agronomy

MDPI

Article

Assessment of the Agronomic Value of Manure-Based Fertilizers

Joana Prado *, David Fangueiro , Paula Alvarenga and Henrique Ribeiro *

LEAF, TERRA, Instituto Superior de Agronomia, Universidade de Lisboa, 1349-017 Lisboa, Portugal
* Correspondence: jprado@isa.ulisboa.pt (J.P.); henriqueribe@isa.ulisboa.pt (H.R.)

Abstract: Producing manure-based fertilizers (MBFs) with specific nutrient ratios is a solution to overpassing the imbalance of nitrogen and phosphorus in manures, and a way to recycle manure's nutrients, promoting sustainable agricultural practices. Several MBFs with different tailored N:P ratios (0.5:1, 1:1 and 2:1) were produced to determine their agronomic value in a pot experiment with oat (0.5:1 ratio: cattle manure with pig slurry (CaM+PiS), cattle manure with poultry manure (CaM+PoM) and poultry manure with superphosphate (PoM+SP); 1:1 ratio: poultry manure with cattle slurry (PoM+CaS) and poultry manure with pig slurry (PoM+PiS); 2:1 ratio: cattle slurry with the liquid fraction of cattle slurry (CaS+CaS-LIQ), pig slurry with the liquid fraction of pig slurry (PiS+PiS-LIQ) and poultry manure with urea (PoM+U)). The performance of these MBFs was compared with conventional mineral fertilizers (MFs) in sandy soils (Haplic Arenosols) with different nutrient requirements. Oat fertilized with PoM+SP (0.5:1) and PoM+PiS (1:1) led to yields similar to those obtained with the use of MFs (6.3 and 7.2 mg DM, respectively). The MBFs PoM+SP and PoM+PiS, as well as PiS+PiS-LIQ (2:1), were agronomically equivalent to the MFs. N uptake with those MBFs was equivalent to that obtained with the MFs. Replacing MFs with MBFs in the basal fertilization of oat was demonstrated to be a solution to turn agriculture more sustainable by recycling nutrients efficiently.

Keywords: manure-based fertilizer; tailored N:P ratio; N uptake; P uptake; sustainable agriculture

Citation: Prado, J.; Fangueiro, D.; Alvarenga, P.; Ribeiro, H. Assessment of the Agronomic Value of Manure-Based Fertilizers. *Agronomy* **2023**, *13*, 140. https://doi.org/10.3390/agronomy13010140

Academic Editor: Hans-Werner Olfs

Received: 31 October 2022
Revised: 22 December 2022
Accepted: 27 December 2022
Published: 31 December 2022

1. Introduction

The growing demand for food worldwide led to the need of improving crop production and, concomitantly, agriculture became more dependent on nutrient application in the form of mineral fertilizers (MFs) [1]. Simultaneously, according to Iqbal et al. [1], soil became more deficient in organic matter and nutrients.

Over the last decades, what once was a cohesive ecosystem, now became two separate sectors, where crop production and livestock grew separately, culminating in an open nutrient cycle, with imbalanced flows of nutrients between these two activities, which led to serious environmental and economic issues [2,3]. One of the consequences is the surplus of manure production in some areas, which remains marginally applied to crops due to this separation between livestock production and crop production [4]. The application of manure to the soil is known to have several benefits, such as an increase in the soil's nutrient reserve, enhancing microbial activity, and improving the soils' chemical and physical properties [5]. The high agronomic value of manure should encourage farmers to apply it to soil [6], but its lower nutrient concentration and variability in terms of composition relative to MFs, as well as the lack of knowledge regarding the plant availability of these nutrients, culminates in a low acceptance by farmers on the use of these materials [7]. Moreover, most manure fertilization recommendations are based on the crops' nitrogen (N) requirements, which caused, in many situations, an overapplication of phosphorus (P) to the soil, especially in Flanders and in the Netherlands, with serious environmental consequences concerning surface and groundwater contamination [8].

The concept of a manure-based fertilizer (MBF) emerges as a solution to solve several problems associated with manure application, namely, diminishing the differences between manure and mineral fertilizers, increasing the acceptance of manures by farmers, and enhancing the manure agronomic value by increasing the availability of specific nutrients. Nonetheless, the use of MBFs will also reduce the necessity of applying MFs, which in some cases led to soil overexploitation [9,10]. The use of MBFs with a tailored N:P ratio will address the main issues pointed out by farmers as limitations to the use of manures as fertilizers, since MBFs can contribute to (i) obtaining a material with lower variability in terms of composition, (ii) designing N:P ratios, close to values usually found in MFs and adapted to different soils' fertility classes, (iii) increasing the nutrients concentrations, and (iv) supplying both nutrients and organic matter to the soil, improving the soil's health, important to assure food security and safety [6]. Additionally, livestock farmers have been struggling to dispose manure since the production overpasses the demand [11]. Hence, the production of MBF will solve the problem of manure surplus.

