dispersion frequently leads to unfavorable conditions for plant root development, decreases water permeability, which raises the risk of run-off, flooding, and erosion, and may result in anaerobic conditions in soils and crusting of the soil surface. As the EPP value was higher than the critical value, these wastes cannot be applied to saline and sodic soils. According to EPP models, the investigated wastes can be incorporated into K-deficient soils.

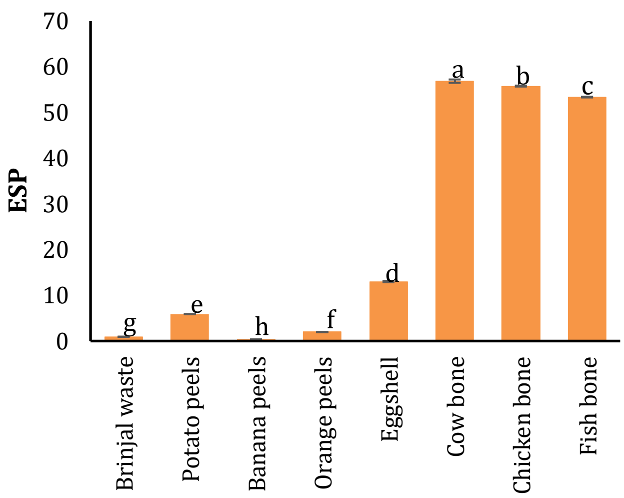

Figure 1. Exchangeable Sodium Percentage (ESP) of non-edible food waste (Mean values on the bars with uncommon superscript letters differ significantly, $p < 0.05$)

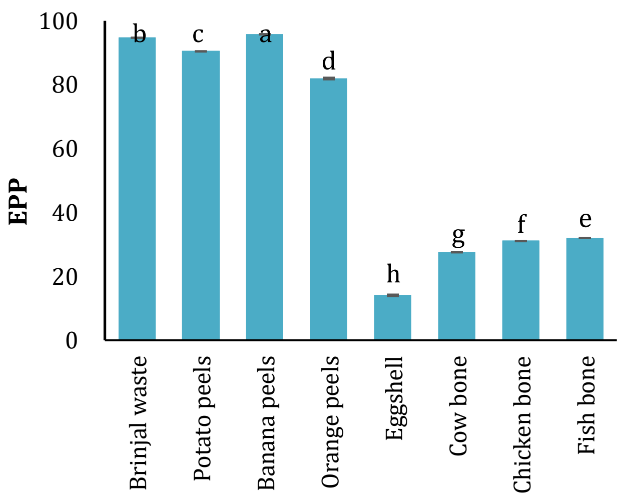

Figure 2. Exchangeable Potassium Percentage (EPP) of non-edible food waste (Mean values on the bars with uncommon superscript letters differ significantly, $p<0.05$)

Sodium Adsorption Ratio (SAR)

The Sodium Adsorption Ratio (SAR) of non-edible food waste is mentioned in Figure 3. All the studied waste biomasses had very low SAR values, with a range of 0.05±0.0001-2.35±0.02. A lower SAR value indicates the presence of less monovalent Na^{+} over divalent ions, namely Ca^{2+} and Mg^{2+}. Results also revealed that animal waste like cow bone, chicken bone, and fish bone had a higher value except eggshell that had a lower SAR value. On the other hand, plant waste had the lowest value, apart from potato peels. The recommended value of SAR of <13 is expected to have structural stability (Enyoh and Isiuku, 2020). The considered waste material with a lower SAR value is very conducive to having a good structure with respect to sodium and would allow the growth of plants. Marchuk and Rengasamy (2010) noted a positive association between SAR and clay dispersion. The results indicated that the higher the SAR value, the higher the potassium ion over divalent cations like Ca^{2+} and Mg^{2+}, and vice versa. SAR values indicate a low risk of sodium-induced structural instability, suggesting these wastes can be safely used in sodic soils.

Potassium Adsorption Ratio (PAR)

The PAR value of the studied non-edible food waste biomasses ranged 0.12±0.003-18.65±0.104. Results indicated that all biomasses except banana peels had a lower PAR value than the critical value mentioned in Figure 4. Vegetable and fruit waste biomasses contained a higher PAR value with a range 3.012±0.06-18.65±0.104. Banana peel had the highest PAR value, followed by potato peel, and brinjal waste, respectively. The PAR value does not cover sodium ion concentration. The biomasses with high PAR values contribute to the dispersion. As all the studied materials have a lower PAR value except banana peels, these can be applied to the soil, even saline soil.

