Revista Brasileira de Ciência do Solo

**Division - Soil Use and Management** | Commission - Soil Fertility and Plant Nutrition

# Immediate and residual effect of tobacco powder compost and of NPK on $N_2O$ emissions and on N use in a wheat/corn crop succession

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**ABSTRACT:** Organic fertilization with tobacco powder compost produced via solid-state fermentation (SSF) is a recent practice that needs to be evaluated through research. This study aimed to evaluate the effect of two nitrogen sources – tobacco powder compost or mineral fertilizer (NPK) – and of compost doses on N use and loss in an immediate and residual way in a wheat/corn crop succession in a subtropical *Argissolo*. The wheat/corn crop succession was established after three successive fertilizer applications with different doses of the compost and of NPK. The following treatments were evaluated: control without application of the compost or mineral fertilizer (C0); mineral fertilization (NPK); and three doses of tobacco powder compost calculated to supply half (C50), the same amount (C100), and double (C200) the N applied via mineral NPK fertilization. To evaluate the residual effect of the fertilizer applications, the C50, C100, C200, and NPK treatments gave rise to additional treatments that did not receive more fertilization: rC50, rC100, rC200, and rNPK, respectively. The C0 generated an additional treatment that came to receive compost, identified as C0-C100. Yield and N accumulation in the aerial part of wheat and corn and $N_2O$ emission were evaluated throughout the two crop periods. Compost, in comparison to NPK, maintained the grain yield of wheat (3.0 *vs* 2.5 Mg $ha^{-1}$) and of corn (10.2 *vs* 9.5 Mg $ha^{-1}$) and increased N accumulation in the wheat plants (96 *vs* 68 kg $ha^{-1}$) and corn plants (191 *vs* 164 kg $ha^{-1}$). Compost increased cumulative $N_2O$ emissions by up to three times compared to NPK (6.84 *vs* 1.93 kg N-$N_2O$ $ha^{1}$ $yr^{1}$). Increasing the compost dose increased cumulative $N_2O$ emissions by 52 % (9.36 *vs* 6.16 $ha^{-1}$ $yr^{-1}$); however, it did not change the emission factor (EF) of $N_2O$, the yield-scaled emission, or N use efficiency. The compost residual effect increased wheat yield up to 93 % and corn yield up to 102 %, whereas no residual effect was observed from NPK. Compost applied on the previous crops did not affect $N_2O$ emissions in wheat or in corn; consequently, a residual effect did not impact the EF of $N_2O$. Therefore, tobacco powder compost has the potential to replace mineral fertilization in wheat and in corn. Considering its residual effect is an important strategy to optimize its use and mitigate $N_2O$ emissions to the atmosphere.

**Keywords:** solid state fermentation, greenhouse gases, nitrogen, organic fertilization.

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**Received:** April 15, 2024

**Approved:** August 02, 2024

**How to cite:** Oruoski P, Aita C, Pujol SB, Bazzo HLS. Immediate and residual effect of tobacco powder compost and of NPK on $N_2O$ emissions and on N use in a wheat/corn crop succession. Rev Bras Cienc Solo. 2025;49:e0240083. https://doi.org/10.36783/18069657rbcs20240083

**Editors:** José Miguel Reichert and Jeferson Dieckow.

## INTRODUCTION

Using agricultural and industrial waste as raw material for production of organic fertilizers lessens the pollution potential associated with inadequate disposal of this waste in the environment (Viaene et al., 2017). Tobacco production is a highly important activity in Brazil. The country is the largest exporter and second-largest producer of tobacco worldwide (Trindade and Beppler, 2020); the South region of Brazil, particularly the state of Rio Grande do Sul, is responsible for 95 % of Brazilian production (Afubra, 2023). Tobacco processing in industries generates significant amounts of waste, generally referred to as "tobacco powder" (Kist et al., 2016). This waste, basically composed of the leaf blade and stems of the tobacco plant, as well as soil that adheres to the plant, represents an environmental liability, for Brazilian legislation restricts depositing untreated solid waste on the soil (Brasil, 2010).

In this respect, transforming tobacco powder into compost for agricultural use through solid-state fermentation (SSF) is a recent alternative used to treat tobacco waste generated by the tobacco industries in the South of Brazil (Kist et al., 2016). The tobacco powder SSF process is divided into two steps. In the first, which lasts approximately three days, the waste is moistened, receives inoculation of microorganisms, and is turned over. In the second step, which lasts approximately 105 days, the moist, inoculated tobacco powder is stored in static piles, without the addition of water and without turning over for oxygenation of the system, until it is stable. This second step differentiates this process from other traditional composting processes, which are generally aerobic throughout all the steps (Epstein, 1997; Andrade et al., 2018; Tratsch et al., 2019). In spite of these differences in the process, according to Oruoski (2019), the characteristics of the compost generated meet the requirements of Brazilian legislation for organic fertilizers: TOC (>15 %), total N (>1 %), moisture (maximum 50 %), C/N ratio (maximum 20:1), and pH (minimum 6.0) (Brasil, 2009).

Few studies have been related to tobacco powder compost up to this time. The first study, developed by Oruoski (2019) in the laboratory, determined the carbon (C) and nitrogen (N) mineralization dynamic of the tobacco powder compost in the soil and served as a basis for another study developed by Bremm (2021). The latter shows the compost has potential to replace mineral fertilization, where the highest doses applied resulted in yields near 9, 8, and 4 Mg $ha^{-1}$ in Sudan grass, corn, and soybean, respectively. Nevertheless, due to the low concentration of mineral N and mineralized organic N in the compost (Oruoski, 2019), large amounts of compost needed to be applied to meet the N demand of crops.

Despite the benefits of organic fertilization on agricultural production (Luo et al., 2018), studies show that organic fertilizers may increase nitrous oxide ($N_2O$) emissions to the atmosphere (Ding et al., 2013; Zhou et al., 2017; Aita et al., 2019; Pilecco et al., 2020). Nitrous oxide is one of the main greenhouse gases related to the destruction of the ozone layer, with a global warming potential 273 times greater than that of carbon dioxide ($CO_2$) (IPCC, 2021). In Brazil, the agricultural crop and livestock sector is one of the largest contributors to $N_2O$ emissions, and soils in planted areas contributed 31.0 % of the emissions in this sector in 2020 (MCTI, 2022). The $N_2O$ emissions from the soil result from the microbial processes of nitrification and denitrification following the addition of nitrogen sources (Charles et al., 2017). Higher $N_2O$ emissions have been reported from organic sources than from mineral sources (Zhou et al., 2017; Pilecco et al., 2020) because organic sources not only supply inorganic N, but also labile C, substrates for $N_2O$-producing microorganisms (Lazcano et al., 2021). However, there are reports of higher $N_2O$ emissions in soils with mineral fertilizers (Ding et al., 2013; Chirinda et al., 2021). These contrasting results can be attributed to differences in soil characteristics, such as texture and C content (Pelster et al., 2012), and in organic fertilizers, such as labile C, mineral N, dry matter, and the C/N ratio, which affect $N_2O$ emissions (Charles et al., 2017). Therefore, these contrasts among studies reveal the need for research in this area.

Another factor that may contribute to $N_2O$ emissions from organic sources is their residual effect, since they impact C and N stocks in the soil (Davis et al., 2019). According to Aguilera et al. (2013), the typically slow and prolonged release of N from organic fertilizers can extend the $N_2O$ fluxes beyond the growing season, as reported in some studies (Ding et al., 2013; LaHue et al., 2016; Zhang et al., 2017). The tobacco powder compost showed a residual effect on plant production for three consecutive crop seasons after application to the soil (Bremm, 2021). In this case, this residual effect of the compost may increase $N_2O$ emissions, both in the current crop season and in crop seasons subsequent to its application, impacting the $N_2O$ emission factor (EF). However, the Intergovernmental Panel on Climate Change establishes a constant value of 1 % for the EF of fertilizers, regardless of the source, of the rate of N applied (Charles et al., 2017), and of the residual effect of the fertilizers (LaHue et al., 2016). Therefore, we believe that considering these differences can help reduce the uncertainty associated with the EFs induced by fertilizers and more accurately evaluate the contribution of fertilization to $N_2O$ emissions in agriculture.

Emissions of $N_2O$ tend to increase exponentially with an increase in the rate of N applied through fertilizers (Chen et al., 2019; Davis et al., 2019), especially when the N dose exceeds crop demand (Song et al., 2019), because the excess can be used by the microbial processes of nitrification and denitrification (Feng et al., 2016). Reducing the N rate effectively mitigates $N_2O$ emissions (Venterea et al., 2012; Li et al., 2020). Yet, although reducing the amount of N through the tobacco powder compost improved N use efficiency, it significantly decreased plant production (Bremm, 2021). Thus, the compost doses that result in the highest crop yield may also lead to the highest $N_2O$ losses. It is essential to optimize the N application rates to maximize nutrient uptake by the plants and reduce N loss through gas emissions to the atmosphere (Thangarajan et al., 2013).