The importance of having a distinct N:P ratio in a fertilizer is to adjust nutrient concentrations, not only to crops requirements, but also to the soil fertility status [12]. The production of MBFs would strengthen the link between the livestock and crop production sectors, not only by recycling manure nutrients, but also by making their concentrations similar to those found in MFs. Furthermore, MBFs will be available for crop farmers during the whole year, in contrast with animal manure that is generally available during specific periods of intensive farming. Hence, the application of MBFs will reduce nutrient losses and contribute to a circular economy by closing the nutrients' cycle [13], avoiding, for instance, N losses from manure, which can be as high as 80% [14]. The partial replacement of MFs with MBFs can be a first step to guaranteeing food security since nutrients are recovered to the food chain [15], contrarywise to MFs, which need to be produced from non-renewable sources, such as phosphate rocks [16].

Aligned with this idea, there is currently a proposal to lessen the legal restrictions on the application of manure and derived products if those fertilizers comply with the RENURE criteria (i.e., ratio N mineral/N total > 90%, or ratio total organic carbon/N total $\leq$ 3) [17]. If these criteria are achieved, application of MBFs in nitrate-vulnerable areas would not be as restrictive (maximum 170 kg N ha^{-1} $year^{-1}$), allowing N application rates similar to those when using MFs [17], and the production and use of MBfs would be encouraged.

The aim of this study was to determine the agronomic efficiency of a set of MBFs with specific N:P ratios in terms of their ability to replace MFs for basal fertilization. These MBFs were obtained considering two scenarios: (i) "on-farm", where manures produced by a single animal species can be mixed with small amounts of mineral fertilizer to tailor their N:P ratios; and (ii) a "central-solution" for manure processing, where manures and derived products are obtained by a technical treatment (solid–liquid separation) and then mixed to optimize their N:P ratios. The two scenarios considered two perspectives. One scenario, where the farmers would produce the MBFs on their own, and the second is more similar to MFs, where the production of MBFs would be at a centralized plant, but still using available manure resources. The second scenario appears to be a solution for regions with a surplus of all manures, since the continuous production of these organic materials can become an environmental problem [10]. In previous studies, Prado et al. [15] indicated that N availability in soils fertilized with MBFs depends on the type of manure considered, as well as on the mixture produced. However, these results were obtained in a laboratory incubation experiment using soil without plants. As the properties of the soil and the plant behavior affect nutrient availability, it is important to evaluate the performance of MBFs in soils with different properties, also considering soil–plant interactions. The application of these MBFs in the basal fertilization for oat was evaluated, assessing the nutrients' availability to the plant by ascertaining nutrient uptake, apparent recovery, and concentrations in the soil. Oat is an important cereal for human and livestock feeding [18], and its fertilization with manure or manure-derived fertilizers would be very important as a strategy to close the nutrients' cycle and increase sustainability in crop and livestock production.

The novelty of this study is that it offers a solution to the use of manures which have an imbalanced N:P ratio compared to the crops' nutrient demand and converets them to a material with a known N:P ratio, a feature currently attributed only to MFs. Recently investigations focusing on MBFs have gained more interest as in some cases MBFs were obtained with new advanced technological solutions [14]. The solutions tested in this study intended to increase the manure potential as MBF, while trying to make the most of its intrinsic characteristics.

2. Materials and Methods

2.1. Manure

The manures utilized in the present study were pig slurry (PiS), cattle slurry (CaS), cattle manure (CaM) and poultry manure (PoM), collected from the same farms as the ones used in previous studies conducted by Prado et al. [19]. These manures were selected according to the Portuguese reality as a result of their surplus in the livestock sector, which indicates their availability all year. CaS and CaM were collected from an intensive dairy farm in Benavente, while PiS was collected from a fattening pig farm in Montijo. CaS was richer in straw bedding material, which increased its dry matter content. PoM was collected at a poultry farm located at Alvalade-Sado. PoM had a high content of rice hull bedding, which may have diluted some of the nutrients and increased its dry matter content. The slurries were treated by solid–liquid separation, to use the resulting liquid fraction (LIQ) as described by Prado et al. [19]. All animal manures and subproducts were analyzed for their pH, dry matter (DM), total organic carbon, total N (N_{Total}), ammonium N (NH_4^+), total P (P_{Total}, expressed as P_2O_5), and total K (K_{Total}, expressed as K_2O) concentrations, following the methodologies described in Rodrigues et al. [20]. The characteristics of all manures and products are summarized in Table 1.

