



USE OF VINASSE IN FERTIGATION: A REVIEW

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ABSTRACT

Vinasse is a liquid effluent generated as by-product of the fractional distillation of fermented sugarcane juice during ethanol production. When properly managed, vinasse can be used in fertigation, offering significant benefits to agricultural production. This review aims to evaluate the effects of vinasse application on fertigated crops and soil quality. This exploratory study involved a literature review of scientific articles and books using the keywords “fertigation” and “vinasse”. When applied as a fertilizer, vinasse can positively influence the physical, chemical and biological properties of soil. The results indicated that vinasse contains essential nutrients that contribute to plant growth. To support its appropriate application, a general equation for calculating the fertigation rate is also presented. The Vinasse Application Plan should include a descriptive report outlining the fertility characteristics of both the soil and the vinasse, along with the calculated application rate. Literature indicates that the use of irrigation equipment for vinasse fertigation in sugarcane cultivation is a technically and economically viable practice. When applied judiciously, this strategy supports the sustainable management of vinasse while minimizing potential environmental impacts.

Palavras-chave:

Água residuária
Reuso
Solo
Irrigação mecanizada

USO DA VINHAÇA NA FERTIRRIGAÇÃO: UMA REVISÃO

RESUMO

A vinhaça é o efluente gerado na destilação fracionada do mosto fermentado obtido no processamento da cana-de-açúcar. Se manejada de forma correta, a vinhaça pode ser utilizada na fertirrigação, trazendo benefícios ao setor agrícola. Nesta revisão teve-se como objetivo abordar os efeitos da vinhaça nas culturas fertirrigadas e na qualidade do solo. A pesquisa é de natureza exploratória, onde foram pesquisados artigos, livros com os assuntos relacionados: “fertirrigação” e “vinhaça”. A vinhaça, sendo utilizada como fertilizante, pode proporcionar efeitos benéficos nas propriedades físicas, químicas e biológicas do solo. Os resultados indicaram que a vinhaça apresenta elementos fundamentais para promover o crescimento das plantas. Apresenta-se uma equação geral para cálculo da lâmina de fertirrigação. O Plano de Aplicação de Vinhaça no solo deve ser constituído de memorial descritivo da prática de aplicação pretendida, contendo os resultados da caracterização de fertilidade do solo e da vinhaça e a dosagem de aplicação calculada. A literatura sobre o assunto mostra que há viabilidade de implantação de equipamentos de irrigação para aplicação de fertirrigação nos canais, prática que se adotada com critério, contribui para um destino apropriado da vinhaça sem afetar o ambiente.

INTRODUCTION

Brazil is the world's largest sugarcane producer and the second-largest ethanol manufacturer, with the sugar and alcohol industry contributing significantly to the country's economy (Lebron *et al.*, 2020). Ethanol production by fermentation, generates a dark brown liquid, commonly referred to as vinasse, “vinhoto”, “restilo” or “tiborna”. This wastewater is noteworthy for its high concentration of organic matter, which can be up to 100 times greater than that found in sanitary sewage (Fues 2014, Pina *et al.*, 2017 and Silva *et al.*, 2020). In addition, this residue contain elevate concentrations of nutrients - particularly potassium - and exhibit acidic characteristics. Consequently, vinasse may pose a significant polluting potential (Hoarau *et al.*, 2018; Madaleno *et al.*, 2020), especially when inappropriately or unevenly applied.

Vinasse, when properly managed and applied, can be beneficial for soil fertility and microbial activity, as well as for crop development (Silva; Campos 2010; Moraes; Costa 2021). According to Padovan (2021), its use in the agriculture, especially in sugarcane cultivation, provides clear benefits for the agronomic, economic and social sectors. Thus, this residue offers an opportunity to reduce mineral fertilizers costs while promoting more sustainable agricultural practices. Fertigation with vinasse constitutes an alternative that enables the rational use of natural resources, prevents its disposal into water bodies, and contributes to soil fertilization (Padovan 2021). However, it is crucial to evaluate its toxicity before recycling it as a fertilizer, since excessive nutrient levels can negatively impact crop health (Rulli *et al.*, 2020), as well as soil and groundwater quality. Therefore, it is essential to follow technically defined annual application rates to enable a legally compliant and economically viable reuse of this residue (Mosse *et al.*, 2012).

The application of vinasse is referred to as “fertigation”, as it involves the delivery of both nutrients (predominantly) and water to the crop. Vinasse can be applied “in natura”, after dilution (typically with water used in the industrial process) or following anaerobic treatment, which enables the

recovery of additional resources, such as methane, a valuable energy source. In Brazil, the majority of vinasse is recycled directly through fertigation.

