

Recycled construction and demolition waste as remineralizers: a sustainable use in the regeneration of degraded soils

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Abstract

Construction and demolition waste (CDW) constitutes a major global environmental liability, and its recycling is essential for improving the sustainability of the construction industry. In this study, recycled CDW samples were collected from four Brazilian cities and chemically characterized to evaluate their potential as soil remineralizers for agricultural use. Neutron activation analysis (NAA) revealed a chemical composition compatible with potential agricultural applications, including elements relevant to plant nutrition. However, substantial differences in elemental composition were observed among samples from the four cities, with distinct multi-elemental patterns associated with each region. Considerable variability was also observed among samples collected from the same city, highlighting the heterogeneous nature of recycled CDW and the importance of considering compositional variability when assessing its suitability for agricultural use.

INTRODUCTION

Globally, the generation of construction and demolition waste (CDW) represents a significant environmental liability, exceeding 10 billion tons annually, with a substantial proportion still being disposed of in landfills [1]. In Brazil, Class A CDW comprises recyclable or reusable materials generated from civil construction, demolition, renovation, paving, and other infrastructure activities. This category includes soil from earthworks; ceramic materials such as bricks, blocks, roof tiles, and cladding tiles; mortar; and concrete, as well as waste generated during the manufacture and/or demolition of precast concrete elements, including blocks, pipes, and curbs [2].

The Solid Waste Panorama in Brazil, published in 2025 by the Brazilian Association of Waste and Environment (ABREMA), reported the generation of approximately 46.4 million tons of CDW in 2024, equivalent to 218 kg per inhabitant. This estimate is based on waste generated by individuals undertaking small-scale residential renovations and demolitions [3]. However, this figure represents only 46% of the total CDW volume generated in the country. When waste generated by other sectors is also considered including construction companies (30%), public agencies (12%), and paving companies (12%) total CDW generation is estimated to have reached approximately 101 million tons in 2024.

Proper management and disposal of CDW are aligned with sustainability principles in the construction industry, which seek to mitigate environmental impacts, ensure economic viability, and enhance the quality of life of present and future generations. This approach is grounded in the concept of the circular economy, which promotes the transition toward renewable energy and materials while decoupling economic activity from the consumption of finite resources. This paradigm is based on three fundamental pillars: eliminating waste and pollution; keeping products and materials in continuous circulation; and regenerating natural ecosystems. Together, these pillars constitute a systemic, solution-oriented approach to addressing global challenges, including climate change and biodiversity loss [4].

To ensure proper management, the collected CDW is transported to recycling facilities equipped with crushers, mills, conveyor belts with electromagnets, and sorting screens. The processed material is

classified into different particle-size fractions for a wide range of applications, including the restoration of rural roads, gabions for slope and embankment stabilization, crushed stone for reuse in concrete production, and coarse sand for construction applications as a substitute for river-dredged sand. From this stage onward, the material is classified as recycled CDW.

Recycled CDW contains calcite, quartz, and other minerals, as well as essential elements for plant nutrition, such as Fe, Mg, Mn, Cu, Zn, and Ni. These constituents can contribute to the restoration of soil chemical and physical properties [5]. Consequently, these materials have the potential to be used as soil remineralizers, representing a more sustainable alternative to commonly used products such as silicate rock dust. Remineralizers are silicate agrominerals intended for soil fertility management and plant nutrition. Their use is particularly relevant in tropical environments, where intense weathering promotes the leaching of nutrients and the depletion of soil minerals. Remineralization involves the application of multi-element mineral sources at relatively high rates to replenish depleted soil minerals. Beyond supplying essential elements, the use of remineralizers can enhance soil ecosystem functions, including water retention, carbon sequestration, and biodiversity support, thereby contributing to more sustainable agricultural management and reducing environmental impacts [6].

Plants require at least 14 mineral elements for their growth and development. These include the macronutrients N, P, K, Ca, Mg and S, which are required in relatively large quantities (on the order of g kg⁻¹), and the micronutrients Cl, B, Fe, Mn, Cu, Zn, Ni and Mo, which are required in much smaller quantities (on the order of mg kg⁻¹). Agricultural production is frequently limited by the low availability of essential mineral elements and/or by excessive concentrations of potentially toxic elements in the soil solution [7].