Table 1. Physicochemical characteristics of the raw manures considered in the study (mean value ± standard deviation, n = 3). The composition of each manure-based fertilizer was calculated to provide the desired N:P ratios, and the nutrients' concentrations and ratios were calculated considering the values of the raw manure and derived fractions. All concentrations were expressed on a fresh matter basis.

		DM	TOC	N_{Total}	NH_4^+-N	N_{av}	P_{Total}	N:P	K_{Total}
		g kg^{-1}	g kg^{-1}	g kg^{-1}	g kg^{-1}	g kg^{-1}	g P_2O_5 kg^{-1}		g K_2O kg^{-1}
Raw Manures	PiS	32.4 ± 0.6	11.7 ± 0.4	3.32 ± 0.05	2.47 ± 0.01	1.99 ± 0.05	0.99 ± 0.02	2.0	2.14 ± 0.08
	PiS-LIQ	16.4 ± 0.4	5.2 ± 0.2	2.60 ± 0.05	2.26 ± 0.03	1.56 ± 0.04	0.09 ± 0.01	17.5	1.86 ± 0.01
	CaS	160.9 ± 3.3	48.8 ± 1.9	3.87± 0.05	1.70 ± 0.01	2.32 ± 0.03	0.75 ± 0.02	3.1	7.16 ± 0.22
	CaS-LIQ	48.2 ± 1.9	20.8 ± 2.5	3.96± 0.01	1.80 ± 0.02	2.38 ± 0.03	0.32 ± 0.01	7.4	0.87 ± 0.10
	CaM	197.4 ± 0.1	88.8 ± 0.1	5.85± 0.16	2.75 ± 0.04	2.93 ± 0.05	4.14 ± 0.12	0.7	11.03 ± 1.12
	PoM	742.5 ± 3.3	356.7 ± 5.9	23.34± 0.50	3.67 ± 0.13	11.67 ± 0.02	9.96 ± 0.46	1.2	16.50 ± 0.93
0.5:1 Ratio	CaM+PiS	187.8	83.8	5.8	2.7	2.9	4.1	0.7	10.9
	CaM+PoM	204.4	91.9	6.3	2.8	3.1	4.3	0.7	11.2
	PoM+SP	724.4	348.0	22.8	3.6	11.4	22.8	0.5	16.1
	07:14:14	-	-	70.0	50.0	70.0	140.0	0.5	140.0
1:1 Ratio	PoM+PiS	419.7	199.9	14.2	3.1	7.3	5.9	1.2	10.0
	PoM+CaS	517.3	238.3	15.9	2.7	8.1	6.5	1.2	11.3
	10:10:10	-	-	100.0	75.0	100.0	100.0	1.0	100.0
2:1 Ratio	PiS-LIQ+PiS	29.8	11.3	3.2	2.4	1.9	0.8	2.3	2.1
	CaS-LIQ+CaS	144.1	45.5	3.9	1.1	2.3	0.9	2.5	2.7
	PoM+U	728.0	349.7	31.9	12.6	20.5	9.8	2.1	16.2
	13:06:18	-	-	130.0	105.0	130.0	60.0	2.2	180.0

PiS: pig slurry; PiS-LIQ: liquid fraction from pig slurry; CaS: cattle slurry; CaS-LIQ: liquid fraction from cattle slurry; CaM: cattle manure; PoM: poultry manure; PoM+U: poultry manure with urea; PoM+SP: poultry manure with superphosphate; +: mixed with; DM: dry matter; TOC: total organic carbon; N_{Total}: total nitrogen; NH_4^+-N: ammonium nitrogen; N_{av}: available nitrogen (calculated as according to [21]; P_{Total}: total phosphorus, expressed as P_2O_5; N:P: abbreviation for N_{av}:P_2O_5; K_{Total}: total potassium, expressed as K_2O.

