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Production of Yerba Mate Extract with Zero Waste Principle Using Agricultural Recycling

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Abstract

This study revealed that the yerba mate residue (YME) generated in producing *Ilex paraguariensis* tea extract is non-hazardous and non-inert. Reintroduced YME can make Mn, Fe and Zn available in yerba mate cultivation soil. A dose of YME (84.6, 56.4, 28.2, 14.1 $t.ha^{-1}$ or not = control) was reintroduced into 5 recipient areas of the yerba mate forest in Paraná, Brazil to avoid unnecessary disposal from YME to landfill. The effect of reintroducing YME was evaluated in terms of soil change (potassium, phosphorus, sodium, calcium, magnesium, pH, and electrical conductivity) for two depths (0 to 10 cm or 10 to 20 cm), change in leaf composition, and growth of its branches for up to 210 days. YME agricultural recycling increased ($p<0.05$) the potassium content in both soil layers from the 90th day onwards and was beneficial for leaf productivity and branch growth. Additional studies must be carried out to determine the long-term effects. Even so, YME recycling is recommended to minimize the export of nutrients from the soil since there are no agronomic, sanitary, and safety restrictions, offering an innovative and environmentally sustainable solution for this industrial waste of yerba mate extract. Additionally, recycling minimizes unnecessary expenses with soil improver for small yerba mate producers. It extends the useful life of the landfill, which is also advantageous for the community surrounding the company.

Keywords: Yerba Mate Industry, Zero Landfill; Soil Fertility; Nutrient Recycling; Agricultural Sustainability; Sustainable Waste Management.

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Produção de Extrato de Erva Mate com Princípio de Desperdício Zero Utilizando Reciclagem Agrícola

Resumo

Este estudo revelou que o resíduo de erva mate (YME) gerado na produção do extrato de chá de *Ilex paraguariensis* não é perigoso e não inerte. O YME reintroduzido pode disponibilizar Mn, Fe e Zn no solo de cultivo de erva-mate. Uma dose de YME (84,6, 56,4, 28,2, 14,1 $t.ha^{-1}$ ou não = controle) foi reintroduzida em 5 áreas receptoras da floresta de erva-mate no Paraná, Brasil para evitar destinação desnecessária de YME para aterro. O efeito da reintrodução de YME foi avaliada quanto a alteração do solo (potássio, fósforo, sódio, cálcio, magnésio, pH e condutividade elétrica) para duas profundidades (0 a 10 cm ou 10 a 20 cm), alteração da composição foliar e crescimento de seus ramos por até 210 dias. A reciclagem agrícola do YME aumentou ($p<0,05$) o teor de potássio em ambas as camadas do solo a partir do 90º dia e foi benéfica para a produtividade das folhas e para o crescimento dos ramos. Estudo adicionais devem ser realizados para conhecer efeitos a longo prazo. Mesmo assim, recomenda-se a reciclagem do YME para minimizar a exportação dos nutrientes do solo uma vez que não existe restrições agronômicas, sanitárias e de segurança, oferecendo uma solução inovadora e ambientalmente sustentável para este resíduo industrial do extrato de erva-mate. Aditivamente, a reciclagem minimiza gastos desnecessários com melhorador de solo para os pequenos produtores de erva-mate e prolonga a vida útil do aterro, o que também é vantajoso para a comunidade do entorno da empresa.

Palavras-chave: Indústria da Erva-Mate, Aterro Zero; Fertilidade do Solo; Reciclagem de Nutrientes; Sustentabilidade Agrícola; Gestão Sustentável de Resíduos.

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1 Introduction

The global market value of yerba mate was estimated at around US$2,18 billion for 2023 and a potential that will exceed US$3,79 billion in 2032. Processed beverage sales were estimated to reach US$434.2 million in 2023 as it has been an ideal alternative to tea, coffee, and other beverages. This is due to the obvious health benefits this product offers. (MÉNDEZ, 2023). Yerba mate (*Ilex paraguariensis* St. Hil.) has beneficial pharmacological properties, such as antioxidant (BOAVENTURA et al., 2015, MÉNDEZ, 2023), antimutagenic, vasodilation, lipid-reducing, anti-glycation, and weight reduction properties, despite its inadequate consumption of “chimarrão”, a drink characteristic of southern South American culture, may be associated with oropharyngeal cancer (BRACESCO et al., 2011). Yerba mate contains selenium, zinc, caffeine, and other nutrients in large quantities and is associated with increased immunity, reduced risk of heart disease, improved digestion and reduced blood sugar levels, reduced stress, obesity, and the spread of diseases (MÉNDEZ, 2023). Furthermore, "chimarão" may contain Cd at undesirable levels, but this should not be relevant in terms of toxicity for regular consumption (ULBRICH et al., 2022). The fragmented leaves are used to produce a tasty yerba mate drink by cold or hot extraction (THEA et al., 2016). Alternatively, they can be roasted to produce a tea that is also highly appreciated (SILVEIRA et al., 2014). Industrially, a concentrated extract of this tea has been produced to prepare packaged drinks for consumption (ISOBELLA et al., 2010), in the cosmetics and personal care sector etc. Its dry extract has therapeutic properties associated with preventing premature aging of skin and hair, reduces inflammation induced by UV rays and protects the skin's collagen, responsible for the elasticity and firmness of tissues. (MÉNDEZ, 2023).