Because of the probable impacts of the compost on the soil C and N levels, which may affect the use of N by plants and emissions of nitrous oxide to the atmosphere, we have the following hypotheses: i) the compost meets the N demand of wheat and corn and replaces mineral fertilization for these crops; ii) the compost increases $N_2O$ emissions in relation to mineral fertilization due to an immediate effect together with the residual effect of the organic source; iii) increasing the dose of the compost improves plant production, but increases N losses in the form of $N_2O$. This study aimed to evaluate the effect of N sources (tobacco powder compost × NPK mineral fertilizer) and doses of organic compost in a wheat/corn crop succession on N use and loss in an immediate and residual manner.

## MATERIALS AND METHODS

### Site, climate, and soil

The experimental area was located at the Universidade Federal de Santa Maria (29° 43’ 36’’ S, 53° 43’ 28’’ W, altitude of 107 m), Rio Grande do Sul, Brazil. The climate in the area is humid subtropical (Cfa type, according to the Köppen classification system), with mean annual rainfall of 1,660 mm and mean air temperature ranging from 14 °C in June to 25 °C in January. Soil at the site is classified as an *Argissolo Vermelho Alumínico úmbrico* (Santos et al., 2018) or Ultissol (Soil Survey Staff, 2014), with 192 g $kg^{-1}$ of clay and 443 g $kg^{-1}$ of sand (pipette method; Teixeira et al., 2007) in the 0.00-0.10 m soil layer. Other properties in the 0.00-0.10 m soil layer, determined in October 2018, before the first crop in the experimental area, were as follows: $pH(H_2O)$ 1:1 = 5.5; extractable Ca (KCl) = 5.9 $cmol_c$ $dm^{-3}$; Mg = 2.6 $cmol_c$ $dm^{-3}$; $Al^{3+}$ = 0.0 $cmol_c$ $dm^{-3}$; base saturation = 62 %; cation exchange capacity (pH 7) = 14.1 $cmol_c$ $dm^{-3}$; P (Mehlich-I) = 13.8 mg $dm^{-3}$, and K = 78.5 mg $dm^{-3}$. Total C content was 19.2 g $kg^{-1}$, and total N content was 1.9 g $kg^{-1}$, determined by dry combustion (Flash EA 1112, Thermo Finnigan, Milan, Italy).

## Experimental design and treatments

The experiment was set up in October 2018 and conducted in a randomized block design, initially with eight replications and plots of 20 m$^2$. The five original treatments of the experiment were the control, without application of the compost or another fertilizer (C0); mineral fertilization (NPK); and three dosages of tobacco powder compost to supply half (C50), the same amount (C100), and twice the amount (C200) of N applied via NPK mineral fertilization.

The following crops were sown in the area: corn (*Zea mays* L.) in summer 2018/19, vetch-oats mixtures (*Avena strigosa* Schreb. and *Vicia sativa* L.) in winter 2019, corn in summer 2019/20, wheat (*Triticum aestivum* L.) in winter 2020, and corn in summer 2020/21. In growing wheat in 2020, the treatments were split, such that the original five treatments with eight replications gave rise to ten treatments with four replications. This adjustment was also made to evaluate the residual effect of the fertilizer applications beyond the immediate effect of the first compost application and reapplication to each crop. In this case, the treatments C50, C100, C200, and NPK gave rise to additional treatments that did not receive more fertilization, so as to reveal a possible residual effect: rC50, rC100, rC200, and rNPK, respectively. The C0 control treatment generated an additional treatment that received compost at the same dose as C100, identified as C0-C100. A schematic representation of the splitting of the treatments and their distribution in plots is shown in figure 1. The present study encompasses only the post-splitting period, which includes the last two crops, the wheat/corn succession.

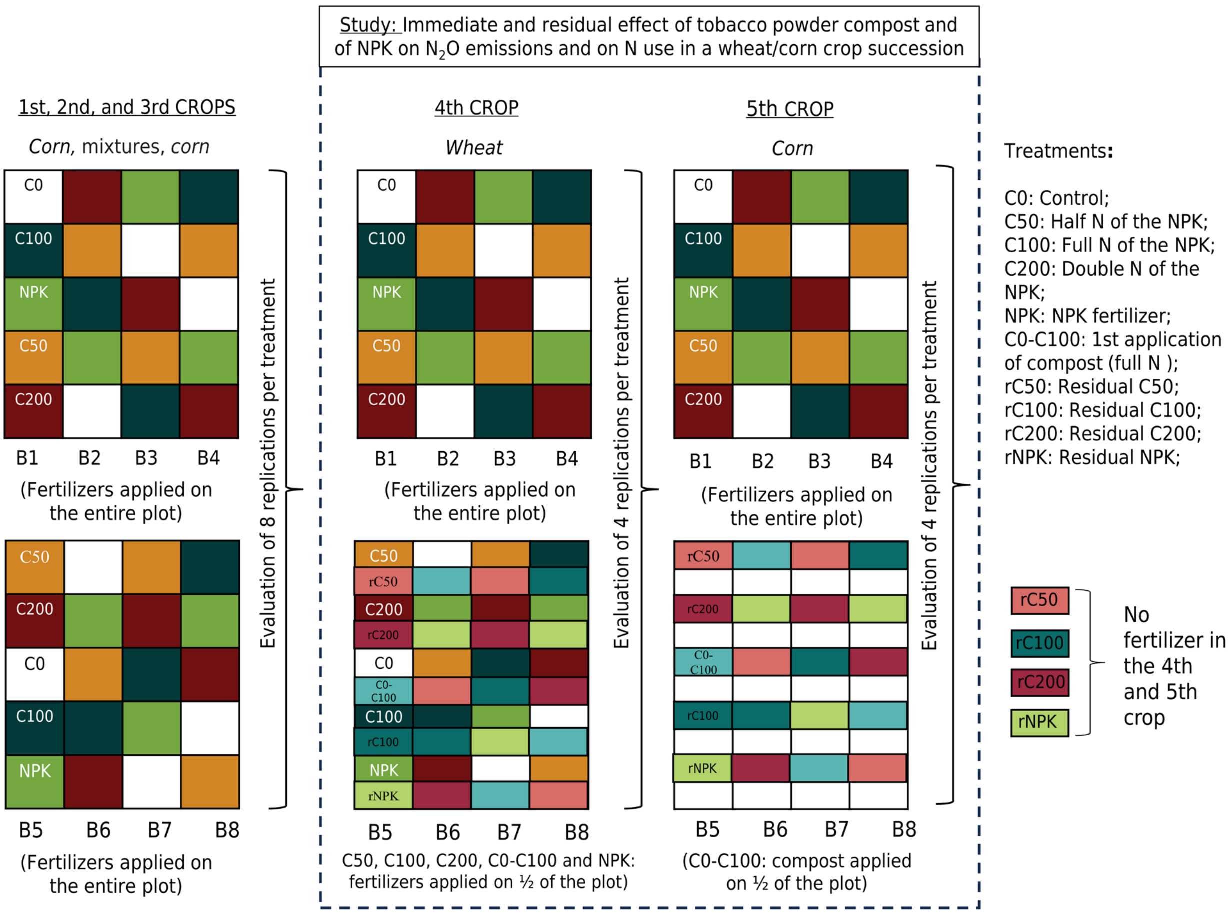


**Figure 1.** Crop sequence established in the experimental area and experimental design of the study developed in the wheat/corn succession and previous studies. In the wheat crop, in blocks B5, B6, B7, and B8, the rC50, rC100, rC200, and rNPK treatments were evaluated in the lower half of the plots, where the fertilizers were not applied; in the upper half of the plot, the fertilizers were applied on the wheat and were not applied on the corn, to assess, on the corn, the residual effect from four fertilizer applications. Compost in C0-C100 was applied on the lower half of the plot in wheat, and on the upper half of the plot in corn.

The mean air temperature and rainfall throughout the study were obtained from a weather station approximately 500 m from the experimental area. The amounts of compost, C, and nutrients added to the soil in the first application, in the reapplication of the tobacco powder compost in the wheat and corn crops, and in the previous crops (residual effect) are shown in table 1. Carbon and nitrogen accumulated by the aerial part of the crops grown in the experimental area before the present study are shown in table 2.

### Mineral fertilization

Mineral fertilization of the NPK treatment followed the recommendation of the Soil Chemical and Fertility Commission of the states of RS and SC (CQFS-RS/SC, 2016), according to the wheat and corn requirements for an expected yield of 3 and 8 Mg ha[1], respectively. The manually applied fertilizers were urea as a source of N, triple superphosphate as a source of $P_2O_5$, and potassium chloride as a source of $K_2O$. Triple superphosphate and potassium chloride were applied at sowing, on the soil surface. Urea application was split between sowing and topdressing on the soil surface. In wheat, 24 kg ha$^{-1}$ of N was applied at sowing and 40 kg ha$^{-1}$ of N at tillering, for a total of 64 kg ha$^{-1}$ of N. In corn, 34 kg ha$^{-1}$ of N was applied at sowing and 90 kg ha$^{-1}$ of N in topdressing at the V6 stage, for a total of 124 kg ha$^{-1}$ of N. In wheat, in the NPK treatment, the total amount of $P_2O_5$ applied was 45 kg ha$^{-1}$ and of $K_2O$, 30 kg ha$^{-1}$. In the NPK treatment, 160 kg ha$^{-1}$ of $P_2O_5$ and 80 kg ha$^{-1}$ of $K_2O$ were applied in corn. Total amounts of N, $P_2O_5$, and $K_2O$ applied on the crops before the wheat, correspondings to the residual effect in the rNPK treatment, were 263, 390, and 260 kg ha$^{-1}$, respectively. Total amounts of N, $P_2O_5$, and $K_2O$ applied on the crops before the corn, which corresponds to the residual effect in the rNPK treatment, were 327, 435, and 290 kg ha$^{-1}$, respectively.