In this context, the main objective of this review was to evaluate the effects of vinasse on soil quality, to examine its impacts on crops fertigated with vinasse, and to provide an overview of this reuse practice in Brazil.

MATERIAL AND METHODS

The research was exploratory in nature and included articles and books related to “fertigation” and “vinasse”. The literature search was conducted using Google Scholar, Scopus and Web of Science platforms, in addition to digital repositories of theses and dissertations from Brazilian universities. More than 100 bibliographic sources were identified during the search. Among these, 45 were cited in this study, including 25 articles published in international journals, 8 articles in national journals, 3 books, 1 master's thesis, 5 communications presented at journals, conferences or similar events, and 3 state laws.

RESULTS AND DISCUSSION

Effects of vinasse on soil quality

The effects of vinasse application on soil depend on several factors, including the quantity and quality of the wastewater, soil chemical composition, regional topography, the crop to be fertigated, and other conditions involved in the process (Silva, 2007).

Vinasse application via fertigation can positively influence the physical, chemical, and biological properties of the soil (Prado *et al.*, 2013; Santos *et al.*, 2020).

The mean characteristics of sugarcane vinasse, highlighting its high content of organic matter and nutrients, as well as its widespread use as a fertilizer — particularly through fertigation — are presented in Table 1.

Fertigation with vinasse is common in sugarcane-growing regions, as it has shown promising results in increasing the concentration of nutrients such as potassium, calcium, magnesium, as well as enhancing soil organic matter (Bebé *et al.*, 2009).

Table 1. Characteristics of sugarcane vinasse

Variable	Approximate mean value
pH	4.5 a 5.5
COD (Chemical Oxygen Demand)	30000 a 50000 mg L ⁻¹
BOD (Biochemical Oxygen Demand)	15000 a 25000 mg L ⁻¹
Total organic matter	15000 a 30000 mg L ⁻¹
Potassium (K)	1500 a 2500 mg L ⁻¹
Phosphorus (P)	50 a 200 mg L ⁻¹
Total nitrogen (N)	400 a 1000 mg L ⁻¹
Organic load	20 a 40 kg m ⁻³
Electrical conductivity	6 a 12 dS m ⁻¹
Total solids	20000 a 30000 mg L ⁻¹
Suspended solids	500 a 1500 mg L ⁻¹
Temperature (when newly generated)	60 a 80 °C

Source: Adapted from Moraes et al., 2015 and Condori et al., 2025

Further studies by the same authors demonstrated that fertigation using this residue did not alter soil pH over time and consistently increased potassium concentration at all soil depths where fertigation was applied. According to Paulino *et al.* (2011), the higher content of available potassium supplied by vinasse contributed to increased sugarcane productivity, and sucrose accumulation in the stalks.

According to Santos *et al.* (2020), fertigation with vinasse contributed to increasing the soil organic matter content, in addition to enhancing the concentration of various nutrients, especially potassium. The organic matter present in vinasse, when incorporated into the soil, is metabolized by fungi and bacteria, which transform it into humus and help neutralize soil acidity, thereby providing favorable conditions for microbial survival. Consequently, the addition of vinasse stimulates the activity of these microorganisms, which are involved in nitrogen mineralization and immobilization, as well as nitrification, denitrification and biological nitrogen fixation (Silva *et al.*, 2007). However, the rapid increase in soil organic matter may exacerbate oxygen consumption, thereby promoting the formation of anaerobic regions and reducing the soil oxidation-reduction potential (Brito *et al.*, 2009).

Vinasse also alters soil porosity and specific mass, properties closely related to soil compaction. The formation of larger aggregates improves soil aeration and enhances the availability of nutrients

and organic matter for crops (Jiang *et al.*, 2012). Zolim *et al.* (2011) reported that initial vinasse application increased total organic carbon content, positively affecting soil specific mass, porosity and cation exchange capacity. Silva *et al.* (2014) found that calcium and magnesium oxides present in vinasse may help reduce soil acidity, while its elements such as Ca, Mg and K contribute to raising soil pH by diluting H⁺ ions. Conversely, Orlando Filho (1981) observed no significant improvements in soil fertility, pH, or cation availability following vinasse use. However, the author suggested that its application could increase the labile inorganic phosphorus pool, potentially reducing the need for phosphate fertilizer over time.