The average yield of manual harvesting varies from 15 to 25 kg of green leaves per tree (DANIEL, 2009), with the average yield of green leaves per hectare increasing by 23% from 2007 to 2016 (IBRAMATE, 2018). This operation causes an export of nutrients by removing the leaves that obtain them from the soil. For example, the main elements present in yerba mate from the southern states of Brazil revealed decreasing concentration levels for K (12.82 g.kg^{-1}) >Ca (7.01 g.kg^{-1}) >Mg (4.48 g.kg^{-1}) >Mn (1.36 g.kg^{-1}) >P (1.12 g.kg^{-1}) >S (0.98 g.kg^{-1}) >Al (349 mg.kg^{-1}) >Fe (242 mg.kg^{-1}) >Ba (68 mg.kg^{-1}) >Zn (63 mg.kg^{-1}) >Sr (33 mg.kg^{-1}) >B (37 mg.kg^{-1}) >Rb (31 mg.kg^{-1}) >Cu (9.4 mg.kg^{-1}) >Ti (6.2 mg.kg^{-1}) >Ni (2.46 mg.kg^{-1}) > other elements (ULBRICH et al., 2022). The yerba mate production system in Brazil has not been improved due to the inherited tradition of cultivation in the family succession of rural properties. Thus, the failure to fertilize or reintroduce soil-improving agents justifies the reduction of more than 63% in average productivity in recent decades. K export varies between 18.96 kg.ha^{-1} and 63.24 kg.ha^{-1} depending on the type of pruning of the yerba mate crop (SOUZA et al., 2008), which requires chemical replacement in the solo or use of other replacement options. For example, simple actions such as organic fertilization with chicken litter provide P and K to meet the needs of yerba mate (BENEDETTI et al., 2017).

The industrial production of yerba mate extract is conducted in a percolator subjected to the action of steam and hot water. This operation allows for the removal of various elements that will be present in water at 100°C during tea production. Some exhibit high absorption rates (81–100%) for K > Rb > Ni > Cs > B, while others show elevated rates (51–80%) for Mg > Cu > S > P > Mn. Intermediate absorption rates (21–50%) are observed for Zn

> Li > Mo > Se, whereas low rates (10–20%) are seen for Ca > As > Pb > Sr > Al > Ba and Cd. Additionally, some elements exhibit very low absorption rates (<10%), such as Ti > Fe > V (ULBRICH et al., 2022). In addition to the extract, a solid industrial residue is produced, which also can be called Tea Waste and Tea Stem (ISOBELLA et al., 2010, GAR; OGATA, 2020). In the specific case of the production of mate tea extract, the solid waste generated will be called yerba mate waste (YMR). The YMR has been burned or discarded in landfills or the open, which causes loss of lignocellulosic material or nutrients from the soil through the export of micro and macronutrients from the vegetable. Thus, there have been innovative studies on its use as a lignocellulosic raw material to compose composites that replace wood (GAR; OGATA, 2020), as well as the production of essential oils, pectin, animal feed, activated carbon, pollutant adsorbents, and recovery energy (BATUECAS et al., 2019; MAHATO et al., 2018). Additionally, the disposal of YMR from the yerba mate extract production industry in landfills should be unfeasible with the maturity of legal requirements on limiting the disposal of organic waste to landfills as required in Europe (UE, 1999). In this context, the greatest demand for this vegetable has increased the export of nutrients from the soil, and the reintroduction of residue to the soil can increase agricultural productivity (YADAV; GARG, 2013). Over the years, agricultural residues (TROEH; THOMPSON, 1993), livestock by-products (SILVA; MENEZES, 2007; WILD, 1993; BENEDETTI et al., 2017), and even sewage sludge (Guedes et al., 2006) have been recognized as valuable sources of essential nutrients such as nitrogen, phosphorus, and potassium. Recommendations for their application can be found in guidelines provided by specialized associations, as “Comissão de Química e Fertilidade do Solo” (CQFS, 2004). However, it's important to note that the latter two sources may harbor pathogens, as indicated by standards set by Associação Brasileira de Normas Técnicas (ABNT, 2004) and research (SAIDELLES; REINERT; SALET, 2003).".

Additively, plants require several different metallic elements for growth, development, and reproduction. These metals must be mobilized from the soil matrix and absorbed by the roots as metal ions. They are destined by the plant's vascular tissues for distinct parts of the plant (DALCORSO et al., 2014). Several metals are described as essential metals for healthy plant growth but can be toxic when present in excess. To this end, metal ion transporters have mechanisms for absorption, translocation, and compartmentalization to maintain metal homeostasis. Several metal ions are free, and others are linked to small organic molecules to facilitate the absorption and transport of metal ions with low solubility and as chelators involved in the sequestration for tolerance and storage of metals. For example, mugineic acid, nicotianamine, organic acids (citrate and malate), histidine, and phytate are ligands for iron (Fe), zinc (Zn), copper (Cu), manganese (Mn), and nickel (Ni) in plants and proteins identified as their transporters (HAYDON; COBBETT, 2007). In this regard, the utilization of YMR can supply a significant quantity of these elements, which may not have been entirely extracted during hot water processing (ULBRICH et al., 2022), thus effectively fulfilling the intended purpose of YMR for soil enhancement, particularly beneficial for small yerba mate producers.

In this study, YMR was classified as industrial waste by Brazilian regulatory standards. Furthermore, it was utilized as a soil improver as recommended at that time, and evaluated for its impact on the leaf composition and branch growth of yerba mate trees over 210 days.