Brazil is highly dependent on fertilizer imports, which account for approximately 98% of domestic demand. This dependence, coupled with fluctuations in energy and raw material costs, contributes to higher fertilizer prices and greater uncertainty in agricultural production costs. The situation poses challenges to agricultural sustainability and may, at times, contribute to trade imbalances [8]. In this context, remineralizers derived from recycled CDW may represent a promising and more sustainable alternative for addressing soil nutrient deficiencies and improving crop nutrition.

To effectively utilize RCD-R as remineralizers, it is necessary to understand their chemical composition [9]. Specific legislation regulates the use of remineralizers in Brazil. Normative Instruction No. 5, issued on March 10, 2016 (IN 5/2016), establishes requirements regarding their definition, classification, specifications, and guarantees. It sets maximum permissible limits for potentially toxic elements, such as As, Cd, Hg and Pb, and minimum requirements for the combined contents of CaO, K₂O, and MgO [10]. Thus, the chemical characterization of recycled CDW is essential for evaluating the parameters required for its safe reuse as a remineralizer [8]. This study applies neutron activation analysis (NAA) to investigate the potential of recycled CDW as a soil remineralizer, assessing its suitability as an accessible and sustainable resource aligned with SDG 2 (Target 2.4) and SDG 11 (Target 11.6), while offering an alternative for the regeneration of Brazilian soils.

MATERIALS AND METHODS

The geographic distribution of the 53 cities affiliated with the Brazilian Association for Construction and Demolition Waste Recycling (ABRECON) [11] across the Brazilian states (Fig. 1) served as the basis for planning the sampling campaigns. Samples were collected from three municipalities in the state of São Paulo (Araraquara, Piracicaba, and Ribeirão Preto), where the highest concentration of recycling plants was observed, and from one municipality in the state of Goiás (Catalão).

Sampling was conducted according to the protocol established by ABNT NBR 10.007/2004 for solid waste. A trier sampler with a 500-g capacity was used to collect recycled CDW directly from the piles formed after waste processing. The samples were then placed on a laboratory bench and allowed to air-dry for 8 to 10 days. After drying, the samples were comminuted using a suitable mill to obtain a particle size of less than 200 μm and subsequently stored in hermetically sealed glass containers.

For NAA, aliquots of 200 mg were weighed into high-purity polyethylene capsules (Posthumus Plastics, Beverwijk, the Netherlands). NiCr alloy wires were placed between the capsules to monitor the neutron flux [12]. Geological certified reference materials SRM 2710 Montana Soil, SRM 2711 Montana Soil, SRM 2702 Inorganics in Marine Sediment, and IAEA Soil 7 were used for analytical quality control. Empty capsules were analyzed as analytical blanks to assess potential contamination from the polyethylene matrix.

Irradiation was carried out for 4 h in a thermal neutron flux on the order of $7.5 \times 10^{12} \text{ cm}^{-2} \text{ s}^{-1}$ at the IEA-R1 nuclear research reactor of the Nuclear and Energy Research Institute (IPEN), under the Brazilian National Nuclear Energy Commission (CNEN), in São Paulo, SP, Brazil. Induced radioactivity was measured by high-resolution gamma-ray spectrometry using an HPGe detector with a relative efficiency of 50% at the 1332 keV photopeak of ^{60}Co . The mass fractions of the chemical elements and their associated uncertainties were calculated using Quantu software [13, 14]. To determine residual moisture and express results on a dry-weight basis, 2-g aliquots were placed in metal containers (50 mm in diameter and 10 mm in height) and dried in an oven at 105°C for 24 h. After drying, the samples were weighed again to calculate their moisture content.

To evaluate the results, descriptive statistics were calculated, including the mean and standard deviation of the mass fractions of chemical elements for each city/region studied. Subsequently, principal component analysis (PCA) was applied to reduce data dimensionality and assess the contribution of chemical elements to the discrimination among groups.

RESULTS AND DISCUSSION

NAA enabled the quantification of 22 chemical elements in the recycled CDW samples: As, Ca, Ce, Co, Cr, Cs, Eu, Fe, Hf, K, La, Na, Rb, Sb, Sc, Sm, Ta, Tb, Th, U, Yb and Zn, six of which are rare-earth elements. Table 1 summarizes the mean mass fractions and standard deviations of the chemical elements

determined in samples collected from the municipalities of Araraquara (SP), Catalão (GO), Piracicaba (SP), and Ribeirão Preto (SP).

