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Effect of Mineral or OFMSW Digestate Fertilization on Ryegrass and Nitrogen Leaching

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Abstract: The current guidelines of waste management are aimed at the recovery and recycling of biowaste while respecting the protection of human health and the environment. The recent European legislation on fertilizers provides for the use of digestates derived from the organic fraction of municipal solid waste (OFMSW). The objectives of this study were to verify the fertilizing effect of three types of OFMSW digestates on the ryegrass culture comparing mineral fertilization and to evaluate the nitrogen lost to leaching in soil diversely fertilized following simulated rainfall. The ryegrass was grown in pots. The soil was fertilized with mineral fertilizer or OFMSW digestates. For each treatment, five mowing procedures were performed on the crop, and the ryegrass biomass production and nitrogen concentration were determined from the ryegrass samples. During the experiment, six rains were simulated, and the leached nitrogen was analyzed. The results showed that: (i) the fertilizing effect of OFMSW digestates on nitrogen nutrition of ryegrass was similar to ammonium sulphate fertilization, confirming the agronomic validity of these by-products to reduce the use of synthetic fertilizers; (ii) soil fertilization with OFMSW digestates had a positive effect limiting nitrogen loss due to leaching compared to mineral fertilization, highlighting the soil-improving properties of these by-products, in particular of the composted digestate.

Keywords: organic fraction of municipal solid waste (OFMSW); sustainable agriculture; biowaste valorization

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1. Introduction

The waste management system is moving in a strategic direction to improve the quality of the re-usable matrices and to reduce the quantity of waste produced. This approach was adopted by the European Commission, which established the principles for the sustainable management of digestate within the Circular Economy Package [1]. This agreement moves the EU towards a higher level of sustainability in waste management. In the action plan, the use of fertilizers derived from by-products of anaerobic digestion is a great opportunity to achieve sustainability in compliance with the circular economy model [2,3]. The recovery and recycling of OFMSW through composting or anaerobic digestion processes complies with the indications given by the European Community in relevant directives [4–6].

The European regulation 2019 [7] (Regulation (EU) 2019/1009) defines the criteria according to which a biodegradable waste can be marketed as fertilizer if it complies with strict conformation criteria (End of Waste). These criteria can be summarized in requirements on: (1) product quality; (2) input materials; (3) processes and treatment techniques; (4) provision of information and (5) quality management procedures. The aim of the regulation is to limit the impact on the environment and human health and to incentivize the development of the most appropriate treatment technologies. The recycling of biodegradable waste for agricultural use could be considered as a recommended sustainable soil management practice for maintaining or improving soil quality [8]. The organic fraction of these products administered to soil could counteract the phenomenon of soil carbon decline, and the negative alterations of the soil structure, while also improving the drainage capacity. Furthermore, biodegradable waste contains nutrients (especially nitrogen and phosphorus) and organic substances that could be recovered and not disposed of. Biowaste can be processed through composting or anaerobic digestion to stabilize the organic fraction and produce bio-based fertilizers. The optimization of transformation processes from waste to resource plays a key role in the production of quality by-products suitable for agricultural use [9–12]. Studies conducted on the potential of waste management through composting have demonstrated its benefits, such as reducing landfill waste and greenhouse gas emissions while improving soil quality for agriculture [13–15]. Anaerobic digestion (AD) is a technology used to treat the organic waste stream, primarily due to its capacity to produce methane as renewable energy. Main feedstocks for anaerobic digestion, both mono-fermented and co-digested, are animal manures, crop residues, wastes from the food industry, and municipal solid wastes [16]. The soil amendment with bio-based fertilizers could reduce the use of chemical fertilizers and improve crop productivity and residual soil fertility. Furthermore, the addition of exogenous organic matter to the soil through, for example, an organic amendment, can influence the mineralization processes of the native organic matter of the soil as a function of numerous parameters, including the degree of stability of the added organic matter, the N content, and the carbon/nitrogen ratio [17,18]. In the short- to medium-term, there could be an acceleration of the decomposition processes of the soil organic substances with the release of nutrients available for crop nutrition. Subsequently, humification processes could prevail increasing soil organic matter [19,20]. For example, some studies conducted by the authors have shown that long-term application of composted sewage sludge increased humification processes and heavy-metal stabilization in soil, minimizing the heavy-metal contamination risk [21]; moreover bio-based fertilizers, such as compost and digestates, had a more significant impact on plant growth and nutrient uptake than mineral fertilizers [22,23]. Barłóg and colleagues [24] found that digestate application can increase soil organic carbon and plant-available nutrients. The study suggests that digestate application can be a viable alternative to mineral fertilization, but its effectiveness may depend on the specific soil and nutrient conditions. Overall, the study highlights the potential of digestate application as a sustainable fertilizer option, but more research is needed to fully understand its benefits and limitations. Additionally, organic fertilizers improved soil structure and increased soil porosity [25]. Many studies investigated agricultural valorization of zootechnical or agro-industrial digestates, but there is a need to implement knowledge on the reuse in agriculture of the by-products of anaerobic digestion of the organic fraction of municipal solid waste.