2 Materials and methods

2.1 Characterization of Yerba Mate grounds as an additive

The potential availability of yerba mate waste (YMR) was estimated with technical visits to the company in Paraná in the early 2010s and YMR a significant sample was produced. The presence of arsenic, cadmium, lead, and chromium was characterized according to SMWW 3120 B (SMWW, 2012), EPA 6010 C (USEPA, 2014), and mercury, according to EPA 245.7 (USEPA, 2005). The YMR was characterized according to agronomic aspects for pH, density, humidity, organic matter (total, organic, inorganic, and compostable), nitrogen, sulfur, and boron (RICE et al., 2012). Phosphorus, potassium, magnesium, calcium, zinc, iron, copper, sodium, and manganese were determined in according to the “Manual de métodos analíticos oficiais para fertilizantes minerais, orgânicos, organominerais e condicionador do solo do Ministério da Agricultura, Pecuária e Abastecimento do Brasil” (MAPA, 2013). These results were used to characterize some potential beneficial elements to improve soil and yerba mate production (ULBRICH et al., 2022).

2.2 Prior characterization of soil agrochemical components

A composite sample from each block was used for initial soil characterization. The composite sample for each block consisted of twenty-five subsamples collected between the planting rows, at a depth of 0-10 cm, using a Dutch auger. Previous chemical analysis (n=5) of the soil was carried out for pH, some ions (Al^{3+}, $H^{+}+Al^{3+}$, Ca^{2+}, Mg^{2+}, K^{+}), the sum of bases, effective cation exchange capacity (CTC) at pH 7.0, phosphorus, carbon (total and organic), base saturation and aluminum saturation (PAVAN et al., 1992).

2.3 Agricultural area receiving yerba mate waste

A 27-year-old commercial herb located in the municipality of Fernandes Pinheiro (7,187,704,000 N; 543,377,000 E), Paraná, Brazil, was selected to conduct the field experiment. The region's climate is type Cfb (warm temperate, without a dry season, with a mild summer and an average temperature of the hottest month below 22ºC), according to Koppen's climate classification (APARECIDO et al., 2016). The soil in the experimental area was classified as typical dystrophic Red Oxisol, alic, medium texture (23% to 37% sand) and the relief is gently undulating (LOURENÇO et al., 1997). Previous leaf production and the history of management and fertilization practices were obtained through an unstructured interview with the farmer who owned the herb. A flat area of grass with a spacing between grasses of 3 m x 1.5 m (between rows x between plants) was treated in full sun.

2.4 Setting the yerba mate waste dose

Various approaches can be utilized to determine the optimal quantity of yerba mate waste (YMW) for application within yerba mate production forests. In this study, nitrogen was identified as the primary target nutrient. Recommendations for application rates were established based on guidelines provided by the CQFS RS/SC of the "Sociedade Brasileira de Ciência do Solo - Núcleo Regional Sul" (CQFS, 2004) at the time of the research. The treatments corresponded to no addition (control) of (YMR) or addition of 50%, 100%, 200%, and 300% of the nitrogen fertilization:

a) The calculations for replacement were based on the levels present in the receiving soil and the source of nitrogen fertilizer (YMR).

b) The replacement was 60 kg of nitrogen ha^{-1} for soils with organic matter between 2.6% and 5% and expected above 12 $t.ha^{-1}$ of yerba mate (green mass).

c) The YMR in natural humidity contained 0.85% nitrogen. Considering a nitrogen mineralization fraction of 25% of that contained in the residue, it is estimated that the available nitrogen concentration was 0.21%.

d) The quotient between the recommendation (60 kg of nitrogen ha^{-1}) and the concentration of nitrogen available from the residue (0.21%) corresponds to a quantity of residue (28.2 t.ha^{-1}) that must be applied to the soil to supply 100% of the recommended replacement nitrogen fertilizer.

The univariate study of the effect of the added mass of YMR per area (Table 1) to make recommended nitrogen available (100%) to the soil (Table 1) was carried out with two levels below (0% = control and 50%) and two above (200 and 300%) the value recommended (T3-100/140/62) by the CQFS RS/SC (CQFS, 2004). Common fertilizer formulations typically include a balance of three primary nutrients essential for plant growth: nitrogen (N), phosphorus (P), and potassium (K). So, the corresponding additions of phosphorus (as P_2O_5) and potassium (as K_2O) are also highlighted.

Table 1: Macroconstituent equivalent available for different single application treatments of yerba mate residue (YMR) in the soil of the yerba mate plantation.

Treatment	**Equivalent (%)**			**YMR to be applied, t.ha^{-1}**
	N	**P_2O_5**	**K_2O**	
T1-0/0/0	0	0	0	0
T2-50/70/31	50	70	31	14.1
T3-100/140/62	100*	140	62	28.2
T4-200/280/124	200	280	124	56.4
T5-300/420/186	300	420	186	84.6

Source: The Authors. Values was calculated based on the recommendation for nitrogen fertilization (COMMISSION OF CHEMISTRY AND SOIL FERTILITY – RS/SC, 2004). *Recommended dose of nitrogen (reference element).

2.5 Experimental design of yerba mate waste disposal receiving agricultural area

YMR was applied only once to the recipient area. After the initial characterization of the soil and establishing the amount of YMR to be applied as per the recommendation detailed above, the YMR was spread manually, with the aid of 20 L buckets, on the surface of the rows, approximately 20 cm away from the planting line, in the amount corresponding to the doses calculated based on the recommendation agronomic. Weed control was previously conducted using a mechanical brush cutter throughout the experimental area.

The design used was randomized blocks, with five treatments and five replications. The treatments were applied randomly in each of the plots, each measuring 10 m on a side, with a 3 m border between them. The plots have an average of 20 herbs.

2.6 Effect of applying yerba mate waste (YMR) on soil agrochemical characteristics

Soil samples were collected after 60, 90, 120, 150, 180, and 210th days just after one YMR application, with two composite samples for each experimental plot. They consisted of 20 subsamples for the surface layer, from 0-10 cm, and for the subsurface layer, from 10-20 cm. The methodology used was the same as previously reported for the prior characterization of soil agrochemical components.