Cation Ratio on Structural Stability (CROSS)

The results revealed that the investigated waste materials contained a CROSS-value with a wide range (0.17±0.004 to 11.71±0.06). Animal waste biomass had a lower CROSS value than vegetable and fruit waste. The CROSS value was lower than the critical value of 13 for all waste. The eggshell waste showed the lowest CROSS value (0.17±0.004) whereas banana peel showed the highest value (11.71±0.063). The CROSS model is the most accepted model that covers all causal factors. The lower CROSS value of non-edible food waste implies the comparatively lower presence of monovalent ions (Na^{+} and K^{+}) over divalent cations (Ca^{2+} and Mg^{2+}) and vice versa. Rengasamy and Marchuk (2011) mentioned that low CROSS-links inhibit the dispersion of soil clay. Al-Hadidi and Al-Ubaydi (2021) also stated similar findings: low CROSS-values prevent dispersion of soil clay but reduce hydraulic conductivity. As the studied waste biomass had a lower CROSS-value than the critical value, these biomasses can be incorporated into any kind of soil, especially highly dispersed soils.

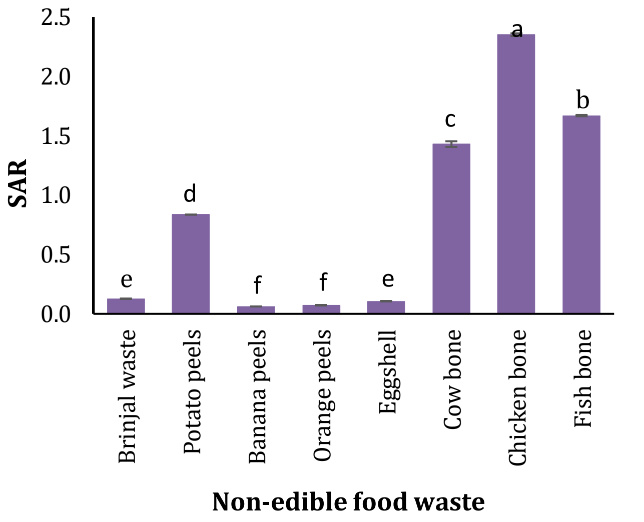

Figure 3. Sodium Adsorption Ratio (SAR) of non-edible food waste (Mean values on the bars with uncommon superscript letters differ significantly, $p < 0.05$)

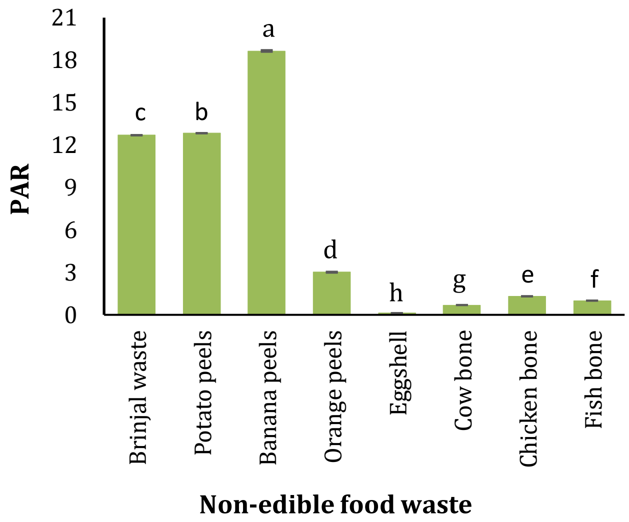

Figure 4. Potassium Adsorption Ratio (PAR) of non-edible food waste (Mean values on the bars with uncommon superscript letters differ significantly, $p<0.05$)