The generation of municipal solid waste (MSW) worldwide is approximately 1.3 billion $t\,y^{-1}$ and this value could be increased to 2.2 billion $t\,y^{-1}$ for 2025 [26]. According to the European Environment Agency, the biowaste fraction of the MSWs represents more than 34% of the total amount, accounting for the biomass waste production of about 86 million tons in 2017 [27]. Therefore, the adequate treatment of these biowastes is an important component of any integrated solid waste management strategy, mainly because it could reduce the toxicity and volume of the MSWs requiring final disposal in a landfill. This is to limit the impact on the environment and human health and to incentivize the development of the most appropriate treatment technologies for energy production and nutrient recovery in by-products [28–30].

Particular attention must be paid to soil-amendment practices using digestates in soils vulnerable to nitrogen leaching risk, as established by Council Directive 91/676/EEC with the aim of to protect waters from pollution caused by nitrates from agricultural sources. The Directive sets out the measures to be taken at the national level to reduce the impact of agricultural practices on water quality and promote the use of alternative sources of nutrients [31]. Climate change can also cause an increase in nitrogen losses from the soil by leaching due to the increase in rainfall concentrated in short periods. Nitrate leaching was affected by both temperature and precipitation, and organic farming practices can help to reduce nitrate leaching [32,33]. This research couples the study on the suitability of fertilizing use of OFMSW digestates differently treated (as such, dried or composted) with the evaluation of their impact on nitrogen loss by leaching into groundwater.

The objectives of this research were: (i) to verify the effects of soil fertilization with OFMSW digestates differently processed on nitrogen ryegrass nutrition; (ii) to evaluate their impact on nitrogen loss due to leaching.

2. Materials and Methods

2.1. Soil Analysis

At the outset of the study, prior to the implementation of amendment treatments, an analysis was conducted on the soil utilized in the pot experiment. The soil was collected from the surface layer (0–0.30 m) and subsequently oven-dried at 105 °C prior to analysis.

The humidity was determined by weighing a known quantity of a sample of material as such, placing it in an oven at 105 °C until the weight is constant (24 h) and weighing the sample again. Soil analyses were performed on air-dried soil. The analyzed values were subsequently referred to dry soil at 105 °C using the appropriate conversion factors. The main physical and chemical properties of the soil were established using the Official Methods of the Ministry of Agriculture (Italy) [34]. Soil pH was determined by means of a glass electrode using a water-to-soil ratio (v/w) of 2.5:1; particle size was assessed through a sedimentation procedure; total soil organic carbon and nitrogen were measured using a Leco RC-612 carbon analyzer and Nitrogen Leco FP-528, respectively, while cation exchange capacity (CEC) and exchangeable cations (Ca, K, Mg, Na) were determined through the ammonium acetate procedure and after extraction with 1 M ammonium acetate solution, respectively. In addition, available phosphorus was measured using the Olsen method through a spectrophotometer [35].

The soil was A1-Fluventic Xerochrepts (USDA) [36], sub-alkaline pH, clay-loam texture, with a favorable supply of organic matter content and macro-elements (N, P, K), and well-balanced ratios among exchange bases in relation to CEC (see Table 1).

Table 1. Soil chemical-physical characteristics at the beginning of research (values are referred to d. m. at 105 °C).