**Table 1.** Amounts of compost; total C (TC); nitrogen (N): total (T), inorganic (I), organic (O), and available (A); phosphorus ($P_2O_5$); and potassium ($K_2O$) added to the soil with reapplication of the tobacco powder compost in wheat and corn crops, and in previous crops (residual)

| Crop | Treatment | Dose of compost | TC | N | | | | $P_2O_5$ | $K_20$ |
|---|---|---|---|---|---|---|---|---|---|
| | | | | T | I | O | A[3] | | |
| | | Mg ha$^{-1}$ | | kg ha$^{-1}$ | | | | | |
| Before wheat | rC50 | 21[(1)] | 6.3 | 539.0 | 82.5 | 456.5 | 131.3 | 88.5 | 823.8 |
| | rC100 | 42 | 12.6 | 1,078.0 | 165.0 | 913.0 | 262.6 | 176.8 | 1,347.6 |
| | rC200 | 84 | 25.2 | 2,156.0 | 330.0 | 1,826.0 | 525.2 | 353.6 | 3,295.2 |
| Wheat | C0-C100 | 10[2] | 3.0 | 247.2 | 39.0 | 208.0 | 64.0 | 40.0 | 356.6 |
| | C50 | 5 | 1.5 | 123.6 | 19.5 | 104.0 | 32.0 | 20.0 | 178.3 |
| | C100 | 10 | 3.0 | 247.2 | 39.0 | 208.0 | 64.0 | 40.0 | 356.6 |
| | C200 | 20 | 6.0 | 494.4 | 78.0 | 416.0 | 128.0 | 80.0 | 713.3 |
| Before corn | rC50 | 26 | 7.8 | 662.6 | 102.0 | 560.5 | 163.3 | 108.5 | 1,002.0 |
| | rC100 | 52 | 15.6 | 1,325.2 | 204.0 | 1,121.0 | 326.6 | 217.0 | 1,004.0 |
| | rC200 | 104 | 31.2 | 2,650.4 | 408.0 | 2,242.0 | 653.2 | 434.0 | 4,008.0 |
| Corn | C0-C100 | 20 | 6.4 | 512.0 | 72.0 | 240.0 | 124.0 | 32.0 | 888.0 |
| | C50 | 10 | 3.2 | 256.0 | 36.0 | 220.0 | 62.0 | 16.0 | 444.0 |
| | C100 | 20 | 6.4 | 512.0 | 72.0 | 240.0 | 124.0 | 32.0 | 888.0 |
| | C200 | 40 | 12.8 | 1,024.0 | 144.0 | 280.0 | 248.0 | 64.0 | 1,776.0 |

[(1)] Residual doses correspond to the sum of the doses added in crops prior to the wheat and corn in each one of the treatments. [(2)] Compost doses (dry basis) added to supply 100 (C0-C100), 50 (C50), 100 (C100), and 200 (C200) % of the available N supplied by mineral fertilization. C0-C100 refers to the first application of the compost. [(3)] Available N = [Inorganic N + (12/100) × organic N]

**Table 2.** Nitrogen and carbon accumulated by the aerial part of the crops grown in the experimental area prior to the wheat/corn succession

| Treatment | Nitrogen | | | | Carbon | | | |
|---|---|---|---|---|---|---|---|---|
| | Corn | vetch-oats mixtures | Corn | Total | Corn | vetch-oats mixtures | Corn | Total |
| | kg ha$^{-1}$ | | | | Mg ha$^{-1}$ | | | |
| C0 | 73.21 | 69.50 | 100.39 | 243.10 | 4.18 | 1.11 | 5.45 | 10.75 |
| C50 | 84.29 | 89.59 | 152.33 | 326.21 | 4.88 | 1.74 | 7.14 | 13.76 |
| C100 | 108.36 | 99.32 | 195.76 | 403.44 | 5.42 | 2.31 | 9.66 | 17.39 |
| C200 | 126.89 | 117.62 | 297.97 | 542.48 | 5.91 | 2.66 | 11.42 | 19.99 |
| NPK | 111.24 | 110.71 | 175.55 | 397.50 | 5.30 | 2.35 | 9.26 | 16.90 |

### Origin and characterization of the compost and organic fertilization

The compost was provided by the tobacco residue treatment unit, operated by an environmental protection foundation (*Fundação para Proteção Ambiental de Santa Cruz do Sul* - FUPASC), RS, Brazil. The SSF process of tobacco powder has two steps. The first lasts approximately three days, during which the tobacco powder is mechanically turned over while it is moistened and impregnated with a solution of microorganisms (BioLeaf commercial product), basically composed of *Bacillus subtilis* and *Saccharomyces cerevisiae*. The second step is fermentation and maturation, in which the inoculated tobacco powder is stored in static piles and lasts an average of 105 days (Kist et al., 2016). The final product is an organic fertilizer, FertiLeaf, registered in the Brazilian Ministry of Agriculture (Ministério da Agricultura, Pecuária e Abastecimento - MAPA), referred to in this study as tobacco powder compost.

The compost was manually applied on the soil surface on the same day as the sowing of the crops. At the time the compost and the mineral fertilizers (in the NPK treatment) were applied, the plot area designated for the gas collection was marked off and isolated to receive the exact dose of the material, separately from the rest of the plot.

The compost was analyzed to determine moisture, pH, total and inorganic C and N concentrations, and P and K concentrations. Moisture was determined after drying approximately 50 g of the compost in a forced-air-circulation laboratory oven at 65 °C for 48 h. The pH was determined in water, as described in Tedesco et al. (1995). Total C and N concentrations of the dried and finely ground samples were obtained by dry combustion in an elemental analyzer (Flash EA 1112, Thermo Finnigan, Milan, Italy). Inorganic N was extracted following the methodology adapted from Tedesco et al. (1995) and inorganic N concentration ($NH_4^+$ and $NO_3^-$) was determined by colorimetry in a continuous flow analyzer (CFA, San Plus, Skalar, Breda, the Netherlands). Phosphorus and K concentrations in the compost were determined after nitric-perchloric acid digestion of the samples (Carmo et al., 2000). Phosphorus concentration was determined according to the methodology of Murphy and Riley (1962) by colorimetry in a spectrophotometer, and K concentration was determined in a flame photometer. Main characteristics of the compost are shown in table 3.

The doses of the compost added to the wheat and corn and the previous crops were established considering their available N, including the inorganic N with a mineralization index of 12 % of the organic N (Oruoski, 2019). To establish the doses of the compost to be used on each crop, the residual effect from the previous applications was not considered.

**Table 3.** Properties of the compost applied to the wheat and corn crop

| Property | Wheat | Corn |
|---|---|---|
| pH | 6.0 | 6.2 |
| C:N | 12.4 | 12.5 |
| DM (g $kg^{-1}$) | 820.0 | 790.0 |
| TC (g $kg^{-1}$) | 307.5 | 319.7 |
| TN (g $kg^{-1}$) | 24.7 | 25.6 |
| IN (g $kg^{-1}$) | 3.9 | 3.6 |
| ON (g $kg^{-1}$) | 20.8 | 22.0 |
| AN(1) (g $kg^{-1}$) | 6.4 | 6.2 |
| $P_2O_5$ (g $kg^{-1}$) | 4.0 | 1.6 |
| $K_20$ (g $kg^{-1}$) | 35.7 | 44.4 |

C:N: carbon/nitrogen ratio; DM: dry matter; TC: total carbon; TN: total nitrogen; IN: inorganic nitrogen; ON: organic nitrogen; AN: available nitrogen; $P_2O_5$: phosphorus; $K_2O$: potassium. Results are expressed on dry basis. (1) Available N = [Inorganic N + (12/100) × organic N].

### Crop management

Wheat and corn were sown with a no-till planter. The wheat cultivar was IPR Potiporã, of medium cycle, with a population of 300,000 plants $ha^{-1}$, sown in May 2020 with a between-row spacing of 0.17 m. Topdressed fertilization was urea, which was applied in the NPK treatment at 43 days after sowing, in the tillering stage. The crop was grown without irrigation. The corn hybrid was P3016VYHR, with a population of 60,000 plants $ha^{-1}$, with a between-row spacing of 0.5 m, sown in October 2020. Topdressed fertilization with urea in the NPK treatment was performed at 32 days after sowing, in the V6 stage. Corn was irrigated under a conventional sprinkler system. Sprinklers were set up at a height of 2.5 m from the soil surface and evenly distributed in the experimental area to have overlap of the wetted areas and to apply an even water layer at all points of the area, adjusted so as not to create differences in the water layer applied at each base. Four irrigation events were carried out during the crop cycle: at 18, 45, 54, and 68 days after sowing, at around 5:00 in the afternoon. A 30 mm irrigation layer was applied in the first three events, and 45 mm in the last. Pests, diseases, and weeds were chemically controlled whenever necessary.