Principal Component Analysis

Figure 6 depicts the principal component analysis (PCA) of mathematical models of cations like ESP, EPP, SAR, PAR, and CROSS, respectively. It was constructed by maximizing the sum of the coefficients of variance of cationic parameters using Kaiser normalization and varimax rotation. Based on the eigenvalue, the principal component analysis was constructed. When it was considered greater than 1, only one component formed. If the eigenvalue was greater than 0.5, two principal components, PCA1 (79.50%) and PCA2 (16.41%), with EPP, PAR, and CROSS (ESP and SAR, respectively), were developed. Results revealed that components EPP, PAR, and CROSS are strongly correlated. The studied non-edible food waste biomasses contained a higher concentration of K^{+} as compared to the other mono- and divalent cations, which leads to a strong positive relationship. The ESP and SAR, on the other hand, were strongly correlated because these values are influenced by Na^{+}. Some of the findings agree with Farahani et al. (2018), where they found relationships between K and Na concentrations, the K:Na ratio, and cationic indicators (CROSS, SAR, PAR, ESP, and EPP) in soils.

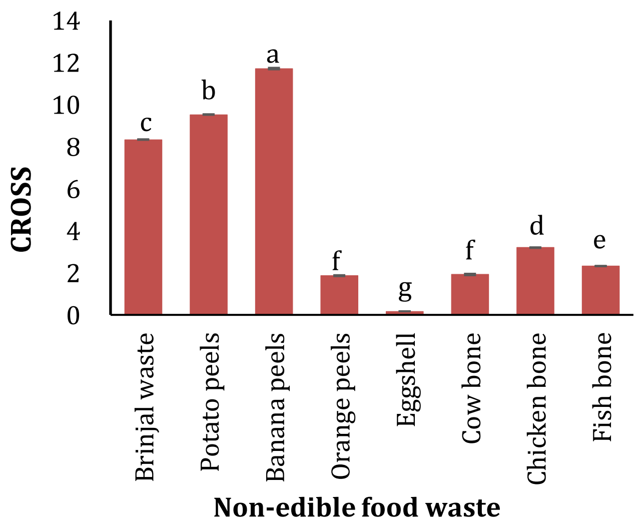

Figure 5. Cation Ratio on Structural Stability (CROSS) of non-edible food waste (Mean values on the bars with uncommon superscript letters differ significantly, $p < 0.05$)

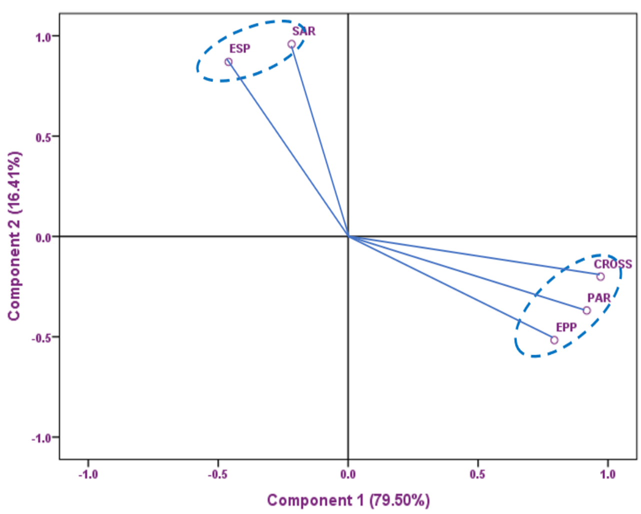

Figure 6. Principal Component analysis (PCA) of mathematical models (ESP, EPP, SAR, PAR, and CROSS)

Conclusion

The non-edible food waste contains a significant amount of monovalent and divalent cationic plant nutrients, viz., K^+, Na^+, Mg^{2+}, and Ca^{2+}, which are essential for soil improvement. The concentration of these cations varies depending on the type of waste material. According to the ESP model, all investigated waste except cow bone, chicken bone, and fish bone waste might be used to make sodic soil. However, the EPP model suggests that considered waste cannot be congenial to address the salinity and sodicity issues but can be added to the K-deficient soil. Nevertheless, based on the SAR, PAR, and CROSS models, the investigated waste can be incorporated into any kind of soil to build a stable soil structure and increase nutrient availability, including saline and sodic soils. This evaluation underscores the potential of non-edible food wastes, particularly banana peels and other plant-derived materials, to serve as sustainable potassium sources and improve soil fertility. Further research should focus on field-scale applications to assess the long-term effects of these wastes on soil structure and fertility.

Acknowledgments

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