Parameter	Value	Parameter	Value
Reaction pH	7.50	Sand g kg^{-1}	267
TOC g kg^{-1}	21.1	Silt g kg^{-1}	453
SOM g kg^{-1}	36.4	Clay g kg^{-1}	280
Total N g kg^{-1}	1.8	Texture (USDA)	Clay-loam
C/N ratio	11.7	CEC cmol(+) kg^{-1}	25.48
P_2O_5 g kg^{-1}	0.08	Ca cmol(+) kg^{-1}	19.66
K_2O g kg^{-1}	0.80	Mg cmol(+) kg^{-1}	3.08
$EC_{1:2.5}$ dS m^{-1}	0.213	K cmol(+) kg^{-1}	1.71
		Na cmol(+) kg^{-1}	1.03

2.2. Characterization of Organic Fraction of Municipal Solid Waste (OFMSW) Digestates

The Italian Composting Consortium (CIC) provided three types of OFMSW digestates that were analyzed for their chemical-physical characteristics through an accredited external laboratory, in accordance with the Annex IV of Regulation (EC) 2003/2003 and the Decree of the Ministry of Agricultural, Food and Forestry Policies (MiPAAF) of 19 July 1989, and subsequent amendments [37,38]. The three types of digestates were: digested OFMSW (F), dried digested OFMSW (FE), and digested and composted OFMSW (FEC). The parameters analyzed included total solids, volatile solids, total organic carbon, total nitrogen, organic nitrogen, total phosphorus, total potassium, total heavy metals and pH (as shown in Table 2). The parameters analyzed showed that the total N% content varies from 2.2% to 4.3%, the total organic C in % from 23.3 to 48.6%, alkaline pH, humidity varies from 16.3 to 72.7. Phosphorus, expressed in P_2O_5, varies from 0.7% to 3.6%. Approximately 5 L of each organic residue was collected, thoroughly mixed, and stored in 0.25–0.50 L plastic bottles at −20 °C until use.

Table 2. Characterization of OFMSW digestates (d.w.).

Parameter	F	FE	FEC
Humidity %	72.7	16.3	36.8
Reaction pH	8.5	8.4	8.0
Non-volatile solids %	82.4	47.9	67.3
Volatile solids %	17.6	52.1	32.7
Total N g kg^{-1}	43	39	22
Organic N g kg^{-1}	30	31	21
Organic C g kg^{-1}	338	233	486
C/N ratio	7.86	5.89	22.1
P (P_2O_5) g kg^{-1}	36	34	7
K (K_2O) g kg^{-1}	7	8	13
Cu mg kg^{-1}	93	102	56
Zn mg kg^{-1}	310	344	182
Pb mg kg^{-1}	2	0.5	3
Cr mg kg^{-1}	12	9	5
Cd mg kg^{-1}	0.4	0.1	0.1
Ni mg kg^{-1}	8	5	7
Hg mg kg^{-1}	<0.05	<0.05	<0.05

2.3. Pot Study Description

The pot experiment was conducted in Monterotondo, Rome (Italy), in an open greenhouse with only a roof to prevent rain from falling on the pots. The soil (density 1.1 Mg m^{-3}) was air dried and sieved to 5 mm. The pots (diameter 25 cm, soil height 25 cm) were filled with 5 kg of soil mixed with fertilizer. Two 10 mm diameter holes were made in the bottom of each pot to allow for water-leaching and its collection during the experiment. Whatman No. 41 filter papers were placed at the bottom of each pot to prevent soil loss.

The temperatures and relative humidity detected during the experimentation are shown in Figure 1.

The experimental design included five treatments: untreated soil (C); soil + ammonium sulphate (AS); soil + digested OFMSW (F); soil + dried digested OFMSW (FE); and soil + composted digested OFMSW (FEC). Each treatment was replicated four times and pots were arranged in a fully randomized experimental design.

To each treatment, an amount of fertilizer corresponding to 180 kg N ha^{-1} was added to the soil. The soil and corresponding treatment (AS or OFMSW digestates) were thoroughly mixed and the mixture obtained was used to fill pots. After three weeks, perennial ryegrass (*Lolium perenne* L. cv. Belida) was sown at 2.5 g m^{-2}. This crop was chosen due to its high nitrogen requirement and ability to endure frequent mowing [39,40].