2.2. Manure-Based Fertilizer Preparation

The target N:P ratios for the MBFs considered were 0.5:1, 1:1, and 2:1. The available N (N_{av}) and P content (expressed as P_2O_5) were used to define the ratios in order to follow the same criteria used for mineral fertilizers (referred to hereafter as N:P ratio). N_{av} was calculated according to Portuguese legislation, where the amount of N_{av} is equal to 60% or 50% of the total N content of the manure for animal manures with DM < 20% and DM > 20%, respectively [21].

The MBFs used were designed according to two scenarios previously referred to as (i) "on-farm" with only one type of manure, enriched with a small amount of mineral fertilizer to obtain the desired N:P ratios and (ii) "central-solution", where the processing of different types of manures from different animal species is possible. The solid–liquid separation of the slurry was considered a pre-treatment. Each N:P ratio was designed to be more adequate for a specific soil type with a different nutrient status. In the case of the 0.5:1 N:P ratio, the blends designed were: (i) Cattle manure with pig slurry (CaM+PiS); (ii) Cattle manure with poultry manure (CaM+PoM); (iii) Poultry manure with superphosphate (PoM+SP). For the 1:1 ratio, the following mixtures were considered: (i) Poultry manure with cattle slurry (PoM+CaS), (ii) Poultry manure with pig slurry (PoM+PiS). For the 2:1 N:P ratio the mixtures considered were: (i) Cattle slurry with the liquid fraction of cattle slurry (CaS+CaS-LIQ); (ii) Pig slurry with the liquid fraction of pig slurry (PiS+PiS-LIQ); (iii) Poultry manure with urea (PoM+U). The main characteristics of the blends are also presented in Table 1.

2.3. Pot Experiment

The crop utilized in the present study was oat (*Avena strigosa* cv Saia). To remove bacterial pathogens, a preventive treatment with bleach was performed on the seeds [22].

Three sandy soils, all classified as Haplic Arenosols, with very distinct extractable P content, which corresponded to three different nutrient classes according to the Portuguese classification system, were used: poor (soil 1), fertilized with 0.5:1 MBFs and MF; medium (soil 2), fertilized with 1:1 MBFs and MF; and rich (soil 3), fertilized with 2:1 MBFs and MF (for more soil characteristics see Table 2). The fertilization was planned according to the crop needs for basal fertilization and the soil type (Table 2). The basal fertilization was based firstly on the plant requirement regarding N, and it was checked on whether P was not being over-applied. The Portuguese recommendation for oat fertilization is to add 1/3 to 1/2 of the N needs via basal fertilization [23]. In this study, the decision was to add 1/2 of the N needs to maximize the N input. Apart from the MBFs, three commercial MFs were applied to the soil, selected in accordance with the soil, N:P ratios, and the crop's needs: 07:14:14 (0.5:1 N:P ratio) for Soil 1, 10:10:10 (1:1 N:P ratio) for Soil 2, and 13:06:18 (2:1 N:P ratio) for Soil 3. The MF 10:10:10 had 10% of N (2.5% NO_3^--N and 7.5% NH_4^+-N) and 10% of P (expressed as P_2O_5), the 13:06:18 presented 13% of N (2.5% NO_3^--N and 10.5% NH_4^+-N) and 6% of P (expressed as P_2O_5), and the 07:14:14 presented 7% of N (2% NO_3^--N and 5% NH_4^+-N) and 14% of P (expressed as P_2O_5). For each soil, an unfertilized treatment was used as control. The quantity of N, P, and K applied per pot with each MBF or MF was calculated (Table 3).

Table 2. Soil initial characteristics and the respective basal fertilization recommendation.

		Soil 1	Soil 2	Soil 3
Soil characteristics	NO_3^--N (mg kg^{-1} soil)	1.9	2.8	10.6
	Extractable P_2O_5 (mg kg^{-1} soil) *	22.5	62.1	418.1
Basal fertilization recommendation	Nitrogen available applied (mg pot^{-1})	117.0	117.0	117.0
	Phosphorus applied (mg P_2O_5 pot^{-1})	200.0	100.0	50.0

* Extracted with Egner-Rhiem method.