### Plant grain yield and N accumulation

Wheat grain yield was determined by harvesting the grain from the plants in the 23 central rows of the 20 $m^2$ plots, and from the 10 central rows in the 10 $m^2$ plots, disregarding the 0.5 m at each end of the plot rows, for a total area for data collection of 11.7 and 5.1 $m^2$, respectively. For corn, the six central rows were harvested in an area of 9.0 $m^2$ and the three central rows in an area of 4.5 $m^2$ in the 20 $m^2$ and 10 $m^2$ plots, respectively. Grain moisture was adjusted to 13 % to calculate yield.

Shoot (straw and grain) dry matter (DM) of the plants was evaluated to determine N accumulation. In corn, five plants were collected at random in the plot area used for data collection; and in wheat, the plants were collected in four 0.5-m linear segments within the plot area used for data collection. The plants and grain samples were dried on a laboratory oven at 65 °C until reaching constant weight, and then subsamples were finely ground. In these subsamples, N concentration was determined by dry combustion in an elemental analyzer (Flash EA 1112, Thermo Finnigan, Milan, Italy). The N of the DM was converted into kg $ha^{-1}$ considering the plant population or the grain production in the plot area used for data collection; then this was extrapolated to hectares.

The indices of N use efficiency, N agronomic efficiency (NAE), and N uptake efficiency (NUE) by the plants were calculated based on grain yield and the amounts of N accumulated in the aerial part of the plant, respectively. The NAE (kg grain per kg of N applied) and the NUE (% N uptake by plants) were calculated by equations 1 and 2, respectively. Calculation of the NUE disregarded a possible priming effect.

$$NAE = \frac{\text{Grain yield (treatment)} - \text{grain yield (control)}}{N\text{applied (treatment)}} \quad \text{Eq. 1}$$

$$NUE = \frac{N\text{uptake(treatment)} - N\text{uptake(control)}}{N\text{applied(treatment)}} \times 100 \quad \text{Eq. 2}$$

These indices were calculated in two ways: one calculation using the usual method, where the total N applied is used in the denominator, and the other using an alternative method, which considers the available N (inorganic N + 12 % organic N) applied to the soil with each dose of the compost as the denominator.

### Nitrous oxide fluxes

The $N_2O$ emissions from the soil were evaluated in seven of the ten treatments listed, namely: C0, C0-C100, C100, C200, NPK, rC100, and rC200. The choice was made to select and restrict the number of treatments due to operational limits for these evaluations. The $N_2O$ fluxes from the soil surface were measured over the period of 320 days, from wheat sowing to corn harvest, in 51 sample collection events, from 10:00 to 12:00 h in the morning, using the static chamber method. In the first 30 days after sowing and application of the fertilizers on the crops, measurements were made two to three times a week, and then at intervals of seven to fifteen days. The collection events were preferentially before and after rainfall and irrigation application.

On the same day as fertilizer application and crop sowing, metal bases with dimensions of 0.70 × 0.40 × 0.15 m (length, width, and height) were inserted in the soil at a depth of 0.10 m in each plot of the experimental area. A total of 28 bases were placed, one in each plot (seven treatments and four blocks), over the wheat or corn plant row. The bases remained in the soil throughout the crop cycles; they were removed only for the harvest, application of the treatments, and sowing operations. Immediately after these operations, the bases were placed back in the soil. The bases had a channel in the upper part to which water was added at each collection to prevent gas exchanges between the inside of the chamber and the outside environment. Galvanized steel chambers were fitted over the channels of the metal bases during gas collections. An adhesive thermal covering was placed on top of the chambers. The wheat and corn plants within the bases were immediately removed after emergence.

The first gas sample was taken two days after the wheat was sown and one day after the corn was sown. On each sampling date, at 0, 15, 30, and 45 min after the chambers were coupled to the bases, air samples were collected using 20 mL polypropylene syringes, which were coupled to a three-way stopcock valve inserted into the chamber. The syringes were sealed, placed in a cooler, and immediately sent to the laboratory for analysis. The air samples from the syringes were transferred to previously evacuated 12 $cm^3$ vials. At most five days, the air samples were analyzed for $N_2O$ concentration by gas chromatography (GC-2014, Greenhouse model, Shimadzu).

Along with each gas collection, the following data were collected: internal and external temperature of the chambers and the soil temperature, using thermometers, and relative humidity inside and outside the chambers, indicated by a thermo-hygrometer. The $N_2O$ fluxes on the soil surface (μg $m^{-2}$ $h^{-1}$) were calculated using the rate of change in $N_2O$ concentration (dG/dt; mmol $mol^{-1}$ $s^{-1}$) within the chamber during sample collection (Rochette and Hutchinson, 2005), according to equation 3.

$$FN_2O = \frac{dG}{dt} \times \frac{V}{A} \times \frac{Mm}{Vm} \times \left(1 - \frac{ep}{p}\right) \quad \text{Eq. 3}$$

in which: G (µmol $mol^{-1}$) is determined in samples of dry air, V ($m^3$) is the volume of the chamber, A ($m^2$) is the area covered by the chamber, ep (kPa) is the partial water vapor pressure in the air of the chamber, P (kPa) is the barometric pressure, Mm (g $mol^{-1}$) is the molecular weight of $N_2O$, and Vm ($m^3$ $mol^{-1}$) is the molecular volume at the temperature of the chamber and barometric pressure. Cumulative N-$N_2O$ emissions were obtained by linear interpolation of the fluxes between consecutive sampling dates during the two crops in a 320 day evaluation period. Therefore, the annual cumulative emission refers to this period.

Emission factors were calculated in the usual way for all the treatments, according to equation 4, and in an alternative way for the C100 and C200 treatments, according to equation 5. In equation 5, the $N_2O$ emissions from C100 and C200 were subtracted from the emissions from rC100 and rC200, respectively.

$$EF\ \% = \frac{cumulative\ N_2O\ emissions\ (treat.) - cumulative\ N_2O\ (control)}{N\ applied} \times 100 \quad \text{Eq. 4}$$

$$EFr\ \% = \frac{cumulative\ N_20\ emissions\ (treat.) - cumulative\ N_2O\ emissions\ (residual)}{N\ applied} \times 100 \quad \text{Eq. 5}$$

The EFs in the two equations were calculated in two ways, considering the total N and available N applied with the compost in the denominator. The EF was determined per crop and annually. Annual EF was determined considering the cumulative emissions over the 320 day period and the cumulative amount of N applied with the wheat and corn. The yield-scaled $N_2O$ emissions for each treatment were obtained by dividing the cumulative N-$N_2O$ emissions by the amount of grain produced and per unit total N uptake, as proposed by Van Groenigen et al. (2010).

### Soil sampling and analysis

During the gas collection period, soil samples were also taken from the 0.00-0.10 m layer to determine gravimetric water and inorganic N ($NH_4^+$ + $NO_3^-$) concentrations. Soil moisture was determined on all the dates of air sampling. Inorganic N concentrations were determined only in some samples, mainly in periods of greater probability of $N_2O$ emissions, such as after fertilization at sowing and topdressed fertilization. Soil samples were composed of five simple samples collected with a soil sampling auger (3 cm diameter) at random points in the plot. Inorganic N ($NH_4^+$ + $NO_3^-$) was extracted by shaking 20 g of soil with 80 mL of 1 mol $L^{-1}$ KCl for 30 min. After decanting for approximately 30 min, the supernatant was filtered and frozen for later analysis by distillation and titration. The $NH_4^+$ and $NO_3^-$ concentrations were quantified by sequential distillation in the presence of magnesium oxide (MgO) and Devarda's alloy, respectively, followed by titration with diluted sulfuric acid ($H_SO_4$), according to Tedesco et al. (1995).

Gravimetric water content was determined after drying the soil in a laboratory oven at 105 °C for 24 h. Based on the water content, soil bulk density (determined before sowing the crops), and soil particle density, the percentage of the water-filled pore space (WFPS) was calculated in each evaluation using equation 6, as described by Paul and Clark (1996).

$$WFPS\% = U \times \left(\frac{da}{1}\right) - \left(\frac{da}{dp}\right) \quad \text{Eq. 6}$$

in which: U is the soil gravimetric water content (g $g^{-1}$); da is the soil bulk density (g $cm^{-3}$); and dp is the soil particle density (g $cm^{-3}$), considered to be 2.65 g $cm^{-3}$.

### Statistical analysis

The normality of the residual effects and the homogeneity of the variances were checked for the results of the following variables: grain yield, cumulative N, NAE, and NUE for wheat and for corn; cumulative emission of N-$N_2O$; EF (calculated according to the IPCC formula); and yield-scaled emission. Then, variance analysis (ANOVA) was carried out. In the event of statistical difference, the treatments were compared using the Scott-Knott test at the 5 % probability of error level. Furthermore, the t-test was used to compare the values of the different N-$N_2O$ emission factors (considering the $N_2O$ emissions from the control or the respective residual effect as the denominator) calculated for the C100 and C200 treatments.