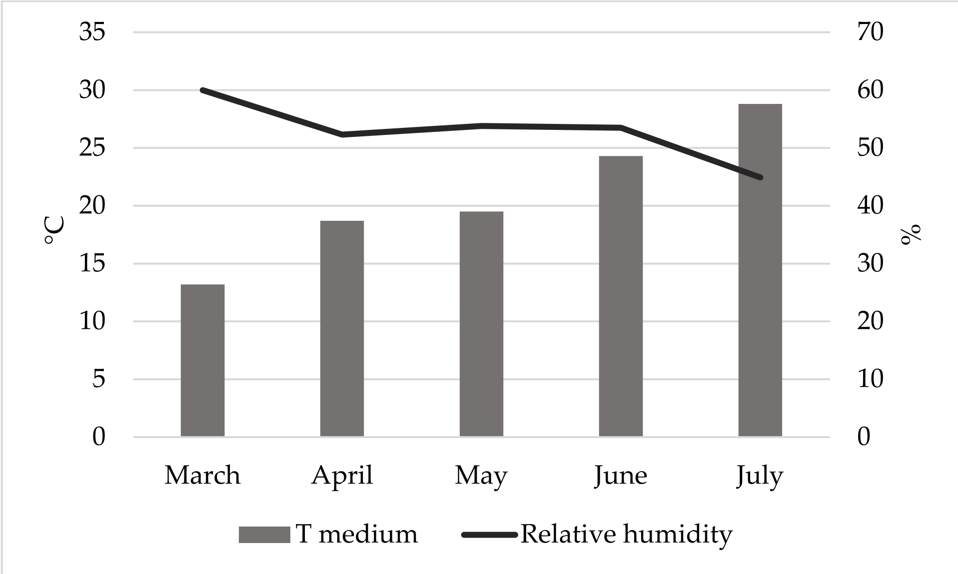

Figure 1. Temperatures and relative humidity (average monthly).

The experiment involved 5 harvests of ryegrass, with the first being conducted 40 days after sowing (H1) and subsequent harvests (H2–H5) being carried out over time. At each harvest, the aerial biomass of each pot was cut, weighed for fresh weight, and then dried at 65 °C for 72 h. The dried biomass was then weighed to determine the dry matter production, and ground into a fine powder for storage until the nitrogen concentration analysis was performed.

2.4. Simulated Rain Procedure

A simulated rain procedure was initiated 20 days after sowing (DAS) using an automatic sprinkling system to add water to each pot once every 10 days (Table 3). The amount of water added was determined based on pluviometric monthly data recorded over the last five years using the Open Data Latium Region (Italy) database as a reference [41]. One hundred and twenty water samples of eluates were collected during the experiment, frozen at −20 °C until analysis, and then analyzed for nitrogen forms colorimetrically using a continuous flux analyzer (Autoanalyser Technicon II. AxFlow S.p.A. Milan. Italy). Concentrations of NO_3 + NO_2 and N-NH_4 were determined for each sample of eluates to calculate nitrogen losses in the leached waters caused by the simulated rains.

Table 3. Timetable of ryegrass harvest, simulated rains and sampling of leachates. DAS = Days After Sowing; R = rain; H = harvest; L = leaching.

DAS	**20**	**30**	**40**	**48**	**50**	**59**	**60**	**68**	**70**	**82**
R	R1	R2	R3		R4		R5		R6	
L	L1	L2	L3		L4		L5		L6	
H			H1	H2		H3		H4		H5

2.5. Statistical Analysis

All data were analyzed using one-way analysis of variance (ANOVA) at each sampling time and for cumulative data (∑) (biomass yields, nitrogen concentration in ryegrass biomass, N uptake and N leaching). The homogeneity of variances was tested using Levene's test and Box–Cox transformation was performed when needed. Significant differences between the theses were assessed by means of Tukey's Honest Significant Difference (HSD) test at p value $\leq$ 0,05 when the F test of ANOVA was significant (α level = 0.05).

3. Results

3.1. Effects of OFMSW Digestate Fertilization on Ryegrass

3.1.1. Crop Productivity

The analysis of crop productivity for each harvest (Table 4) revealed a significant increase in dry matter production in AS, F, and FE treatments compared to C, but only in the second harvest (H2). No significant difference was observed for cumulative production among treatments and with respect to control. However, the highest total ryegrass biomass productions were present in AS and F compared to the other treatments and the control.

Table 4. Crop productivity (g pot^{-1} d.w.—mean ± sd, *n* = 4).