The experiment was conducted between January and March 2022. The pots used in this study were circular, 21 cm heigh, and had a surface area of −115.5 cm^2 with a volume of

5 L. Four repetitions per treatment were considered, with a total of 56 pots each filled with 5 kg of soil. Pots were randomly distributed on a growing bench and moved every week to ensure that light exposure was the same for all pots throughout the whole experiment. The soil moisture was kept at 70% of their maximum water holding capacity during the whole experiment. MBFs and MFs in each treatment were incorporated into the soil four days before sowing. This short period between application and sowing is a common practice in winter crops in Portugal and aims to minimize nutrient losses due to heavy rainfall in winter, typical of the Mediterranean climate.Fifty seeds were sown per pot, which were reduced to a total of 25 plants per pot after germination.

Table 3. Fertilizer application rate in each treatment (g pot^{-1}) and the correspondent nutrients applied (g pot^{-1}).

Soil N:P Ratio	Fertilizer	Fertilizer Application Rate (g pot^{-1})	Nutrient Applied (mg pot^{-1}) N_{av}	N_{Total}	P_2O_5
Soil 1 0.5:1 ratio	Control	no fertilizer	-	-	-
	CaM+PiS	40.1	117.0	232.8	163.6
	CaM+PoM	37.2	117.0	233.3	159.1
	PoM+SP	10.3	117.0	233.3	233.9
	07:14:14	1.7	117.0	117.0	233.0
Soil 2 1:1 ratio	Control	no fertilizer	-	-	-
	PoM+PiS	16.0	117.0	228.5	94.2
	PoM+CaS	14.5	117.0	229.0	94.4
	10:10:10	1.17	117.0	117.0	117.0
Soil 3 2:1 ratio	Control	no fertilizer	-	-	-
	PiS+PiS-LIQ	60.8	117.0	194.4	51.0
	CaS+CaS-LIQ	50.1	117.0	194.4	47.1
	PoM+U	5.7	117.0	181.9	55.7
	13:06:18	0.9	117.0	117.0	53.8

PiS: pig slurry; PiS-LIQ: liquid fraction from pig slurry; CaS: cattle slurry; CaS-LIQ: liquid fraction from cattle slurry; CaM: cattle manure; PoM: poultry manure; PoM+U: poultry manure with urea; PoM+SP: poultry manure with superphosphate; +: mixed with.

2.4. Plant Analyses, Yield, and Nutrient Uptake Calculations

After two months of growth, the aboveground part of the plants was cut, and the fresh weight, the dry weight (DM) (after three days in an oven at 60 °C), and the nutrient content were evaluated. Total N content was measured by the Dumas method using close to 80 mg of dry plant material [24] in a NDA 702 DUMAS Nitrogen Analyzer (VELP Scientific, Usmate Velate, Italy). The other elements were analyzed by inductively coupled plasma optical emission spectrometry (iCAP 7000 Series ICP Spectrometer, Thermo Fisher Scientific, Waltham, MA, USA) after a wet digestion of close to 0.2 g of dry plant material with aqua regia (nitric acid:hydrochloric acid ratio 3:1 v/v) at reflux conditions, maintained for 2 h in a block digestion system (Digipress MS, SCP Science, Canada).

The N and P uptake per pot was calculated as follows:

$$\text{Uptake} = \text{Dry Matter (kg)} \times \text{Nutrient content (g kg}^{-1}\text{ DM)} \quad (1)$$

The apparent N recovery was calculated and expressed as a percentage of the N_{av} and N_{Total} applied to the soil by the fertilize, following Shah et al. [25].

$$\text{Apparent N recovery (\%)} = (\text{N Uptake}_{\text{treatment}} - \text{N Uptake}_{\text{control}} \times 100)/\text{N applied} \quad (2)$$

The yield increase relative to the control ($\text{Yield}_{\text{increase}}$), obtained for each soil was calculated following Cai et al. [26]:

$$\text{Yield}_{\text{increase}}\text{ (g)} = \text{Yield}_{\text{treatment}}\text{ (g)} - \text{Yield}_{\text{control}}\text{ (g)}. \quad (3)$$

2.5. Soil Analyses

At the end of the experiment, the soil from each pot was collected, using a auger, thoroughly mixed, dried at room temperature and sieved using a 2 mm sieve. The pH and electric conductivity (EC) were measured in a water:soil suspension (1:2.5 *w*/*v*) after 1 h of agitation (pH meter model: Orion 3 Star and EC meter model: Orion star A212, Thermo Fisher Scientific, Waltham, MA, USA). The NO_3^--N was determined after a one-hour extraction with 2M KCl (soil:solution ratio 1:5 *w*/*v*) in the supernatant using a segmented flow autoanalyzer (San^{++} System, Skalar B.V., Breda, The Netherlands) [27]. Extractable P concentrations were measured based on the Egner-Rhiem method [28] by inductively coupled plasma optical emission spectrometry (iCAP 7000 Series ICP Spectrometer, Thermo Fisher Scientific, Waltham, MA, USA).