## RESULTS

### Meteorological conditions

The mean daily air temperature ranged from 5.4 to 26.6 °C (mean of 15.7 °C) during the wheat crop, and from 16.9 to 30.6 °C during the corn crop (mean of 22.9 °C). Cumulative rainfall in the period from wheat sowing to corn harvest was 1,311 mm. Of the cumulative total, 637 mm occurred during the wheat crop, with approximately 56 % in the first 50 days after sowing. In the corn crop, cumulative rainfall was 674 mm, with only 27 % in the first 50 days. Of the cumulative total in corn, 105 mm came from the sprinkler irrigation applied to the area (Figure 2a).

### Water-filled pore space and inorganic nitrogen of the soil

The WFPS values ranged from 49.8 to 97 % during the wheat crop and from 52.9 to 95.7 % during the corn crop, with values higher than 60 % in 96 % of the measurements made during the cycles of the two crops (Figure 2b). In general, the increases in inorganic N in the soil through fertilization in wheat were less expressive than in corn (Figures 2c and 2d). The $NH_4^+$ content in the soil remained below 6.7 mg kg$^{-1}$ throughout nearly the entire wheat crop period in almost all the treatments. Only the NPK treatment reached 16.8 mg kg$^{-1}$, a seven-fold increase compared to C0, four days after topdressed urea application. In the wheat crop, the $NO_3^-$ content in the soil oscillated from 0.2 mg kg$^{-1}$ in C0 to 16.4 mg kg$^{-1}$ in C200, in which the largest dose of compost was applied.

Expressive amounts of inorganic N were detected in corn after fertilization at sowing and at topdressing (Figures 2c and 2d). Treatments with the highest $NH_4^+$ concentrations in the soil were C200 (39.9 mg kg$^{-1}$), 13 days after application of the compost at sowing, and NPK (31.8 mg kg$^{-1}$), 2 days after topdressed application of urea. In the samples taken from 6 to 39 days after sowing corn, there was an increase in the $NO_3^-$ concentrations in the soil, with maximum values of 114.0, 65.6, and 40.5 mg kg$^{-1}$ of $NO_3^-$ in C200, C0-C100, and C100, respectively. The rC100 and rC200 treatments had concentrations lower than 8.9 mg kg$^{-1}$ of $NH_4^+$ and 20.2 mg kg$^{-1}$ of $NO_3^-$ in both crops, with values near those observed in C0.

### Nitrous oxide emissions

The only peak of N-$N_2O$ emissions during wheat growing occurred on the day following fertilization and sowing. After this initial peak, the N-$N_2O$ fluxes decreased to levels near those observed in C0, and they increased again around 20 days after fertilization and sowing of corn (Figure 2e). In wheat, the peaks of N-$N_2O$ emissions reached maximum values of 4554, 3360, and 1982 µg m² h$^{-1}$ in C200, C0-C100, and C100, respectively. The corn crop showed this same order for the maximum N-$N_2O$ peaks – 4278, 3537, and 3356 µg m² h$^{-1}$ – gradually decreasing to values near those observed in C0, which had N-$N_2O$ emissions lower than 111 µg m² h$^{-1}$ throughout the period of evaluations. In the NPK fertilizer, the maximum value of N-$N_2O$ flux was 304 µg m² h$^{-1}$, two days after adding topdressed urea in corn. The N-$N_2O$ fluxes in rC100 and rC200 remained at levels near those observed in C0 throughout the period.

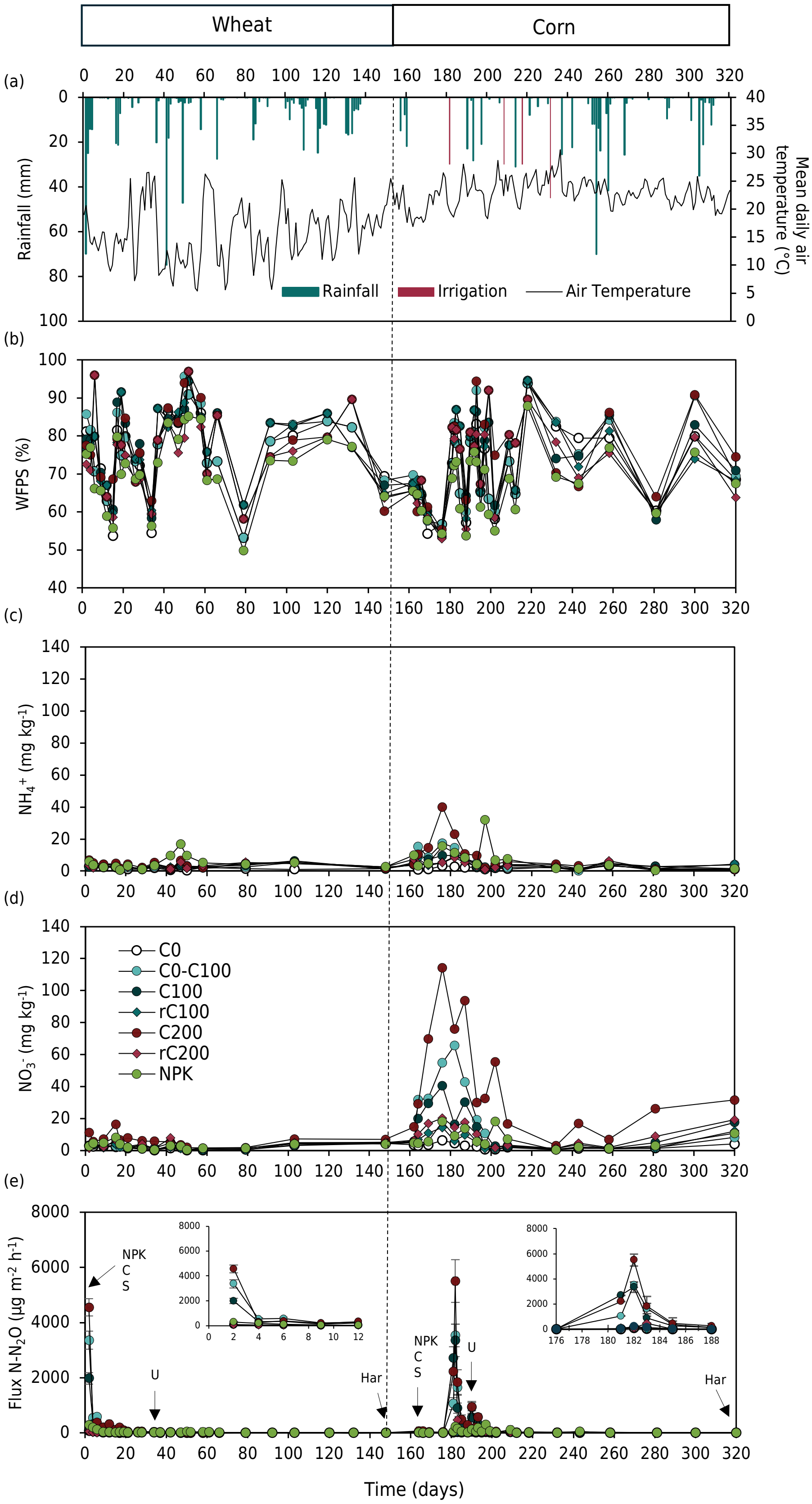


**Figure 2.** Rainfall, irrigation, and mean daily air temperature (a), water-filled pore space (WFPS) (b), $NH_4^+$ concentration (c) and $NO_3^-$ concentration (d) in the 0.00-0.10 m soil layer, and N-$N_2O$ fluxes (e) throughout wheat and corn growing (in detail the $N_2O$ emission peaks). Each point in figures b, c, d, and e refers to a sampling date. C0: control; C0-C100: first application of compost, same amount of N as mineral fertilizer; C100 and C200: compost, same amount of N and double the N of mineral fertilizer, respectively; NPK: mineral fertilizer; rC100 and rC200: residual effect of C100 and C200, respectively. The terms NPK, C, S, U, and Har. with arrows indicate the following operations: mineral fertilizer application, compost application, sowing, topdressed urea fertilization in the NPK treatment, and crop harvest, respectively. Vertical bars indicate standard error.

The annual cumulative N-$N_2O$ emissions (sum of the emissions in the wheat and corn growing periods) differed among the sources and the amounts of N added with the compost (Table 4). Annual cumulative N-$N_2O$ emissions in C100 and in C200 increased 7.7 and 11.7 times compared to C0, respectively. In addition, C200 emitted 52 % more N-$N_2O$ than C100 did. In contrast, NPK, rC100, and rC200 resulted in annual N-$N_2O$ emissions similar to C0. The C0-C100, resulted in annual emissions similar to C100, with a mean emission of 6.5 kg $ha^{-1}$ $yr^{-1}$ of N-$N_2O$. The cumulative N-$N_2O$ emissions in corn followed the same tendency observed in the annual emissions. However, NPK resulted in N-$N_2O$ emissions 2.6 times higher in wheat than C0. Furthermore, in wheat, the N-$N_2O$ emissions from the NPK treatment were only 42 % of the amount of the emissions from C100 and only 26 % of the emissions from C0-C100, even though NPK, C100, and C0-C100 received the same amount of available N. The C0-C100 emitted 57 % more N-$N_2O$ than C100 did.