	H1 (**)	H2	H3 (*) (**)	H4 (**)	H5 (**)	∑ H1–H5 (*) (**)
C	3.97 ±0.33	2.75 b ± 0.30	5.54 ±0.32	2.25 ±0.32	3.27 ±0.71	17.78 ±1.04
AS	4.11 ±0.72	3.66 a ± 0.18	5.48 ±0.76	3.38 ±0.46	4.52 ±0.41	21.14 ±1.52
F	4.22 ±0.36	3.51 a ±0.36	5.19 ±1.56	3.26 ±1.59	3.39 ±2.35.	19.57 ±5.71
FE	3.34 ±0.61	3.49 a ±0.16	5.65 ±0.19	2.13 ±0.62	2.67 ±1.25	17.28 ±1.47
FEC	3.86 ±0.81	3.12 ab ±0.35	5.61 ±0.36	1.95 ±0.41	4.16 ±1.43	18.70 ±2.56

Means in each column followed by the same letter are not significantly different (Test HSD Tukey—*p* level ≤ 0.05)—(*) Box–Cox data transformation—(**) Test F ANOVA not significant.

3.1.2. Nitrogen in Ryegrass

The nitrogen concentrations in ryegrass biomass were determined at each harvest and the results are shown in Table 5 as percentages.

Table 5. N percentage in vegetal tissues (% d. w.-mean ± sd, *n* = 4).

	H1	H2 (*) (**)	H3 (*) (**)	H4 (*) (**)	H5 (*) (**)	Mean H1–H5 (*) (**)
C	6.18 b ±0.06	6.13 ±0.09	5.90 ±0.19	5.90 ±0.29	4.39 ±1.10	5.70 ±0.33
AS	6.76 c ±0.09	6.31 ±0.12	6.12 ±0.20	5.93 ±0.05	5.62 ±0.35	6.14 ±0.10
F	5.71 a ±0.14	5.88 ±0.58	5.06 ±1.24	4.76 ±1.17	4.74 ±1.26	5.23 ±0.85
FE	5.82 a ±0.12	5.95 ±0.10	5.48 ±0.95	5.59 ±0.96	5.09 ±1.70	5.58 ±0.34
FEC	6.28 b ±0.08	6.00 ±0.06	5.68 ±0.48	5.83 ±0.95	4.67 ±1.10	5.69 ±0.48

Means in each column followed by the same letter are not significantly different (Test HSD Tukey—*p* level ≤ 0.05)—(*) Box–Cox data transformation—(**) Test F ANOVA not significant.

In the first harvest (H1), ryegrass fertilized with ammonium sulfate had a higher nitrogen concentration than those fertilized with organic fraction of municipal solid waste digestates or the control. However, in subsequent harvests (H2–H5), there were no significant differences in nitrogen concentration among the fertilization treatments.

The mean of nitrogen quantities analyzed in ryegrass in five cuttings followed the trend: F < FE < FEC ≃ C < AS. When the average nitrogen concentration in plant tissues is considered, the ryegrass fertilized with ammonium sulphate absorbed more nitrogen than the other treatments, but without significant differences. In examining these results, it should be considered that all harvests were carried out after watering the soil (simulated rain). This induced a loss of available nitrogen analyzed in the eluates.

In Table 6, the values of nitrogen uptake by ryegrass are reported. The nitrogen uptake was calculated by multiplying nitrogen concentration in ryegrass per weight of the dried biomass production.

Table 6. N-uptake (g pot^{-1} d.w.—mean ± sd, *n* = 4).

	H1 (**)	H2 (*)	H3 (**)	H4 (*) (**)	H5 (**)	∑ H1–H5 (*) (**)
C	0.24 ±0.02	0.17 a ±0.02	0.33 ±0.01	0.13 ±0.02	0.15 ±0.06	1.02 ±0.08
AS	0.28 ±0.05	0.23 b ±0.01	0.34 ±0.04	0.20 ±0.03	0.25 ±0.03	1.30 ±0.10
F	0.24 ±0.02	0.21 ab ±0.04	0.28 ±0.13	0.17 ±0.11	0.18 ±0.15	1.08 ±0.43
FE	0.19 ±0.03	0.21 ab ±0.01	0.31 ±0.06	0.12 ±0.05	0.13 ±0.08	0.97 ±0.15
FEC	0.24 ±0.05	0.19 ab ±0.02	0.32 ±0.04	0.12 ±0.04	0.21 ±0.10	1.08 ±0.20

Means in each column followed by the same letter are not significantly different (Test HSD Tukey—*p* level ≤ 0.05)—(*) Box–Cox data transformation—(**) Test F ANOVA not significant.

In H1, no significant differences were found between differently fertilized plots compared to the control. In H2, the significant difference between the C and AS treatments may be attributed to the amount of readily available nitrogen added with the mineral fertiliser. The nitrogen uptake values in ryegrass treated with differently treated OFMSW digestates were like AS. In H3 in all theses, an increase in nitrogen uptake was observed. This trend is mainly due to the higher production of vegetable biomass found in the third cut compared to the other harvests (Table 4).