2.6. Statistics

The statistical analysis was performed using one-way ANOVA for each N:P ratio and soil type. Whenever significant differences were found, a Tukey test was performed at $p < 0.05$ using the Statistix 7 software, to futher illustrate differences among the means.

3. Results

3.1. Plant Yield

The yields obtained in soil 3 were always higher than those obtained in soil 1 or soil 2 (Figure 1). This was even verified for the Control, because soil 3 had a high level of fertility, as a result of its nutrients content (Table 2). Hence, to accurately compare the different treatments, the yield increase was calculated. Comparing those results shows that fertilizer application had a significantly higher impact on yields on soil 1 than on soil 2 and on soil 3 (i.e., the fertilization was more important in the "poorer" soil).

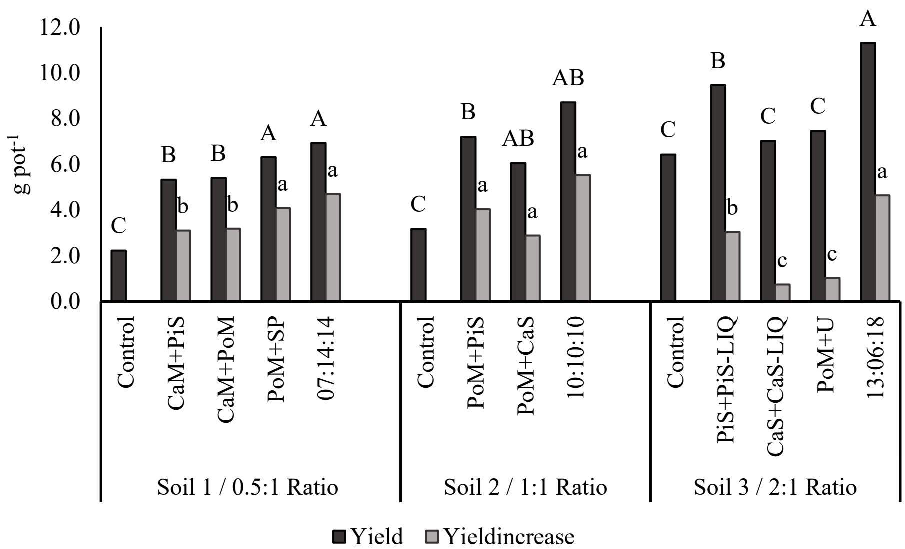

Figure 1. Total yield (DM) and yield increase ($Yield_{increase}$). Within each ratio, different letters represent significant differences for $p < 0.05$ (Tukey test), with capital letters referring to yield and small letters referring to yield increase. PiS: pig slurry; PiS-LIQ: liquid fraction from pig slurry; CaS: cattle slurry; CaS-LIQ: liquid fraction from cattle slurry; CaM: cattle manure; PoM: poultry manure; PoM+U: poultry manure with urea; PoM+SP: poultry manure with superphosphate; +: mixed with.

Assessing the treatments for each soil type, the major differences in total yield were observed between fertilized pots and the control without any fertilizer (Figure 1). On Soil 1 (fertilized with the 0.5:1 N:P ratio) the application of PoM+SP produced similar yields as the mineral fertilizer 07:14:14 (~6.6 g DM per pot). Significantly lower yields, compared to PoM+SP and 07:14:14, were observed with the application of CaM+PiS and CaM+PoM, which resulted in a $Yield_{increase}$ of ~3.1 g per pot.

On Soil 2 (fertilized with the 1:1 N:P ratio), the application of PoM+PiS led to a total yield increase without significant differences from the one obtained with the MF 10:10:10 application. The PoM+CaS treatment led to a significantly lower yield compared to the MF. This had consequences on the relative yield increase observed, which was significantly lower for PoM+CaS than for the mineral fertilizer 10:10:10 (2.88 g and 5.53 g per pot, respectively).

On soil 3, the impact of the application of the fertilizers, both organic and mineral, on yield was lower than on soil 1 and soil 2, when compared with the results obtained for the control, because soil 3 was richer in nutrients. Nonetheless, PiS+PiS-LIQ led to higher yield increases (~3 g per pot), which was significantly lower in the case of CaS+CaS-LIQ or PoM+U application, with a ~1 g per pot yield increase.