Tabela 1 Chemical elements (mg kg ⁻¹ , dry weight) determined in recycled construction and demolition waste samples from four Brazilian municipalities. Mean mass fractions and standard deviations				
	Araraquara (n = 11)	Catalão (n = 5)	Piracicaba (n = 17)	Ribeirão Preto (n = 12)
As	2.6 ± 0.2	3.91 ± 0.35	4.5 ± 1.1	2.6 ± 1.0
Ca	25600 ± 2290	49200 ± 3460	38000 ± 5930	34400 ± 3140
Ce	55.8 ± 9.0	134 ± 120	51.8 ± 5.2	62.9 ± 9.0
Co	6.94 ± 1.15	6.54 ± 0.45	11.4 ± 3.0	13.1 ± 1.6
Cr	58.9 ± 19.8	60.5 ± 5.4	55.5 ± 26.2	28.5 ± 6.8
Cs	0.843 ± 0.104	3.32 ± 0.24	1.83 ± 0.71	0.87 ± 0.25
Eu	0.781 ± 0.063	0.94 ± 0.23	1.03 ± 0.22	1.24 ± 0.09
Fe	31300 ± 2370	21300 ± 670	43200 ± 7900	58900 ± 3300
Hf	5.79 ± 1.10	5.95 ± 0.54	7.83 ± 1.26	8.51 ± 1.85
K	3690 ± 460	12800 ± 1090	6430 ± 970	5320 ± 890
La	23.6 ± 5.3	67.6 ± 70.9	23.0 ± 2.8	26.9 ± 4.7
Na	1120 ± 150	3120 ± 320	4610 ± 1920	2130 ± 750
Rb	20.9 ± 3.3	81.1 ± 6.4	38.2 ± 5.4	29.0 ± 3.6
Sb	0.298 ± 0.017	0.568 ± 0.092	1.27 ± 0.91	0.399 ± 0.207
Sc	9.34 ± 0.66	8.22 ± 0.27	11.6 ± 2.2	15.5 ± 0.8
Sm	3.35 ± 0.55	8.33 ± 6.15	4.11 ± 0.67	4.79 ± 0.47
Ta	1.15 ± 0.08	1.70 ± 0.44	1.01 ± 0.09	1.30 ± 0.06
Tb	0.397 ± 0.054	0.721 ± 0.182	0.568 ± 0.097	0.627 ± 0.079
Th	6.91 ± 2.34	26.4 ± 27.2	6.56 ± 1.14	7.07 ± 3.27
U	1.41 ± 0.32	3.51 ± 0.30	2.04 ± 0.28	1.38 ± 0.44
Yb	1.20 ± 0.06	2.32 ± 0.58	1.86 ± 0.16	1.66 ± 0.22
Zn	59.4 ± 7.0	52.6 ± 3.1	113.0 ± 36.5	100.0 ± 9.9

Fe, Ca, Na and K exhibited the highest mass fractions among the elements determined. The data revealed variations in the elemental profiles of recycled CDW among the cities, which may be associated with regional differences in the composition of construction materials and geochemical characteristics. For example, higher Fe mass fractions were observed in samples from Ribeirão Preto and Piracicaba, potentially reflecting the influence of highly weathered soils enriched in iron oxyhydroxides characteristic of these regions [15]. In Catalão, Ca, Ce, K, La, Rb and Th exhibited notably higher mass fractions, with values exceeding twice the averages observed in the other cities. These findings highlight the heterogeneity of the elemental profiles of recycled CDW according to geographic origin.

In a study conducted in Italy using different particle-size fractions of CDW, chemical characterization revealed variations in elemental profile according to particle size. Higher mass fractions of Co, Cr, and Zn were observed in the < 0.075 mm fraction [16]. Another study conducted in Quebec, Canada, chemically characterized CDW collected from three sites at three different times between 2019 and 2020 to assess variations in As, Cu, Pb, and Zn mass fractions. The results revealed heterogeneity in the distribution of these elements among the different samples analyzed [17]. The findings of these studies underscore the heterogeneous nature of these wastes, which comprise various materials and exhibit compositional variability depending on the collection site, sampling period, and particle-size fraction.