As for the nitrogen uptake cumulative, the higher value was observed in the treatment with mineral fertilizer (AS) without significant differences both with the control and with the theses treated with digestates.

3.2. *Effect of OFMSW Digestate Fertilization on N Leaching*

Table 7 shows the concentrations of nitrogen analyzed in eluates from the simulated rains.

Table 7. N leached (mg pot^{-1}—mean ± sd, *n* = 4).

	L1 (*)	L2 (*)	L3 (**)	L4 (*) (**)	L5 (**)	L6(**)	∑ L1–L6 (*)
C	32.10 a ±9.52	33.90 a ±17.63	14.36 ±8.15	64.03 ±34.90	67.15 ±59.98	38.71 ±6.45	250.24 a ±117.78
AS	147.90 c ±43.49	151.12 b ±101.28	39.47 ±20.07	125.88 ±53.09	96.53 ±28.89	87.50 ±22.27	648.38 b ±169.89
F	70.90 ab ±27.90	53.90 ab ±14.73	18.30 ±12.77	74.20 ±76.74	70.65 ±60.24	93.50 ±73.66	381.70 ab ±197.27
FE	57.80 ab ±13.08	109.00 ab ±58.52	20.10 ±14.51	58.10 ±60.53	70.10 ±53.83	116.40 ±73.60	431.70 ab ±229.40
FEC	108.10 bc ±12.58	38.20 ab ±13.68	15.70 ±3.00	72.00 ±31.42	75.53 ±47.00	51.30 ±41.35	361.01 ab ±91.55

Means in each column followed by the same letter are not significantly different (Test HSD Tukey—*p* level ≤ 0.05)—(*) Box–Cox data transformation—(**) Test F ANOVA not significant.

The leached nitrogen concentrations showed great variability over time. In L1, the highest nitrogen concentrations in eluates were found in AS and FEC. The soil fertilized with AS maintained higher leached nitrogen values than the thesis treated with digestates until the fifth rainfall. In L2, the highest N leachate values were found in AS and FE. In L3, there were lower nitrogen values in all the theses than in L1 and L2. The first harvest (H1) was carried out after the second simulated rain, so the crop had time to utilize nitrogen available for plant nutrition. The following water addition to the soil (L4) stimulated the mineralization process of soil organic substances, which could explain the highest nitrogen values in L4 compared to L3. In L4, a loss of nitrogen higher than all the other theses was highlighted in AS leachate. Cumulative data showed that the control had the lowest nitrogen loss due to leaching, while AS-fertilized soil had the highest loss. The increase in nitrate leachate in AS-fertilized soil was approximately 159% compared to the control. For soil treated with OFMSW digestates, the increase in nitrate leachate ranged from approximately 44% (FEC) to 72% (FE) across different treatments.

4. Discussion

The results obtained did not show significant differences in the production of vegetable biomass and in the absorption of nitrogen by the ryegrass between the plants fertilized with ammonium sulphate and those treated with OFMSW digestate. Del Pino et al. [42] reached similar results in a study conducted to investigate the suitability of digestate derived from agro-industrial residues as a fertilizer for crops and its effects on soil quality. The study was conducted on Setaria grown in greenhouses. The results showed that nitrogen concentration in ryegrass was similar between diammonium phosphate and digestate fertilization. Similarly, Florio [43], in a comparative study between mineral and organo-mineral fertilization conducted on ryegrass in pots, did not observe significant differences in N uptake and yield in crop differently fertilized. Additionally, Sharifi [44], in a test of fertilization with digestates conducted on ryegrass in a greenhouse, did not find significant differences in the concentration of N in plant tissues.

Regarding the objective (i) to verify the effects of soil fertilization with OFMSW digestate differently processed on nitrogen plant uptake in ryegrass, the results obtained in the present study show that these bio-based fertilizers are an alternative source of nitrogen for crop nutrition. OFMSW digestates sustained ryegrass nitrogen nutrition despite losses of available nitrogen induced by the rainfall simulation, as also highlighted by Wang [45], who investigated nitrate accumulation and leaching in surface and groundwater through simulated rainfall experiments in soil.