3.2. Nitrogen Uptake

Plants grown on Soil 1 (0.5:1 ratio) fertilized with the MBFs presented N concentration significantly similar to that found in the MF 07:14:14 (~15 g N kg^{-1} DM; Table 4). The combination of PoM with SP resulted in a N uptake equal to the one obtained after the application of the 07:14:14 MF. On the contrary, the absence of a mineral source in the MBFs, resulted in significantly lower N uptake (Table 4). Additionally, the apparent N recovery in PoM+SP was identical to 07:14:14 MF, i.e., close to 70% of the N_{av} (Figure 2). Nonetheless, oat plants fertilized with MBFs with the 0.5:1 ratio presented the lower N_{Total} apparent recovery (between 20–36%) compared to the 07:14:14 MF.

Table 4. Nitrogen and phosphorus, concentrations in the plant material as well as nutrient uptake calculated based onplant yield and nutrients concentrations in the plant. Results for each ratio in each column followed by different letters differ significantly for $p < 0.05$ (Tukey test).

Soil	Treatments	N	N Uptake	P	P Uptake
N:P Ratio		g kg^{-1} DM	mg N pot^{-1}	g kg^{-1} DM	mg P pot^{-1}
Soil 1 0.5:1 ratio	Control	12.56 c	27.95 d	2.46 b	5.41 d
	CaM+PiS	16.65 a	88.74 b	2.48 b	13.12 c
	CaM+PoM	14.09 bc	76.08 c	2.36 b	13.43 c
	PoM+SP	17.04 a	112.31 a	4.39 a	29.32 b
	MF 07:14:14	15.63 ab	106.66 a	4.98 a	34.51 a
Soil 2 1:1 ratio	Control	12.36 a	33.63 c	3.70 a	10.62 c
	PoM+PiS	14.41 a	96.29 ab	3.88 a	28.67 a
	PoM+CaS	15.04 a	91.03 b	4.31 a	24.66 b
	MF 10:10:10	13.38 a	116.58 a	3.61 a	28.91 a
Soil 3 2:1 Ratio	Control	15.26 d	93.59 d	8.64 b	53.30 c
	PiS+PiS-LIQ	24.37 a	229.83 a	8.24 b	81.66 a
	CaS+CaS-LIQ	21.73 ab	145.60 c	9.90 a	68.35 b
	PoM+U	18.92 bc	145.18 c	9.13 ab	66.20 b
	MF 13:06:18	16.67 cd	185.74 b	7.07 c	79.85 a

PiS: pig slurry; PiS-LIQ: liquid fraction from pig slurry; CaS: cattle slurry; CaS-LIQ: liquid fraction from cattle slurry; CaM: cattle manure; PoM: poultry manure; PoM+U: poultry manure with urea; PoM+SP: poultry manure with superphosphate; +: mixed with; n.a.: not applicable.

On Soil 2 (1:1 N:P ratio), N concentrations in the plants from all treatments (including the control) were similar. However, significant differences were observed regarding N uptake (Table 4). As occurred with the yields, N uptake was not significantly different between PoM+PiS and PoM+CaS, but only PoM+PiS led to a N uptake similar to the higher uptake observed for MF 10:10:10. Despite the available N applied in all treatments being equal (Table 3), the plants fertilized with the 10:10:10 MF had an apparent recovery close to 70% of the N_{av} applied, while in the plants fertilized with PoM+PiS or PoM+CaS the values were only of approximately 50%. The apparent N recovery, as a percentage of the

N_{Total}, was even lower following MBFs application to Soil 2 (i.e., only 30% was utilized), while oat plants fertilized with the MF 10:10:10 used 70% of the total N applied.