The N-$N_2O$ yield-scaled emissions in the two crops and annually, expressed per unit of grain produced or por unit of accumulated N, were higher when the N was applied via compost than in the C0 treatment. In contrast, NPK produced emissions similar to C0 (Table 4). Yield-scaled emission, expressed per unit of grain produced, in C100 was two times greater in wheat and 1.4 times greater annually than in C200. In corn, it was the same for C100 and C200. However, when expressed per unit of accumulated N, yield-scaled emission was the same in C100 and C200, both specifically for each crop and annually. The C0-C100 had a yield-scaled emission greater than C100 did, except in corn, even though both received the same amount of available N on each crop. The rC100 and rC200 resulted in similar yield-scaled emissions, generally equal to C0.

The $N_2O$ emission factor values (EF: proportion of the N applied that is lost to the atmosphere as $N_2O$) were higher considering the available N (AN) compared to total N (TN) added through the compost, except for NPK, where the EFs were the same (Table 5). In both cases (TN and AN), an increase in the N dose did not lead to an increase in the EF of $N_2O$. In relation to the N source (organic and mineral), considering the TN applied, the EFs were similar for the sources, with a mean annual value of 0.66 % among NPK, C0-C100, C100, and C200. In contrast, considering the AN applied through the fertilizers, mineral fertilization resulted in EFs per crop and per year lower than organic fertilization. The annual FE of NPK was 4.5 times lower than the mean of the annual EFs of C0-C100, C100 and C200 (2.78 %), which did not differ from each other. The residual effect of the compost did not affect the EFs at the two doses tested; in other words, the EF of the C100 calculated considering N-$N_2O$ emission from the control was the same as EFr, which was calculated considering N-$N_2O$ emission from its respective residual effect; and the same occurred for C200.

**Table 4.** Cumulative N-$N_2O$ emission and N-$N_2O$ yield-scaled emission per unit of grain produced and per unit of N accumulated by the plant in the wheat and corn crops and annually

| Treatment[(1)] | Cumulative emission | | | Yield-scaled emission | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | Wheat | Corn | Annual | Wheat | Corn | Annual | Wheat | Corn | Annual |
| | kg N-$N_2O$ $ha^{-1}$ | | | kg N-$N_2O$ Mg $grain^{-1}$ | | | kg N-$N_2O$ $kg^{-1}$ N | | |
| C0 | 0.37 e | 0.43 c | 0.80 c | 0.26 c | 0.09 b | 0.13 c | 9.32 c | 5.90 b | 7.09 c |
| C0-C100 | 3.06 b | 3.78 b | 6.84 b | 1.20 a | 0.40 a | 0.57 a | 42.89 a | 25.32 a | 31.00 a |
| C100 | 1.95 c | 4.21 b | 6.16 b | 0.67 b | 0.42 a | 0.47 b | 20.31 b | 22.80 a | 21.80 b |
| rC100 | 0.28 e | 0.52 c | 0.80 c | 0.12 c | 0.07 b | 0.08 c | 3.27 d | 4.33 b | 3.90 c |
| C200 | 3.49 a | 5.87 a | 9.36 a | 1.36 a | 0.50 a | 0.66 a | 22.55 b | 20.75 a | 21.55 b |
| rC200 | 0.26 e | 0.82 c | 1.08 c | 0.10 c | 0.09 b | 0.09 c | 2.04 d | 4.80 b | 3.37 c |
| NPK | 0.81 d | 1.12 c | 1.93 c | 0.34 c | 0.12 b | 0.16 c | 12.00 c | 7.22 b | 8.65 c |
| p-value | <0.001 | <0.001 | <0.002 | <0.001 | <0.001 | <0.001 | <0.001 | <0.001 | <0.001 |

(1) C0-C100 and C100 treatments provided the same amount of available N as NPK; the C100 and C200 treatments provided the same amount of N and double the available N as NPK, respectively; in the rC100 and rC200 treatments, no compost was applied on the wheat and corn crops. Mean values followed by different lowercase letters in the column represent significant differences according to the Scott-Knott test ($p<0.05$).

**Table 5.** Nitrogen dioxide emission factor (EF), per crop and annually, considering total N and available N applied with compost and NPK

| Crop | | C0-C100 | C100 | C200 | NPK | p-value |
|---|---|---|---|---|---|---|
| | | % | | | | |
| | | | Total N | | | |
| Wheat | EF[1] | 1.08 b | 0.63 a | 0.63 a | 0.71 a | 0.009[3] |
| | EFr[2] | | 0.67 | 0.65 | | (0.337)[4] (0.336)[5] |
| Corn | EF | 0.65 | 0.74 | 0.53 | 0.58 | 0.483 |
| | EFr | | 0.72 | 0.49 | | (0.454) (0.418) |
| Annual | EF | 0.79 | 0.71 | 0.56 | 0.62 | 0.077 |
| | EFr | | 0.71 | 0.54 | | (0.497) (0.435) |
| | | | Available N | | | |
| Wheat | EF | 4.18 c | 2.46 b | 2.44 b | 0.71 a | 0.000 |
| | EFr | | 2.61 | 2.52 | | (0.337) (0.336) |
| Corn | EF | 2.71 b | 3.05 b | 2.19 b | 0.58 a | 0.006 |
| | EFr | | 2.98 | 2.03 | | (0.454) (0.418) |
| Annual | EF | 3.21 b | 2.85 b | 2.28 b | 0.62 a | 0.000 |
| | EFr | | 2.86 | 2.20 | | (0.712) (0.497) |

[1] EF for all the treatments calculated considering the N-$N_2O$ emissions from the control treatment. They were compared to each other using the Scott-Knott test ($p<0.05$). Mean values followed by different lowercase letters in the row represent significant differences. [2] EFr for the C100 and C200 treatments were calculated considering the N-$N_2O$ emissions from their respective residual effects. Within each treatment, the two EFs (EF × EFr) were compared to each other using the t-test ($p<0.05$). [3] p-value generated in the Scott-Knott test ($p<0.05$). [4] and [5] p-values generated by comparing the EF × EFr of the C100 and C200 treatments, respectively, using the t-test.

## Grain yield and nitrogen use efficiency

The yields of the two crops were higher with compost application or NPK than in C0, but there were no differences in grain yield between the two N sources (Figures 3a and 3b). In wheat, grain yield was similar with the application of the compost at the doses C50, C100, C200, C0-C100, and NPK, with a mean yield of 2.8 Mg $ha^{-1}$, 87 % higher than the C0. In corn, grain yield increased with the compost dose – in the order of 77, 112, and 139 % for C50, C100, and C200, respectively, compared to C0. Furthermore, C0-C100, C100, and NPK, which received the same amount of N, resulted in similar yields, a mean of 9.7 Mg $ha^{-1}$, 102 % higher than C0. The N accumulated by the plants in the two crops showed a significant increase with the increase in the compost dose, and the accumulation of N in NPK was similar to that in C0-C100 and C50 (Figures 3c and 3d).

The residual effect provided by the previous fertilizer applications with the two highest doses of compost resulted in a significant increase in yield and N accumulation by plants compared to C0 (Figures 3a, 3b, 3c, and 3d). In wheat, the mean increase in yield in the rC100 and rC200 treatments was 83 %, compared to C0. In corn, the yield obtained from rC100 was 58 % higher than that from C0, and the yield from rC200 was 102 % higher. In contrast, mineral fertilization and the lowest dose of the compost did not result in a positive residual effect on grain yield in the two crops or on N accumulation in corn.

Nitrogen use efficiency, determined using the NAE and NUE indices, was higher with the lower doses of compost in wheat and in corn. This result was observed in the two calculation methods used, whether total N or the available N applied were used in the calculation (Table 6). However, there was no difference in N use efficiency between the two highest doses of compost. Higher N use efficiency was observed in mineral fertilization than in organic fertilization when considering the total N applied. In contrast, when the N use efficiency was calculated considering available N, the compost, depending on the dose, generally resulted in equal or higher values than NPK.