Regarding the results of the rainfall simulation to evaluate the nitrogen losses in the leachates, it should be considered that the first simulated rain (L1) was conducted approximately 40 days after mixing the soil with the organic fertilizer, and the second after 50 days (L2). Although the carbon/nitrogen ratio of FEC is higher than in the other digestates, which suggests a corrective effect and slow N release, the amount of N leached in the first rainfall (L1) of FEC was high and similar to the amounts released from AS. In the subsequent rains, the phenomenon stabilized and the composted digestate leached the least amount of nitrogen among the fertilizers used. Generally, the higher the carbon/nitrogen ratio, the longer it will take for the biological material to decompose. Likewise, the lower the ratio, the faster the biological material will decompose [46–48]. The value of the carbon/nitrogen ratio (7.86) of OFMSW digestate as such (F) favors mineralization processes of soil organic matter. Dried OFMSW digestate (FE) was characterized by a low carbon/nitrogen ratio (5.89), which accelerates the process of nitrogen mineralization in soil. The composted OFMSW digestate (FEC) had the highest value (carbon/nitrogen ratio = 22.09) and could promote slow mineralization of soil organic matter, leading to a partial microbial nitrogen immobilization. A study conducted by Masunga [49] analyzed the decomposition of several organic materials, including poultry manure, cow manure and compost. The results showed that the rate of nitrogen mineralization varied according to the type of organic amendment used. In particular, in the intermediate incubation time, the compost amendment mineralized higher amounts of nitrogen than the fresh ones. It should also be noted that in this case, the C/N ratio of the compost had higher values than the fresh amendment (fresh white clover). Similar results had already been highlighted by Tamara [17], who found a peak of mineralized nitrogen in the first 50 days of incubation in the composted amendments compared to the non-composted ones.

These results confirm the influence of the different compositions of OFMSW digestates, in particular the concentration of organic carbon and the carbon/nitrogen ratios, on the mineralization process of soil organic matter and on the concentration of nitrogen available for plant nutrition or lost for runoff or leaching.

Mineral fertilization had the highest amount of nitrogen losses due to leaching compared to soil amendment with MSW digestates. Due to these characteristics, the behavior of FEC in soil could be like a soil amendment, with slow mineralization and lower nitrogen loss by leaching than F and FE.

Regarding the objective (ii) to evaluate the OFMSW digestate impact on nitrogen losses due to leaching, soil fertilization with digestates derived from OFMSW had a positive effect limiting nitrogen loss by leaching compared to mineral fertilization. This effect could depend on the improvement of soil quality due to the soil-improving properties of these by-products of anaerobic digestion, in particular of the co-composted formulation.

5. Conclusions

This study has shown that fertilization with OFMSW digestate supports the nitrogenous nutrition of ryegrass like a synthetic mineral fertilizer and above all, compared to ammonium sulphate, has strongly moderated the phenomena of nitrogen leaching, especially when using the composted digestate. These results highlight the need to expand knowledge on the effects of fertilization with OFMSW digestates on soil quality and nutrient recovery in crops of agricultural interest and in different experimental conditions, while also evaluating their applicability on soils vulnerable to nitrate loss.

The agricultural valorization of biowaste constitutes an added value in the development of the circular economy and agricultural eco-sustainable management, but more effort is needed to overcome the obstacles and promote its widespread adoption. It is necessary to promote biowaste recycling practices and the optimization of by-product transformation processes. The standardized production of digestates could be intended for agronomic use with economic and environmental benefits, as they are recyclable by-products. At the local level, actions aimed at creating small processing plants and supporting non-profit investments that help achieve the environmental objectives corresponding to the new framework of the circular economy and the bioeconomy should be encouraged.

The subsequent treatment processes of OFMSW digestates (for example composting) make it possible to obtain both "quick effect" products with high efficiency of use, which can be used for sustainable and/or precision agriculture techniques, and slow effect products, which increase C stocks in the soil and help mitigate the effects of greenhouse gases. The future and innovative applications of the agricultural use of OFMSW digestates should envisage the development of a model for the production of bio-based fertilizers directly at the MSW treatment plants. The correct management of biofertilizers derived from OFMSW would make it possible to optimize the supply of nutrients (N in particular) in agriculture and their emissions into the environment, and to improve the storage of C and soil functionality.

The large quantities of OFMSW produced in the world and the availability of a wide range of treatment processes and products, together with the knowledge of soil characteristics and plant/soil relationships, would allow this agronomic practice to be optimized and made sustainable.

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