In the present study, various micronutrients were detected in the recycled CDW. The mass fractions of Fe, Co, and Zn were compared with the values established by Brazilian legislation (IN 5/2016) as declaration thresholds, which do not preclude the material from being classified as a remineralizer. Fe exhibited mass fractions ranging from 21,300 to 59,800 mg kg⁻¹ (2.13–5.98%), exceeding the established threshold of 0.1%. In contrast, the mass fractions of Co (6.54–13.1 mg kg⁻¹; 0.000654–0.00131%) and Zn (52.6–113 mg kg⁻¹; 0.00526–0.0113%) remained below their respective reference values of 0.005% and 0.1%. Therefore, among the micronutrients evaluated, only Fe exhibited a mass fraction above the threshold established by the regulation for declaration as a guaranteed nutrient.

Regarding the potentially toxic elements regulated by IN 5/2016, As was detected in the samples at mass fractions between 2.59 and 4.53 mg kg⁻¹, remaining below the regulatory limit of 15 mg kg⁻¹. Cd mass fractions were below the method detection limit (5.4 ± 1.1 mg kg⁻¹) and, therefore, could not be quantified; nevertheless, they remained below the maximum value of 10 mg kg⁻¹ established by the regulation. These results are particularly relevant to assessing the potential use of recycled CDW as a soil remineralizer, considering that the content of potentially toxic elements is a key safety criterion for the application of waste-derived materials to soil.

The calculated K₂O and CaO contents were compared with the 9% minimum sum-of-bases threshold established by IN 5/2016. Based on the mean values for the cities of Araraquara, Piracicaba, and Ribeirão Preto, the sum of bases was below 6%, whereas Catalão exhibited a mean value of 8.4%. Furthermore, the mean K₂O content for Catalão exceeded 1%, meeting the minimum limit established by the regulation. Regarding individual samples, three samples from Piracicaba reached K₂O contents of 0.9%, while two samples from Ribeirão Preto reached 0.8%, despite the substantially lower mean values

for these cities. The results highlight the considerable variability in the mass fraction of these plant nutrients among the collected samples, both between and within regions, underscoring the need to account for compositional variability when assessing the potential use of CDW-derived materials.

When evaluating remineralizers and their potential to supply nutrients to plants, it is important to consider the soluble and exchangeable forms of these nutrients in the soil rather than relying solely on their total concentrations. Nutrient uptake is influenced by several factors, including soil pH, moisture, and interactions among elements [7]. Remineralizers have the potential to modify soil chemical properties and improve nutrient supply. Studies involving the application of rock dust from different sources have reported increased availability of K, Ca, Fe, Mg, P, and Zn in the soil [17, 18]. In another experiment, soil available K and Ca levels increased three- to five-fold two years after the application of rock dust from different sources, resulting in improved development of the forest species evaluated [18]. The accumulation of Ca in the soil, which is essential for the growth and functioning of plant root systems, contributed to improved nutritional balance, an effect also observed in studies involving the application of basaltic rock dust to soybean [19].

PCA of the 22 determined chemical elements showed a cumulative variance of 66.76% for the first two components, with 37.14% explained by PC1 and 29.62% by PC2. The biplot (Fig. 2) reveals differences in the geochemical composition of the recycled CDW from the four cities. Along PC1, elements such as Ce, Cs, K, Rb and U exhibit positive loadings and are associated with the Catalão samples, consistent with their higher mean values reported in Table 1. Along PC2, the Piracicaba samples exhibit the greatest intra-group dispersion. Nevertheless, the ordination indicates chemical similarity between the Piracicaba and Ribeirão Preto samples, which show strong associations with Co, Eu, Fe, Sc and Zn. The segregation of samples according to their chemical composition appears to reflect the geographical distribution of their cities of origin.

CONCLUSION

NAA proved to be a suitable technique for the elemental characterization of recycled construction and demolition waste. The results revealed substantial heterogeneity in the chemical composition of waste collected from four Brazilian cities, likely reflecting differences in urban development patterns and regional geological characteristics. All analyzed samples complied with Brazilian regulatory standards for soil remineralizers regarding safety, as potentially toxic elements (As and Cd) remained below the maximum permitted limits. However, only the samples from Catalão met the agronomic requirements for minimum K_2O content and minimum sum of bases ($K_2O + CaO$). These findings indicate that recycled construction and demolition waste has potential for reuse as a soil remineralizer in agriculture. Nevertheless, the substantial variability observed among and within regions highlights the need for careful material selection and further assessment prior to agricultural application.