2.7 Effect of the application of tea yerba mate waste (YMR) on the chemical characteristics of the leaves and the growth of the herb tree

Plant samples were taken seven months after the treatments applied to evaluate leaf nutrition, dry mass production of herbs, and plant growth. Leaf nutrition analysis was conducted for N, P, K, Ca, and Mg (MALAVOLTA; VITTI; OLIVEIRA; 1997). Fourteen leaves per herb tree were removed from the lower, middle, and upper thirds of six central herb trees in each plot, totaling 84 leaves per plot. The dry mass of a set of ten leaves per plot was determined after drying the leaves in an oven with forced air circulation at 70°C until constant mass. The effect of different dosages on branch growth was conducted by collecting twelve branches from six central herb trees in each plot to determine their length in a straight line (MALAVOLTA; VITTI; OLIVEIRA; 1997).

2.8 Statistical analysis

Data dispersion was assessed through analysis of variance, and means were compared using Tukey's test (both at $p < 0.05$). For prediction purposes, simple linear regression analysis was performed, selecting a significant ($p < 0.01$) higher-order model with a high coefficient of determination. The analyses were conducted using the ASSISTAT 7.6 beta program (ASSISTAT, 2011).

3 Results and discussion

3.1 Characterization of Yerba Mate Waste as an additive

Technical visits revealed that the company in Paraná revealed that 310 t of yerba mate waste (YMR) were generated per month in the early 2010s. YMR is also generated in homes and bars and is universally considered non-toxic waste. On the other hand, some toxic elements were reported in yerba mate (ULBRICH et al., 2022) and the absence of arsenic, cadmium, lead, and chromium was confirmed as it is a solid industrial waste. Thus, YMR was considered a non-hazardous and non-stable waste, due to its biodegradability (ABNT, 2004).

In addition to water, oxygen, and carbon dioxide, plants require 14 essential elements for all plants. Some elements are needed in larger quantities (41,000 $mg.kg^{-1}$ dry base), called macroelements, such as nitrogen (N), phosphorus (P), potassium (K), calcium (Ca), sulfur (S), and magnesium (Mg). Others are demanded in smaller quantities (<100 $mg.kg^{-1}$), micronutrients, or trace elements. For example, chlorine (Cl), iron (Fe), boron (B), nickel (Ni), copper (Cu), manganese (Mn), zinc (Zn) and molybdenum (Mo).YMR agricultural recycling was considered a good option due to the presence of nutrients such as sulfur and boron (Table 2) and micronutrients such as magnesium, calcium, copper, iron, manganese, sodium, and zinc (Table 3-4). YMR was predominantly organic matter (Table 2), but also a source of minerals (1.63%) that can be leached (1.36%) and are essential for plant development. This qualifies YMR as a good material for agricultural recycling by composting on-site and without human intervention, but it may take several weeks (WANG et al., 2024) or possibly pre-treatment by vermicomposting to improve the properties for plant development (SAIDELLES; REINERT; SALET, 2003), a topic that deserves further investigation in future studies. Several elements (Table 2-4) were determined in YMR and in the soil to study the agricultural recycling of this industrial waste (MENGEL et al., 2001).

The YMR had high humidity (66.03%) and low density (0.53 g/cm^3) (Table 2), which negatively affects the economic demand for equipment and costs with installation, material, installation, transportation, employee, energy consumption, land, and landscaping (HASSANPOUR, 2021). However, it can contribute to biodegradation through composting and minimizing greenhouse gas emissions (WANG et al., 2024), and moisture retention in the soil (SHARMA et al., 2010). The pH of the YMR is slightly acidic (6.0), and the C/P ratio (407) is greater than 200, which favors the immobilization of P (RAIJ, 1991). The C/N ratio of YMR (21) was intermediate to *that* of other agricultural products (Table 3), being lower for alfalfa hay (13) and higher for straw (74). A C/N ratio below 40 favors nitrogen mineralization (KAVDIR; KILLI, 2008), that is, YMR makes nitrogen available through agricultural recycling. Furthermore, alfalfa hay is primarily used for animal feed due to its greater nutritional value, which makes its use for agricultural recycling unlikely. In this context, various residues from agriculture, agro-industry, and sewage sludge have been reported as a source of elements that can improve the quality of agricultural soil, with the potential disposal of N, P, and K being highlighted. It should also be noted that fecal and fecal waste can be potentially toxic, especially for operators. So, the C/N ratio of sewage sludge (9) is even lower (Table 3). It is also rich in P. Sewage sludge also contains pathogenic agents and requires a liming process, which makes it more expensive as a soil improver, which causes controversy. between researchers and technical staff (AWASTHI et al., 2016). Furthermore, the conditioning of aerobic biodigestion sewage sludge conditioned with $FeCl_3$ and $Ca(OH)_2$ for dewatering in the final phase makes it rich in these minerals (GUEDES et al., 2006). Similarly, applying animal manure as a soil improver due to N and P is also not well accepted due to food biosecurity, which can be remedied by composting techniques (SAIDELLES, REINERT & SALET, 2003).

Table 2: Agronomic characterization of yerba mate residue (YMR) applied to the soil.