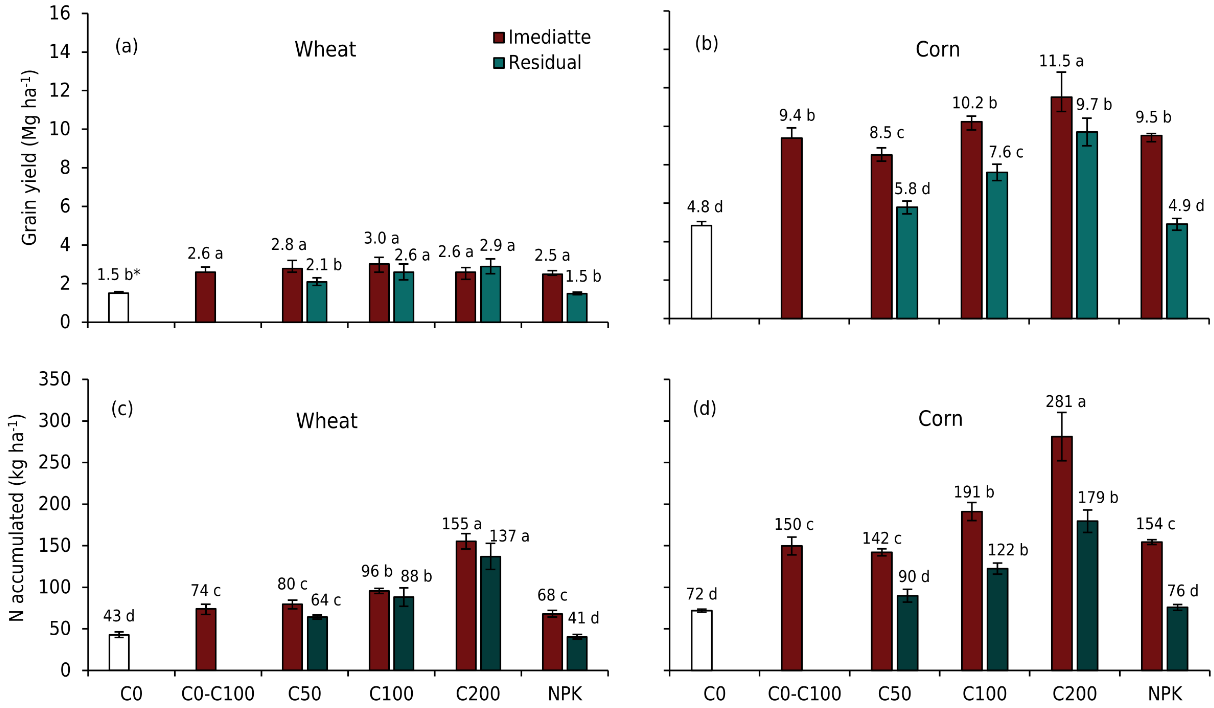


**Figure 3.** Grain yield (a, b) and nitrogen (N) accumulated (straw + grain) (c, d) in wheat and corn. C0: control; C0-C100 first application of compost, the same amount of N as mineral fertilizer; C100 and C200: compost, the same amount of N and double the N of mineral fertilizer, respectively; NPK: mineral fertilizer. * Mean values followed by the same letters do not differ from each other according to the Scott-Knott test (p<0.05). Vertical bars indicate standard error.

**Table 6.** Nitrogen agronomic efficiency (NAE) and N uptake efficiency (NUE) by the wheat and corn plants under the first application of compost and reapplication of different doses of compost and of mineral fertilization (NPK)

| Treatment | Wheat | | Corn | | Wheat | | Corn | |
|---|---|---|---|---|---|---|---|---|
| | NAE(1) | NAE(2) | NAE(1) | NAE(2) | NUE(1) | NUE(2) | NUE(1) | NUE(2) |
| | kg grain kg-1 N | | kg grain kg-1 N | | % | | % | |
| C0(3) | - | - | - | - | - | - | - | - |
| C0-C100 | 4.5 b | 17.6 b | 8.9 c | 36.8 b | 12.5 d | 48.4 c | 15.2 c | 62.3 b |
| C50 | 10.4 a | 40.2 a | 14.4 b | 59.2 a | 29.8 b | 115.1 a | 27.5 b | 112.5 a |
| rC50 | - | - | - | - | - | - | - | - |
| C100 | 5.9 b | 22.9 b | 10.5 c | 43.2 b | 21.5 c | 83.2 b | 23.3 b | 95.4 a |
| rC100 | - | - | - | - | - | - | - | - |
| C200 | 2.2 b | 8.5 b | 6.5 c | 26.8 c | 22.8 c | 88.1 b | 20.4 c | 83.8 b |
| rC200 | - | - | - | - | - | - | - | - |
| NPK | 14.9 a | 14.9 b | 37.4 a | 37.4 b | 39.7 a | 39.7 b | 66.5 a | 66.5 b |
| rNPK | - | - | - | - | - | - | - | - |
| (p-value) | <0.001 | <0.001 | <0.001 | <0.001 | <0.001 | <0.001 | <0.001 | <0.001 |

(1) Indices calculated considering the total N applied. (2) Indices calculated considering the available N applied. (3) In the C0, rC50, rC100, and rC200 treatments, the NAE and NUE were not calculated because no compost was applied to the wheat and the corn. Mean values followed by different lowercase letters in the column represent significant differences according to the Scott-Knott test (p<0.05).

## DISCUSSION

### Immediate effect of the fertilizers on $N_2O$ emissions

The occurrence of peaks in $N_2O$ emissions after application of the compost was directly related to fertilization and to rainfall or irrigation (Figure 2). The increase in $N_2O$ fluxes has been reported after nitrogen fertilization, especially when organic fertilizers with a low C/N ratio are applied to the soil together with rainfall events (Aita et al., 2018; Pilecco et al., 2020). In wheat, the $N_2O$ peak that occurred two days after the application of the compost and sowing was brought about by a 70-mm rainfall. In corn, the lack of rain in the first 17 days after application of the compost and sowing explains the low $N_2O$ emissions in this initial period, with an increase in the $N_2O$ fluxes occurring only after irrigation of 30 mm.

Reduction in $O_2$ levels caused by water from rain/irrigation constitutes one of the main conditions that favor $N_2O$ production in the soil (Congreves et al., 2019; Song et al., 2019). When water increases the WFPS to values higher than 60 %, the dominant process in $N_2O$ production is denitrification (Davidson, 1991; Zhu et al., 2013), which likely occurred in the present study, since the highest peaks of $N_2O$ emission coincided with WFPS higher than 60 % (Figure 2b). After the peaks of $N_2O$ emission, the fluxes returned to the level observed in the control and remained that way throughout the crop cycles, even with increases in the WFPS. In that case, reduction in C and inorganic N availability may have limited denitrification and $N_2O$ production. Oruoski (2019) evaluated the C dynamics of tobacco powder compost in the soil and found that 23 % of the C of the compost was in water-soluble form and, therefore, readily available to soil microorganisms, and that most mineralization of organic C occurred in the first 11 days after the compost had been added to the soil. That explains the $N_2O$ peaks that are concentrated after fertilization.

Carbon and N are factors that directly affect $N_2O$ production (Pelster et al., 2012; Charles et al., 2017); therefore, as in the present study, higher $N_2O$ emissions with organic fertilizer than with mineral fertilizer have also been reported in other studies (Pelster et al., 2012; Thangarajan et al., 2013; Pilecco et al., 2020). However, this increase in $N_2O$ emissions with the organic source compared to the mineral source can be more than compensated by higher rates of C accumulation in the soil with organic fertilizer, as Pilecco et al. (2020) reported. Carbon supply may have favored $N_2O$ production for compost compared to NPK, since C is a substrate for biomass production and energy for denitrifying heterotrophic bacteria. Furthermore, C from organic fertilizer increases the population and activity of heterotrophic microorganisms, accelerating $O_2$ consumption during respiration and favoring the emergence of anaerobic microsites in the soil (Thangarajan et al., 2013). In these locations, available $NO_3^-$ can be reduced to gaseous forms of N during denitrification (Lazcano et al., 2021).

In addition to the compost directly supplying C, it indirectly contributed to an increase in C and N concentrations in the soil through plant biomass. At the highest dose of the compost, the sum of the N and C amounts added to the soil by the above-ground biomass of the crops before the wheat crop was approximately 542 kg $ha^{-1}$ of N and 20 Mg $ha^{-1}$ of C (Table 2). Release of C and N during the decomposition of crop residues likely increased the availability of substrates for $N_2O$ production during the nitrification and denitrification processes.

Inorganic N supplied with the compost when sowing the crops, especially in the form of $NO_3^-$, may also have contributed to the gaseous losses of N, since $NO_3^-$ is positively correlated with $N_2O$ fluxes by denitrification (Chen et al., 2019). In corn, the peak of $N_2O$ emission with the addition of compost coincided with $NO_3^-$ concentrations in the soil reaching 114 mg $kg^{-1}$ of N. In wheat, despite the high $N_2O$ fluxes soon after the addition of compost, the $NH_4^+$ and $NO_3^-$ concentrations were low in the 0.00-0.10 m soil layer, indicating that the high-intensity rain that occurred after fertilization may have leached the mineral N, especially the $NO_3^-$, to deeper soil layers.

Our results showed that when the compost is used as the nitrogen source, replacing mineral fertilizer, the dose of the compost should be adjusted to crop demand and yield expectation. This strategy helps mitigate $N_2O$ emissions, as was observed in the present study, where doubling the dose of the compost and, consequently, the N concentration, led to an 80 % increase in cumulative emission of $N_2O$ in wheat and a 39 % increase in corn (Table 4). In general, $N_2O$ production can increase linearly, or even exponentially, as the N dose increases, especially when the amount of N applied is greater than crop N demands (Kim et al., 2013; Chen et al., 2019; Davis et al., 2019).