When applied in excess to soil, vinasse — and particularly some of its constituent compounds — may leach into groundwater sources. Nitrate is the primary concern due to its high mobility in soil and its potential to compromise groundwater quality. This anion, formed through the oxidation of reduced nitrogen compounds, can migrate downward, increasing contamination risks. According to the Senar bulletin (2019), continuous vinasse application may exacerbate this process by promoting an excess of potassium, which further facilitates anion leaching. This phenomenon highlights the importance of proper fertigation management to prevent groundwater pollution globally.

On the other hand, Silva *et al.* (2021) reported that the compounds identified in soil and

groundwater were not directly related to vinasse application or its degradation products. The authors further emphasized that the primary sources of soil and groundwater contamination are likely linked to modern agricultural practices, since most of the substances detected are commonly used as agrochemicals.

The development of alternative disposal methods for vinasse is essential to overcome the problems associated with its increasing accumulation (Tiburcio, 2022). This accumulation, in turn, may pose significant environmental risks if vinasse is inappropriately applied to soil (Leite *et al.*, 2024), thereby affecting both soil and water quality (Silva *et al.*, 2021). There is growing concern regarding the environmental impacts resulting from the direct application of vinasse to soil, including salinization, aquifer contamination, oxygen depletion, acidification, and the accumulation of nitrates, chlorides and heavy metals, such as lead and zinc (Leite *et al.*, 2024).

Vinasse in agricultural crops: preservation of water resources and use of fertilizer potential

According to the results of the “Irrigation Atlas” (ANA, 2017), irrigation in Brazil accounts for the withdrawal of 969 m³ s⁻¹ and the consumption of 745 m³ s⁻¹. Considering the other consumptive uses surveyed by ANA, these values correspond to 46% of total withdrawal (2,105 m³ s⁻¹) and 67% of the total consumption flow (1,110 m³ s⁻¹). Therefore, it is essential to identify and implement alternative irrigation strategies that promote more efficient water use and contribute to greater sustainability in agricultural production. One viable alternative is the application of vinasse through fertigation, since this approach can provide additional water and nutrients, thereby improving soil quality and crop productivity (Prado *et al.*, 2013).

Oliveira *et al.* (2020) evaluated the economic viability of implementing fertigation and found that the return on investment could be achieved in less than seven years. These findings indicate that applying vinasse through central pivot systems is an effective strategy for enhancing sugarcane productivity, while also providing a sustainable method for its disposal, assuming proper management practices in place. Furthermore,

vinasse application can improve soil ecological conditions and promote plant growth, as it contains minerals, amino acids, crude fiber, and a variety of microorganisms. Additionally, vinasse offers the advantages of low cost and ease of availability (Peng *et al.*, 2016; Ma *et al.*, 2020).

Studies performed by Ma *et al.* (2020), using *Acorus calamus* demonstrated that vinasse, at appropriate concentrations, can promote the formation of iron plaques on the surface of plant roots. This process occurs due to the high heavy metals concentrations in vinasse and the ability of *A. calamus* to remove elements such as lead, zinc, and copper. The results further indicated that vinasse contains essential elements for plant growth, such as carbon, potassium, magnesium, and oxygen.

Barbosa *et al.* (2012) demonstrated that sugarcane fertigated with vinasse was able to meet the crop’s potassium requirement when using subsurface drip irrigation, in addition to promoting greater stalk production compared to the non-fertigated treatment. The authors further reported that the theoretical yield of recoverable sugar was enhanced by applying higher dosages of vinasse.

Paraletti *et al.* (2015) found that potassium contributed to improving the biometric characteristics of basil crop when concentrated vinasse was applied. Prado *et al.* (2014) also reported that soil potassium and organic matter levels increased in response to vinasse application, which was positively correlated with sugarcane productivity. Despite the beneficial effects, high vinasse concentrations can lead to an increase in soil salts and organic compounds, thereby posing a risk of inhibiting plant growth, altering nitrogen and carbon cycles, and reducing nutrient availability to plants (Mosse *et al.*, 2012).

Limitations of practice

Fertigation remains the primary method for vinasse disposal due to its ease of application, relatively low initial investment and maintenance costs, and rapid disposal. However, applying vinasse at maximum rates may be economically unfeasible, as its high concentrations of monovalent cations — especially potassium — can negatively affect soil properties (Barros *et al.*, 2019). To

mitigate these risks, the Vinasse Application Plan should include a descriptive report detailing the intended application practices, along with the results of soil and vinasse fertility analyses and a calculated application rate (CETESB, 2015).

One direct consequence of salinization in fertigated areas is leaching, which can be monitored by analyzing the groundwater characteristics (Fues and Garcia 2014). Changes in soil properties are often related to imbalances between organic and mineral elements, promoting the leaching of ions, especially potassium and nitrate. Therefore, the dosages of each element must be determined based on soil characteristics and nutritional demands of the crop to be fertigated, in compliance with current legislation (Fernandes Filho *et al.*, 2016).