Parameter	Content on a dry basis
Total organic matter (combustion) (%)	95.20
Compostable organic matter (%)	76.77
Total carbon (organic and mineral) (%)	52.90
Organic carbon (%)	42.66
Total mineral residue (minerals) (%)	4.80
Soluble mineral residue (%)	4.00
C/N ratio (total C and N)	21/1
C/N ratio (organic C and N)	17/1
Total sulfur (S) (%)	0.18
Total boron (B) ($mg.kg^{-1}$)	32

Source: The Authors

The levels of N, Mg, and K suggest a loss of these elements in the preparation of tea extract, which is not possible to say for P and for Ca (Table 3). In general, these results can be attributed to the potential incorporation of N and P into cellular biomolecules, as well as the lower solubility of calcium salts and their stronger interactions with the cell wall than Mg and K (GIULIAN et. al., 2007). Thus, the process of preparing yerba mate extract enriches some components in the YMR due to low solubilization in water and depletes in the YMR those that will make up the tea extract, such as K and Mg, which confirms the previous report (ULBRICH et al., 2022). Even so, YMR recycling can potentially minimize the export of all elements. Thus, the elevated levels of Mn, Fe, Zn, and Cu in YMR (Table 4) were predictable due to their presence in complex biomolecules, and the transfer of the element does not always occur to water at 100ºC (ULBRICH et al., 2022), and unexpectedly higher levels of Na were also observed in YMR. In the latter case, it was expected to be lower due to its solubilization as a component of the tea extract.

Table 3: Macroelements (%, dry basis) present in Yerba Mate Residue (YMR) and reported in yerba mate leaves, agricultural residues, sewage sludge and livestock residues.

Matrix	C	N	P	K	Mg	Ca
			(%)			
Yerba mate leaf*[1]	nr	2.21	0.11	1.04	0.88	1.24
Yerba mate leaf*[2]	nr	5.21	0.06	1.72	0.65	0.61
Yerba mate leaf*[3]	nr	nr	nr	nr	nr	0.75
Yerba mate leaf*[4]	nr	2.74	0.12	0.83	0.28	0.89
	nr	2.04	0.11	0.80	0.91	1.10
Average in yerba mate leaves	**nr**	**3.39**	**0.10**	**1.20**	**0.60**	**0.87**
Yerba mate residue (YMR) *[5]	**52.9**	**2.50**	**0.13**	**0.54**	**0.50**	**1.59**
Alfalfa hay *[6]	40	3	nr	nr	nr	nr
Oat Straw *[6]	37	0.5	nr	nr	nr	nr
Sewage sludge *[7]	17.2	1.87	0.94	0.20	0.38	8.64
Goat manure *[8]	nr	3.23	0.55	4.8	nr	nr
Chicken manure [#*9]	nr	2-4	1-1.5	1-1.5	nr	nr
Chicken litter [#*10]	nr	1.56	6.59	2.51	nr	nr
Cattle manure [#*9]	nr	0.5-0.6	0.15	0.6	nr	nr
Liquid pig manure [#*9]	nr	0.3-0.6	0.1	0.2	nr	nr
Bovine manure vermicompost *[10]	nr	0.88	0.37	0.55	0.27	0.55

Source: Adapted from 10 searches. *[1] average of the different samples of the five types of treatment (which did not present significant differences at $p<0.05$) in Fernandes Pinheiro, Paraná, LOURENÇO et al., 1997. *[2] eight-year-old herb in Catanduva, Santa Catarina, BORSOI; COSTA, 2001. *[3] herbal of twenty years, PAGLIOSA et al., 2010. *[4] eight-year-old herb in União da Vitória and Paula Freitas, VALDUGA et al., 1997. *[5] YMR, this research.*[6] TROEH; THOMPSON, 1993 ;*[7] GUEDES et al., 2006; *[8] SILVA; MENEZES, 2007; *[9] WILD, 1993; *[10] BENEDETTI et al., 2017; *[11] SAIDELLES; REINERT; SALET, 2003; nd = not determined in this study. nr = not reported. [#] = wet base

Table 4: Microelements ($mg.kg^{-1}$, dry basis) present in Yerba Mate Residue (YMR) and reported in yerba mate leaves.

Matrix	Zn	Fe	Cu	Na	Mn
Yerba mate leaf*[1]	37.9	113.2	14.66	50.52	219.9
Yerba mate leaf*[2]	30.1	19.8	9.5	92.3	192.9
Yerba Mate Residue (YMR) *[3]	**144**	**527**	**15**	**533**	**1728**

Source: Adapted from 10 searches. *[1] eight-year-old herb in Catanduva, Santa Catarina (BORSOI; COSTA, 2001). *[2] herbal of twenty years (PAGLIOSA et al., 2010). *[3] Contents in applied industrial solid waste (YMR).

3.2 Principle of application of the dose of Yerba Mate Waste (YMR)

Mulching with vegetative materials is a highly beneficial and widely investigated agricultural technique in rainfed areas, but adoption of this practice has been limited due to the local non-availability of mulch biomass (SHARMA et al., 2010). The absence of toxic compounds, the availability of macro and microelements required by vegetables, their inherent C/N ratio, etc. makes agricultural recycling of YMR a good option for the sustainable management of this industrial waste. The amount to be added can be different, such as proportional to the source of the raw material, applying only a fraction to replace the fraction of an exported macroelement, etc. This study chose to reintroduce the N demand recommended by the "Comissão de Química e Fertilidade do Solo" (CQFS, 2004). Consequently, this recycling would also provide 40% more of the P recommendation and only 62% of the K recommendation due to the composition of YMR (T-N%/P_2O_5%/K_2O% = T3-100/140/62). The absence of toxic compounds, the availability of macro and microelements required by vegetables, their inherent C/N ratio, etc. makes agricultural recycling of YMR a good option for the sustainable management of this industrial waste. The amount to be added can be different, such as proportional to the source of the raw material, applying only a fraction to replace the fraction of an exported macroelement, etc. This study chose to reintroduce the amount of YMR (Table 1, 28.2 $t.ha^{-1}$) that would suppress the N demand recommended by the CQFS RS/SC (CQFS, 2004). Consequently, this recycling would also provide 40% more of the P recommendation and only 62% of the K recommendation due to the composition of YMR (T-N%/P_2O_5%/K_2O% = T3-100/140/62). It is noteworthy that soils containing elevated levels of these two elements prevent pest attacks (BORSOI; COSTA, 2001). Thus, two treatments (T4 and T5) were made to make more components available than recommended, one less than recommended (T2) for all components, and a control group (T1) to better understand the cause-effect relationships.