DECLARATIONS

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Author Contribution

LA and VI wrote the main text, performed the calculations for the sum of oxide bases, and organized Table 1 and Figure 1. RL carried out the statistical calculations and generated the PCA plot. AZ contributed to the interpretation of Normative Instruction 5/2016 and the text regarding soil remineralizers. MB was responsible for interpreting the neutron activation analysis (NAA) data and calculating the spectra obtained from the hyperpure germanium detectors. EF is the coordinator.

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Data Availability

Available from the corresponding author on request.

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Figures

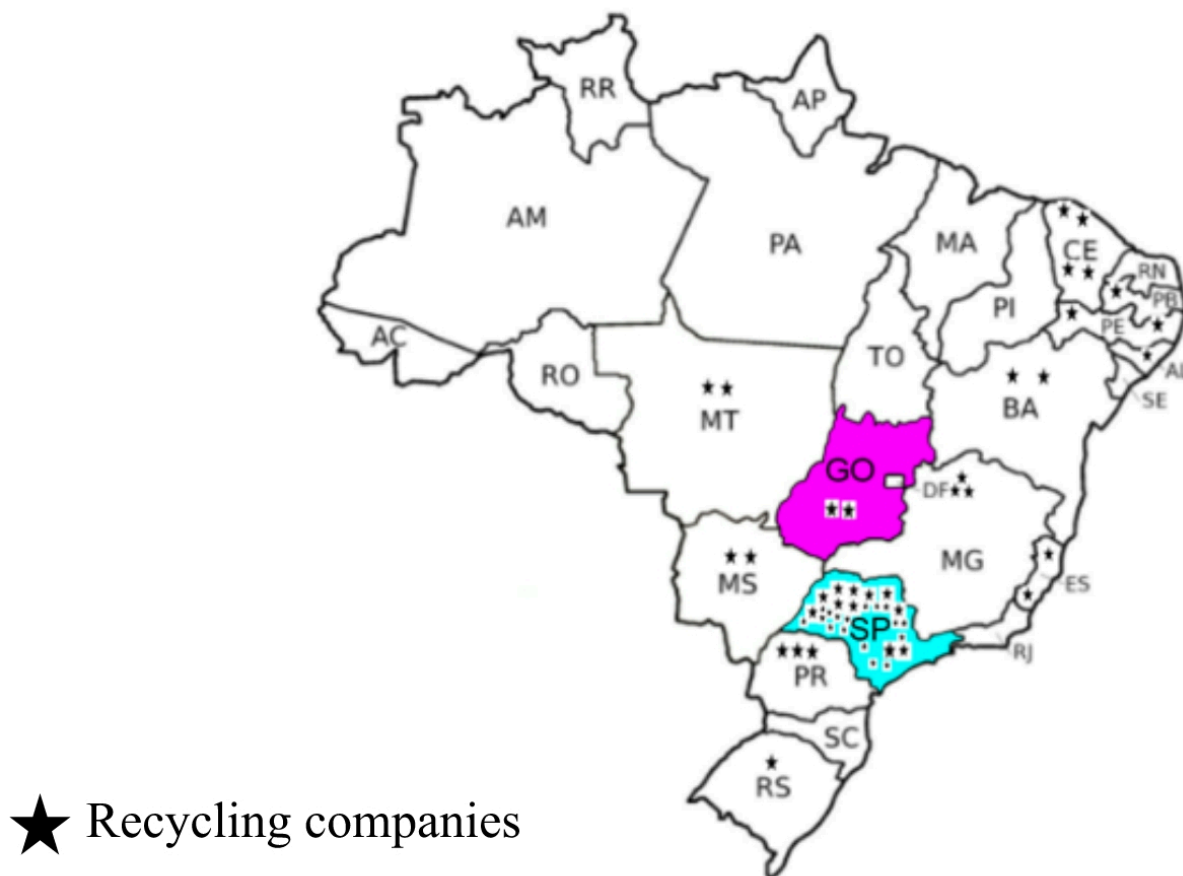


Figure 1

Mapping of construction and demolition waste recycling companies across Brazil according to ABRECON [11].