Rolim *et al.* (2013) observed an increase in groundwater potassium concentration following vinasse application, suggesting potassium saturation in the soil. Ideally, vinasse with lower potassium content should be used, as desalination can allow for higher fertigation rates without compromising environmental safety (Barros *et al.*, 2020).

The high organic load of vinasse stimulates microbial proliferation, which in turn leads to the depletion of dissolved oxygen in the water bodies. This reduction in oxygen levels can result in the death of aquatic flora and fauna, and impair the quality of the affected ecosystems. Furthermore, disposal of vinasse into water bodies generates unpleasant odors and contributes to the transmission of endemic diseases, such as malaria, amoebiasis and schistosomiasis (Christofolletti *et al.*, 2013).

If soil physical properties are severely altered, vinasse may contribute to groundwater deterioration. Additionally, rainfall following a recent and excessive application of vinasse can promote infiltration or surface runoff, thereby compromising nearby water bodies (Silva *et al.*, 2007).

Fues *et al.* (2021), who evaluated fertigation with vinasse, reported that the decomposition of organic matter from raw vinasse in soil can release up to 732.10 kg CO₂-eq ha⁻¹. The authors suggest that prior anaerobic digestion of vinasse is a promising strategy to mitigate pollution problems and enhance resource recovery in sugarcane

refineries.

Brazilian legislation on fertigation with vinasse: current practices and future trends

Calculation of application rate based on Brazilian legislation

According to Matos; Matos (2017), fertigation should be implemented by always considering the concept of a “reference chemical element” or “limiting element”. According to the authors, fertigation involves applying elements (whether nutrients or not) in quantities that can be delivered with the lowest possible dose of wastewater, thus avoiding adverse effects on soil, groundwater, and crop health. The equations established in the legal regulations of the Brazilian states governing fertigation with vinasse, generally adhere to the concept of the reference chemical element. These regulations were issued by the State Council for Environmental Policy of Minas Gerais - COPAM (2011), the State Secretariat for the Environment and Economic Development of Mato Grosso do Sul - SEMAD (2015) and the Environmental Company of the State of São Paulo - CETESB (2015). Although different notations are used in state regulations, a common formulation that respects both agricultural and environmental criteria can be outlined as follows:

$$D = \frac{[(PorT \times T \times V_{soil} \times MM) - K_{solo}] + MK_{ext}}{K_{vin}}$$

where:

D: dose of vinasse (m³ ha⁻¹); T: cation exchange capacity (CEC) (cmol_c dm⁻³); PorT: portion of T to be occupied by potassium (usually 5% or 0.05); V_{soil}: volume of soil in 1 hectare, considering the effective depth of the crop’s root system (m³ ha⁻¹); MM: molar mass of K₂O (kg cmol_c⁻¹); K_{soil}: potassium concentration in soil (cmol_c dm⁻³); MK_{ext}: K₂O extraction capacity of the crop (kg ha⁻¹); K_{vin}: K₂O concentration in vinasse (kg m⁻³).

The general equation presented above encompasses the key factors involved in the application of vinasse to agricultural soils. This “generalized” formulation allows for the fertigation of crops other than sugarcane, with a different MK_{ext} value. Furthermore, the regulations of

São Paulo and Mato Grosso do Sul consider an effective root depth of 80 centimeters, whereas the Minas Gerais standard assumes a root depth of 40 centimeters. Notably, the Minas Gerais regulation does not include the soil potassium concentration (Ksoil) in its calculation.

Although the basic equations for calculating the vinasse application rates are similar among states, variations exist in the specific parameters, constants, and additional requirements for characterizing the vinasse and preparing the application plan. These differences reflect the agricultural and environmental particularities of each region, aiming to optimize the use of vinasse as a fertilizer while minimizing its environmental impacts.

Future trends

According to the National Bioenergy Union - UDOP (2022), Brazil currently has a production capacity of 244.95 million liters per day of hydrated ethanol, representing an increase from 241.79 million liters during the same period of the previous year. For anhydrous ethanol, the maximum production capacity is 131.57 million liters per day, up from 128.92 million liters in January 2021. Currently, 356 plants are authorized to produce biofuel. Notably, all sugarcane processing plants operating in Brazil utilize vinasse for soil nutrient replenishment through irrigation. Furthermore, the number of central pivot system used for vinasse application has increased annually (ABIMAC, 2019).