3.3 Chemical properties of the soil after yerba mate waste (YMR) application

Despite the high potential for the reintroduction of nutrients through YMR agricultural recycling, the wide dispersion of results did not even allow us to prove this phenomenon (Table 5). There was no significant change ($p < 0.05$) in soil acidity after application of YMR over 60, 90, 120, 150, 180, or 210 days, with average values varying between 3.76 and 3.83. This stability can be attributed to the high buffering capacity of the receiving soil. Likewise, organic residues from pruning in gardens and parks also failed to increase the pH of forest soil (BAUHUS; MEIWES, 1994). Changes in pH have been associated with waste containing carbonates and bicarbonates, such as cattle manure (BARCELLOS et al., 2015) and alkalized sewage sludge (AWASTHI et al., 2016), highlighting the potential of these wastes as a preferred option, which should also be considered in terms of biosafety (SAIDELLES; REINERT; SALET, 2003).

Table 5: Chemical properties of the soil of yerba mate planting after 210 days in the superficial (0-10 cm) and subsurface (10-20 cm) layers with a single application (14.1, 28.2, 56.4 or 84.6 t.ha^{-1}) or not (0.0 t.ha^{-1}) of Tea Residue (YMR)

Parameter	Receiving soil	Layer 0-10cm*	Layer 10-20cm*
pH	3.94	3.83±0.09	3.76±0.09
Ca, cmol$_c$.dm^{-3}	0.68	0.80±0.24	0.34±0.17
Mg, cmol$_c$.dm^{-3}	0.46	0.70±0.22	0.26±0.11
K, cmol$_c$.dm^{-3}	0.10	0.14±0.03	0.11±0.02
P, mg.dm^{-3}	2.02	1.34±0.48	0.96±0.39
Na, cmol$_c$.dm^{-3}	nd	0.02±0.01	0.03±0.01
Al, cmol$_c$.dm^{-3}	3.78	3.41±0.36	3.97±0.32
EC, µS.cm^{-1}	nd	57.45±9.07	51.75±8.56

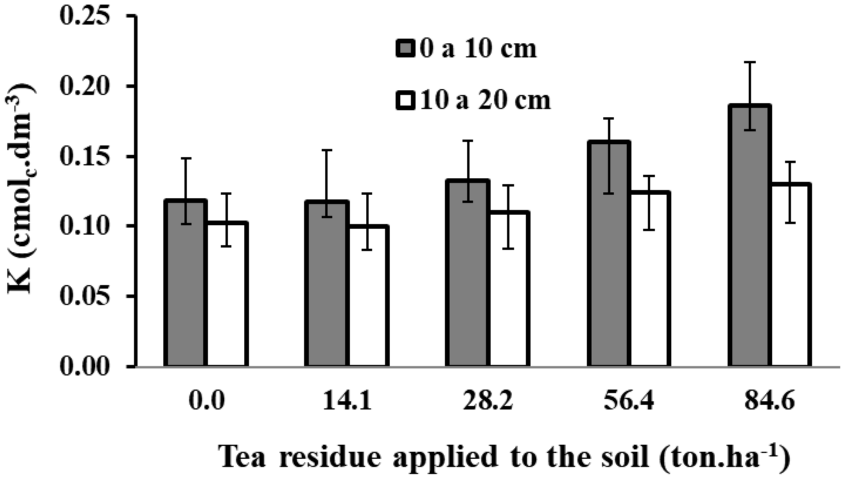
Source: The Authors. * Average ± standard deviation; n=5. nd = not determined

Despite the high Ca content in YMR, there were no changes ($p < 0.05$) in the availability of calcium (Ca) and magnesium (Mg) in the soil. In the case of Ca, its slow release can be attributed to retention by the cell wall and the low solubility of Ca in hot or chilly water (BARBOSA et al., 2015). This is corroborated by the increase in availability associated with the reduction in the size of ground forest residues (0-7 mm), which allows relevant release within 56 and 42 days. Therefore, there is an inverse relationship between the size of organic fractions and the release of nutrients (REICHERT et al., 2015), which would be favorable to the reduced size of YMR particles, and which makes the observed behavior more intriguing. It is noteworthy that a huge portion of Ca remained retained in the organic matrix and was not released into the soil for up to 210 days, requiring further research. Mg concentrations were comparable to those reported for the application of swine manure and municipal solid waste compost, which were 0.52 and 0.47 cmolc.dm^{-3}, respectively (NOBILE; GALBIATTI; MURAISHI, 2012).