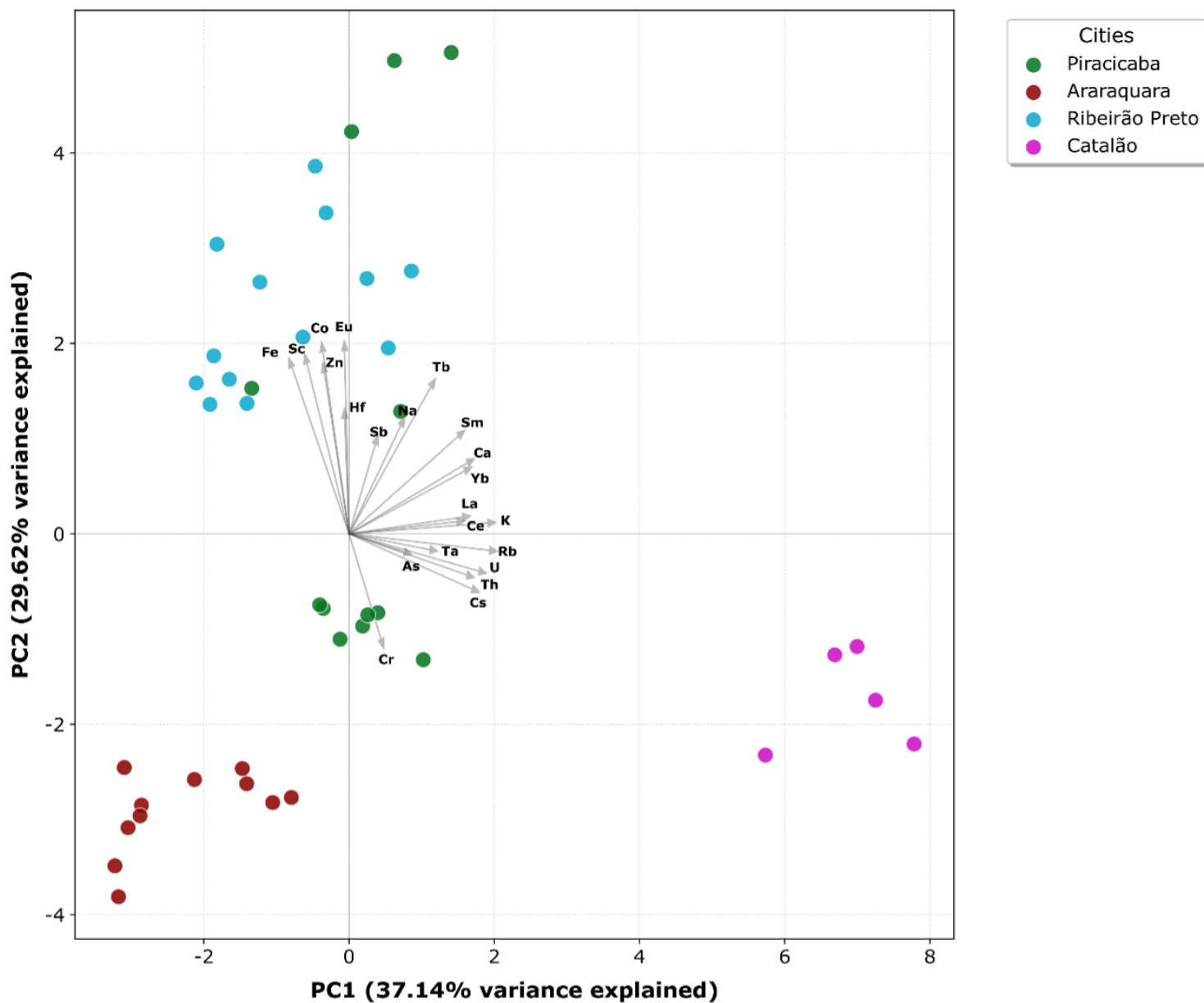


Figure 2

Biplot of principal component analysis for 22 chemical elements determined in recycled construction and demolition waste from four Brazilian municipalities