Yield-scaled $N_2O$ emission indicates the sustainability of the crop system (Van Groenigen et al., 2010). Using this form of expression, it was found that, although the increase in the dose of compost increased cumulative $N_2O$ emission, there was generally no difference in yield scale between the two compost doses (Table 4). Only in the wheat and in relation to grain yield was it found that the increase in the compost dose increased yield-scaled emissions. That may have occurred because the crop grain yield did not respond to the increase in the dose of the compost. This was likely the result of a frost in the wheat flowering stage, which may have hurt the conversion of the N accumulated by the plant into grain. This hypothesis is supported by relating yield-scaled emission per unit total N uptake by wheat, in which there was no difference between the two compost doses.

Increasing the dose of the compost also did not change the proportion of the N in the compost that was converted into $N_2O$, resulting in similar EFs among the doses, regardless of whether the EF was calculated according to total N (TN) or available N (AN) applied with the compost (Table 5). The lack of dose effect of N on the EF of $N_2O$ was also reported by Bratti et al. (2022) and Li et al. (2020) for the use of mineral fertilizer. This result shows that the proportion of applied N converted into $N_2O$ did not increase with an increase in the dose of N applied may indicate a linear response between the N rate and $N_2O$ emissions. In relation to the effect of the N source on the EFs, a difference was found between considering the TN applied, as recommended by the IPCC, or using the AN, as proposed in this study. Use of the TN showed that the N source did not impact the EF values, resulting in a mean annual value of 0.66 %. This value is near the EFs obtained with mineral nitrogen fertilization in studies conducted in subtropical climates in Brazil (Simon et al., 2018; Besen et al., 2021; Bratti et al., 2022) and lower than the 1 % value stipulated by the IPCC for fertilizers (Klein et al., 2006).

Using the amount of AN added with the compost and not the TN for calculating the EF, the mean EF with compost was 2.7 %, which is 4.5 times higher than the EF of mineral fertilization. This value is more than ten times higher than the EFs found using composts in other studies, which obtained maximum values of 0.2 % (Omirou et al., 2020; Charles et al., 2017). This discrepancy between EF values is likely related to the stabilization degree of the composted materials and especially the use of the TN rather than the AN for calculating EF. Composts are generally included in the group of organic inputs, with a medium to low risk of $N_2O$ emissions, as they are biostabilized (Charles et al., 2017). However, our results indicate the tobacco powder compost is likely not completely stabilized and, thus, the EF calculated based on the AN added to the soil results in more realistic and appropriate EF values for comparison with the mineral source than when EF is calculated based on the quantities of TN.

### Residual effect of the compost on $N_2O$ emissions

The $N_2O$ emissions from residual effects of previous fertilization with compost on wheat and corn did not differ from the control (Table 4), indicating the accumulation of C and N in the soil with continual use of the compost does not increase the current emissions of $N_2O$. Therefore, under the conditions of the present study, there was no difference between using the cumulative $N_2O$ emissions of the control, as recommended by the IPCC, or the emissions from the residual effect of previous applications of the compost for calculating the EF.

Residual effect absence of the compost on $N_2O$ emissions can also be confirmed by comparing C0-C100 with C100, as they received the same amount of compost. Greater $N_2O$ emission was expected in C100 because, in this case, there is the effect of the immediate fertilizer application, along with the residual effect of previous fertilizer applications, whereas in C0-C100, there is only the immediate effect of a single application. However, C0-C100 and C100 resulted in similar annual $N_2O$ emissions, indicating that $N_2O$ production was regulated by immediate fertilization and not by the residual effect of previous applications.

The low $N_2O$ emissions as residual effects of the compost can be attributed, in part, to the low inorganic N concentrations detected in the soil. The mineralization dynamics of the N stock in the soil from previous compost applications may have favored synchronization between N supply and demand in the plants, since grain yield and N accumulation in the wheat and corn increased through the residual effect of the compost. Thus, the low availability of N for the microbial process of nitrification and denitrification likely limited $N_2O$ production (Chirinda et al., 2021).

Another factor that may explain the absence of a residual effect of the tobacco powder compost on $N_2O$ emissions is the decomposition dynamics of this organic material in the soil. Evaluating this aspect, Oruoski (2019) found that carbon mineralization of the compost is more intense in the first month after application in the soil and tends to stabilize after this period. Therefore, the rapid decomposition of the more labile C fractions of the compost and the presence of the more recalcitrant remaining fractions may have limited microbial activity and, consequently, $N_2O$ production in the soil.

### Immediate effect of the fertilizers on crop yield and N use efficiency

Compost or mineral fertilizer increased wheat yield by up to 100 % and corn yield by up to 139 %, exceeding the expected yield of the crops and showing the high response potential of wheat and corn to fertilizers. These yields were close to or even higher than those obtained in other studies conducted with organic and mineral fertilizers on wheat and corn in the same region as the present study (Gonzatto et al., 2017; Bacca et al., 2020). With the same amounts of available N from the compost and urea in NPK, the wheat and corn yields were similar, indicating tobacco powder compost can be used as the sole source of N for these two grasses.

The high wheat and corn yields achieved with tobacco powder compost can be attributed not only to the N added to the soil through the compost, but also to other macronutrients, especially P and K (Table 1). Thus, the response of corn to the increase in the compost dose is due to the increased supply of these nutrients. The lack of effect of the dose on wheat yield was an atypical result, but it can be attributed to the frost late in the season that hurt the crop, and the biggest effect was on the wheat with the greatest amount of N, which was in full bloom at the time.

The lowest dose of the compost applied to the wheat and corn resulted in the highest N use efficiency (NAE and NUE), which is in agreement with Stamatiadis et al. (2016). However, the two highest compost doses resulted in the same NAE and NUE, which may have contributed to the similar EF and yield-scaled emission for the two doses. The effect of the N source on N use efficiency differed depending on the N fraction used in the calculation. When total N (TN) was used, the mineral fertilizer resulted in higher NAE and NUE compared to the compost, and considering available N (AN), the compost resulted in N use efficiency similar to NPK. This result suggests that for organic sources such as tobacco powder compost, with low initial inorganic N concentrations and a low organic N mineralization rate (Oruoski, 2019), the use of AN would be more appropriate than the use of TN to compare the compost N use efficiency with the mineral fertilizer.

### Residual effect of the fertilizers on crop yield

Residual effect of the higher compost doses met the N demand of the two crops, likely from mineralization of the N stock in the soil from previous fertilizer applications alone. Therefore, grain yield and N accumulation by the aerial part of wheat and corn increased even without reapplying compost to these crops (Figure 3). This result suggests that after three to four successive applications of tobacco powder compost, the dose can be reduced or, depending on the yield expectation of the crops and the amounts of N added to the soil in previous crops, the compost may not need to be reapplied. The residual effect of organic fertilizers can be attributed to the more recalcitrant fractions, which are not mineralized in the short term and increase nutrient stocks in the soil and the capacity to supply these nutrients to subsequent crops in the longer term (Nyiraneza et al., 2010; Webb et al., 2013).

The absence of a residual effect at the lower dose of compost and for NPK on plant yield and N accumulation indicates that using lower doses of tobacco powder compost and mineral fertilization requires reapplication for each crop. The greater residual effect of the organic source compared to the mineral source may be because the organic fertilizer increases C and N stocks in the soil more significantly than mineral fertilization does (Ding et al., 2013; Luo et al., 2018; Pilecco et al., 2020).

## CONCLUSIONS

Different N sources – tobacco powder compost and NPK – resulted in similar wheat and corn yields, indicating the potential of the compost to replace mineral fertilization for these crops. Furthermore, the residual effect of the compost increased N accumulation and crop yield to levels similar to those obtained from NPK, but there was no residual effect from the mineral fertilizer. Compost increased $N_2O$ emissions compared to mineral fertilization, which was directly proportional to the amount of compost applied. Nevertheless, increasing the dose did not change the proportion of the compost N converted into $N_2O$ (EF) or the yield-scaled emission, possibly because the doses resulted in similar N use efficiency. The increase in $N_2O$ emission was solely the immediate effect of the compost, because there was no residual effect on $N_2O$ emissions and on EF. Therefore, adjusting the dose of the compost and including the residual effect in planning and managing fertilization are effective strategies to ensure crop yield, optimize fertilizer use, and mitigate losses of $N_2O$ to the atmosphere when the compost is used as a substitute for mineral fertilization. Considering the available N (AN) content of the compost, instead of total N (TN), is an option that allows differentiation of the effect of the N source on the EF and N use efficiency. Considering TN, the compost resulted in the same EF than NPK and N use efficiency which was lower than NPK. In contrast, considering AN, the compost resulted in a higher EF than NPK, but and N use efficiency similar to NPK.

## DATA AVAILABILITY

All data was generated or analyzed in this study.

## ACKNOWLEDGMENTS

We would like to thank Coordenação de Aperfeiçoamento de Pessoal de Nível Superior (CAPES), Fundação para Proteção Ambiental de Santa Cruz do Sul (FUPASC) and the JTI (Japan Tobacco Internacional), from Santa Cruz do Sul, Rio Grande do Sul, Brazil.

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