Despite the possible low availability of K in YMR due to its incorporation into hot water (ULBRICH et al., 2022), the availability of K in the soil was directly proportional to the doses applied and was observed in both layers evaluated (Figure 1), confirming the high mobility of K in the soil (TROEH; THOMPSON, 1993). This proves the ease of releasing K, with extraction from biomatrix reaching up to 90% with the action of water alone (BARBOSA et al., 2015; GIULIAN et al., 2007). Field studies conducted under different conditions and with different organic residues also demonstrate the rapid release of K (BAUHUS; MEIWES, 1994; TALGRE et al., 2014; ASSMANN et al., 2014; MACHADO et al., 2016; REICHERT et al., 2015). In the present study, the cumulative effect of K release and retention in the soil resulted in significant differences ($p < 0.05$) observed 90 days after

YMR application. It is noteworthy that periods and intensities of rain were not monitored, which needs to be conducted in future studies as ions with high solubility could be lost. Significant mathematical models ($p < 0.01$) were determined with good coefficients of determination for predicting K concentrations as a function of residue doses ($kg.ha^{-1}$) in the 0-10 cm and 10-20 cm layers: $\hat{Y} = 9.10^{-4}.x + 0.1112$ and $R^2 = 0.97$, and $\hat{Y} = 4.10^{-4}.x + 0.0991$ and $R^2 = 0.92$, respectively. Furthermore, the surface layer showed higher K contents and a more positive response to recycling (Figure 1), despite precipitation and elevated temperatures, which facilitate the release of K from the YMR but also promote diffusion to deeper layers.

Figure 1: Potassium in the soil of yerba mate planting after 210 days in the superficial (0-10 cm) and subsurface (10-20 cm) layers with a single application (14.1, 28.2, 56.4 or 84.6 $t.ha^{-1}$) or not (0.0 $t.ha^{-1}$) of Tea Residue (YMR).



Source: The Authors.

The loss of P to hot water during extract preparation is not as large as K, but it is very relevant (ULBRICH et al., 2022), which could also limit its availability to up to 210 days. There was no increase ($p > 0.05$) in P availability in the soil (Figure 2), even with application rates higher than recommendations (Table 1) due to N being the calculation basis (reference). This can be attributed to the multifactorial processes of microbial activity, mineralization occurrences, and immobilization (HEDLEY; STEWART; CHAUHAN, 1982). For example, this phenomenon depends on the C/P ratio, with the ratio for YMR being greater than 300/1 should favor P immobilization (HEDLEY; STEWART; CHAUHAN, 1982). In this scenario, P from YMR and P from soil are used in microbial growth and incorporation of P into organic compounds, which would potentially make free P available at some point.

Furthermore, the apparent inefficiency of agricultural recycling using YMR to increase the availability of P in the soil (Figure 2) may also be due to the highly weathered nature of the latosol and its high specific P adsorption capacity, reducing the availability of free P (NOVAIS; SMYTH, 1999). Furthermore, the abundance of exchangeable aluminum in acidic environments such as Oxisols leads to a high phosphate (P-Al) supply capacity, further limiting changes in available P concentration. Therefore, the absence of changes ($p > 0.05$) in P availability only with one application of YMR during the evaluated period can also be attributed to the characteristics of the scarcity itself (for example, low P concentration and high C/P ratio) and soil properties (high adsorption capacity and P variation depending on the degree of weathering and exchangeable Al content, respectively) (ASOMANING, 2020).

From an agricultural point of view, the failure to make P available in the soil would inhibit the YMR recommendation if it were this only action. However, it suggests a low eutrophication potential compared to confined residues (BARCELLOS et al., 2015), which could help maintain underground soil moisture. It is noteworthy that the suboptimal availability of P was also related to other organic residues. For example, Reissmann, Radomski & Quadros (1999) reported P concentrations varying between 3.1 and 6.4 mg.dm^{-3} in plants after application of organic fertilizer, including extremely low ones according to SOIL FERTILITY COMMISSION-RS/SC (2004). This reinforces the recommendation for the application of manure containing 7.6 g of P kg^{-1} (dry basis) in the proportion of 129 kg of P ha^{-1} (EGHBALL et al., 2002), despite biosafety restrictions (SAIDELLES; REINERT; SALET, 2003), due to its higher P content (Table 4).

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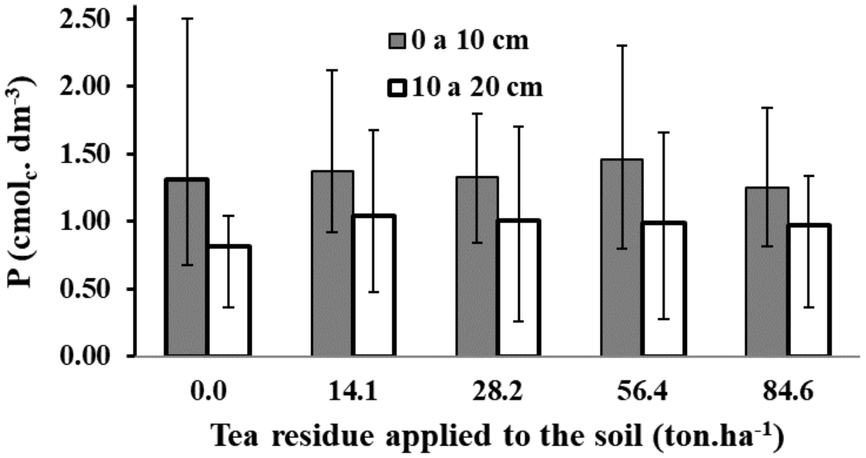
Figure 2: Phosphor in the soil of yerba mate planting after 210 days in the superficial (0-10 cm) and subsurface (10-20 cm) layers with a single application (14.1, 28.2, 56.4 or 84.6 t.ha^{-1}) or not (0.0 t.ha^{-1}) of Tea Residue (YMR).



Source: The Authors

The increase in sodium (Na) availability in the soil of the yerba mate plantation was also not significant ($p > 0.05$) between the periods and layers evaluated. The average sodium content varied between 0.021 and 0.026 cmolc.dm^{-3}, considered low despite its abundance in the residue (181 mg.kg^{-1} or 533 mg.kg^{-1} on a dry basis). However, other studies observed an increase in Na content after the application of animal or industrial waste (lime mud) (AWASTHI et al., 2016). However, like K, the conditions of the study area facilitated its dispersion, although to a more intense degree.