Oliveira *et al.* (2021) discuss the feasibility of central pivot irrigation using reused water, thus providing an excellent alternative for water conservation and pollution reduction. Some central pivot irrigation systems have been adapted specifically for wastewater application by incorporating a PVC lining inside the galvanized steel pipes. This modification prevents corrosion by eliminating direct contact between the wastewater and the steel structure. Vinasse water, a byproduct of the fuel alcohol manufacturing process, is commonly applied in this manner. Thus, irrigation with treated wastewater represents a viable strategy for water reuse and is a valuable tool for improving river water quality, as it prevents

the direct discharge of contaminants into aquatic ecosystems (Viana *et al.*, 2022). Storing vinasse in open lagoons also poses an environmental concern, since it can contribute to water pollution and promote insect proliferation. In Brazil, fertigation may become economically unfeasible when there is shortage of available land for vinasse application, particularly when the harvested material is sourced from external suppliers or is located far from the industrial plant (SILVA *et al.*, 2018).

Ramos *et al.* (2021) highlight that vinasse can undergo anaerobic digestion prior to its use as fertilizer. They further report that applying the resulting digestate at room temperature is more appropriate for fertigation, suggesting the use of mesophilic temperature ranges during the anaerobic digestion process to achieve these conditions.

Anaerobic treatment constitutes another alternative for the appropriate management of vinasse. This process involves the degradation of organic matter by bacteria and archaea under anaerobic conditions and has been shown to reduce vinasse's oxygen demand, neutralize pH and generate biogas (Nakashima and Oliveira, 2020). Buller *et al.* (2021) concluded that replacing raw vinasse with anaerobically digested vinasse is a promising strategy for fertilizing sugarcane crops, offering both environmental and energy benefits. Additionally, vinasse can be utilized in the production of second-generation ethanol (Candido *et al.*, 2021).

An emerging approach for vinasse valorization involves its use in microalgae cultivation, with the aim of subsequently producing biofuel or even food supplements. Tasic *et al.* (2021) demonstrated that algal biomass can be successfully cultivated in biorefinery effluents. Similarly, Ramirez *et al.* (2014) reported that microalgae can be cultivated in media containing up to 40% vinasse, and that both light intensity and vinasse concentration significantly influence biomass production. Another viable, but still underexplored, option for vinasse treatment is coagulation-flocculation followed by dissolved air flotation (C/DAF) using green coagulants. These coagulants are biodegradable, do not alter the pH, generate less sludge, and are considered environmentally friendly and safe for human health (Prabhakaran *et al.*, 2020). Thus,

in addition to enabling the recovery of the sludge for use as an organic fertilizer in fertigation, this process also offers a sustainable alternative for proper management of vinasse wastewater.

Coagulation using organic and tannin-based compounds has already been applied in vinasse treatment. Lebron *et al.* (2020) evaluated the use of microfiltration (MF) and nanofiltration (NF), with and without tannin as an organic coagulant, and concluded that the MF-NF treatment sequence is economically viable for vinasse remediation. Souza *et al.* (2013) performed photocatalytic experiments under UV irradiation and observed a significant reduction in toxicity, which was consistent with the decrease in chemical oxygen demand (COD) when photocatalysis was applied after coagulation/flocculation. The coagulation/flocculation process alone achieved a 98% reduction in turbidity and an 87% reduction in color. When combined with photocatalysis, additional improvements were observed, including significant reductions in absorbance, toxicity and COD — reaching up to 80%.

CONCLUSION

- When properly managed, vinasse can serve as a valuable resource for the agricultural sector by partially replacing commercial fertilizers and reducing the demand for water abstraction from natural sources. In Brazil, sugarcane mills commonly apply vinasse through fertigation to replenish soil nutrients, and evidence suggests that the integration of irrigation systems is both technically feasible and environmentally sustainable. To maximize the benefits of vinasse reuse, it is essential to advance sustainable treatment and conditioning technologies that enable comprehensive resource recovery. These efforts are aligned with the principles of the circular economy, foresting environmental protection and efficient resource utilization.

AUTHORSHIP CONTRIBUTION STATEMENT

OLVEIRA, J. T.: Conceptualization, Data curation, Funding acquisition, Methodology, Supervision, Writing – review & editing; **DOURADO, A. C.**

C.: Data curation, Project administration, Writing – review & editing; **CAMPOS, G. M.:** Formal Analysis, Methodology, Software, Supervision, Writing – review & editing; **BORGES, A. C.:** Funding acquisition, Methodology, Writing – review & editing.

DECLARATION OF INTEREST

The authors declare that they have no financial or personal interests that could influence the work reported in this article.

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