Electrical conductivity (EC) remained unchanged ($p < 0.05$) and remained between the threshold of non-saline (<1100 mS.m^{-1}) and slightly saline (SMITH; DORAN, 1996). This is in line with the low presence of exchangeable cations (Ca, Mg, K, and Na) in the soil. This finding is advantageous for industrial waste management, as YMR would not induce harmful saline effects, even at high doses. The apparent failure for some elements may be due to the demand of several weeks for the processes involved (WANG et al., 2024), which needs to be efficient with similar experiments, but with longer follow-up time.

3.4 Macronutrients in leaf and plant growth

Macronutrient levels in leaves and plant growth of all five treatment types for nitrogen (N), phosphorus (P), potassium (K), magnesium (Mg), and calcium (Ca) (Table 6) were like other studies (VALDUGA et al., 1997; PAGLIOSA et al., 2010). Similarly, the application of YMR did not alter ($p < 0.05$) the production of leaf mass and branch length. Although the evaluation period was shorter (6 months) than in previous studies (18 to 24 months), the outlook remains promising.

Table 6: N, P, K, Ca, Mg in the leaves, dry mass, and average branch size after 210 days with a single application (14.1, 28.2, 56.4 or 84.6 t.ha^{-1}) or not (0.0 t.ha^{-1}) of Tea Residue (YMR).

	Treatment (t.ha^{-1})				
Parameters	T1 (0)	T2 (14.1)	T3 (28.2)	T4 (56.4)	T5 (84.6)
N on the leaf (g.kg^{-1})*	22.22±1.48^{a}	22.12±1.58^{a}	21.89±1.84^{a}	22.44±1.33^{a}	21.60±1.93^{a}
P on the leaf (g.kg^{-1})*	1.10±0.20^{a}	1.01±0.19^{a}	1.15±0.20^{a}	1.15±0.26^{a}	1.11±0.06^{a}
K on the leaf (g.kg^{-1})*	9.10±2.56^{a}	11.13±1.21^{a}	9.13±1.60^{a}	11.63±2.39^{a}	11.13±2.57^{a}
Ca on the leaf (g.kg^{-1})*	11.3±0.98^{a}	11.22±2.22^{a}	13.85±2.26^{a}	13.39±1.83^{a}	12.38±2.08^{a}
Mg on the leaf (g.kg^{-1})*	9.62±2.37^{a}	7.40±1.88^{a}	10.13±2.92^{a}	8.02±1.40^{a}	8.73±2.48^{a}
Dry mass (g.10 leaves^{-1})*	4.88±1.41^{a}	5.95±1.65^{a}	5.22±1.92^{a}	5.24±0.80^{a}	5.36±1.26^{a}
Average branch size (cm)*	56.4±10.20^{a}	60.70±6.83^{a}	61.0±8.05^{a}	68.20±10.48^{a}	59.10±8.08^{a}

Source: The Authors. T-N%/P_2O_5%/K_2O%: T1-0/0/0, T2-50/70/31, T3-100/140/62, T4-200/280/124 and T5-300/420/186. * Mean ± standard deviation. Equal letters do not differ statistically using the Tukey test at 5% probability.

In 120 days, the applied YMR was a source of K and did not have a significant impact on soil acidity nor did it serve as a substantial source of additional nutrients in layers of up to 20 cm of soil. This suggests that YMR can be applied in enormous quantities without causing damage to the receptor system. In this sense, YMR recycling can minimize costs and landfill demands for organic industrial waste following future compliance regulations based on European Union standards (EU, 1999), a potential buyer of extract-based beverages of yerba mate (MÉNDEZ, 2023). Its use in agriculture does not pose risks to human health and can minimize soil impoverishment in yerba mate forests owned by small producers. (ULBRICH et al., 2022).

4 Conclusions

Yerba Mate Waste (YMR) is a waste from the food industry that was classified as non-hazardous and non-inert waste. It presents physicochemical characteristics suitable for application in agricultural recycling, such as the presence of several macro and microelements useful for the development of the plant. The soil of the yerba mate plantation that received agricultural recycling with YMR revealed low fertility and the agricultural recycling of YMR can make P, N, K, Mn, Fe, Zn, etc. available for better plant production.

After applying YMR for 210 days, no variations in pH, electrical conductivity, or phosphorus, calcium, magnesium, and aluminum levels were observed in the surface and subsurface layers. Agricultural recycling with YMR did not cause adverse effects on soil or plants, even at high doses of YMR. Two treatments showed significantly higher sodium concentrations in the soil than in the region without treatment. However, these concentrations were low and posed no risk to the soil or herbs. On the surface and subsurface, an increase in K content was observed proportional to the doses of YMR applied.

The application of YMR did not alter the growth of yerba mate trees, the production of vegetable mass, and the N, P, K, Ca, and Mg contents in the yerba mate leaf, which can be attributed to the natural reserve of these components and the multifactorial process of bioavailability to quickly alter the 28-year-old plant.

Thus, YMR recycling minimizes the unnecessary export of nutrients from the soil with simple environmental management. It makes K available in the soil within 210 days and will potentially make other elements available over a longer period, after severe biodegradation of the YMR tissues. YMR agricultural recycling can reintroduce essential elements exported through plant processing for tea extract production, minimize greenhouse gas emissions, avoid inappropriate treatment or disposal, and avoid the use of other unsustainable options. In this context, the 3,720 t of YMR per year could be used on 132 hectares according to the estimate of replacing 100% of the recommended N. Complementary studies are necessary to confirm all the benefits of YMR recycling for environmentally and economically sustainable agricultural production, especially for small producers.

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