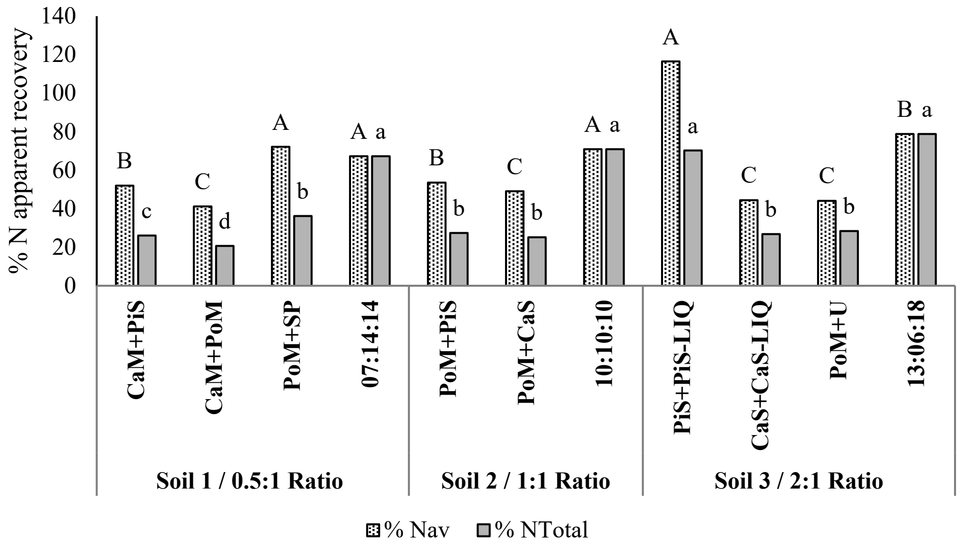

Figure 2. Apparent nitrogen recovery for oat fertilized with different MBFs and MFs, expressed as a percentage of available N (Nav) and total N (NTotal) applied. Results for each ratio in each column followed by different letters differ significantly for $p < 0.05$ (Tukey test), with capital letters referring to Nav and small letters referring to NTotal. PiS: pig slurry; PiS-LIQ: liquid fraction from pig slurry; CaS: cattle slurry; CaS-LIQ: liquid fraction from cattle slurry; CaM: cattle manure; PoM: poultry manure; PoM+U: poultry manure with urea; PoM+SP: poultry manure with superphosphate; +: mixed with.

Considering Soil 3 (2:1 N:P ratio), plants fertilized with PiS+PiS-LIQ and CaS+CaS-LIQ presented significantly higher N concentrations (~23 g N kg^{-1} DM) than the other two fertilized treatments. N uptake was significantly higher when PiS+PiS-LIQ was applied (~230 mg N pot^{-1}) relative to all other fertilizers. Nonetheless, N uptake by plants fertilized with a 13:06:18 mineral fertilizer was significantly higher than the one observed with the two MBFs from the 2:1 ratio (CaS+CaS-LIQ and PoM+U). Apparent N recovery from plants fertilized with PiS+PiS-LIQ corresponded to ~116% of the N_{av} applied and to ~70% of the N_{Total} applied, while those from the mineral fertilizer 13:06:18 were able to achieve an apparent N recovery, relative to N_{Total}, of ~79%. Comparing the MBFs for the 2:1 ratio, the apparent N recovery, compared with N_{av} and N_{Total}, was 2.6 times higher with the application of PiS+PiS-LIQ (Figure 2).

3.3. Phosphorus Uptake

On soil 1 plants fertilized with CaM+PoM and CaM+PiS, which did receive a P mineral source, showed a lower P concentration (~2.4 g P kg^{-1} DM). The addition of a mineral P source to PoM (PoM+SP), was efficient to stimulate a significantly higher P concentration in the plants (Table 4), achieving a concentration similar to the plants fertilized with the MF 07:14:14. In fact, P uptake by plants fertilized with PoM+SP (~29 mg P pot^{-1}) was more than doubled compared to CaM+PoM and CaM+PiS(~13 mg P pot^{-1}).

On soil 2 a similar P concentration in the plants was observed in all treatments, including the control (Table 4).

On soil 3 (2:1 ratio fertilizers) the plants from treatments CaS+CaS-LIQ and PoM+U had the highest P concentration (~9.5 g P kg^{-1} DM) against ~8 g P kg^{-1} DM in the control and in PiS+PiS-LIQ, and only 7 g P kg^{-1} DM in the MF 13:06:18 treatments (Table 4). Yet, considering P uptake plants fertilized with MF 13:06:18 and PiS+PiS-LIQ were able to export a significantly higher amount of the applied P (~80 mg P pot^{-1}).

3.4. Soil Properties at the End of the Experiment

Comparing the soil properties at the end of the experiment, no specific trends or clear benefits were observed (Supplementary Table S1) since no significant differences were observed between the treatments in each soil.

4. Discussion

4.1. Plant Yield

The willingness of farmers to use MBFs depends on several factors, but the most relevant is the need to guarantee the same plant yields as when MFsare applied. This condition can only be met if the nutrients in the MBFs are delivered to the plants at the right time and in the right dose.

Soil application of PoM+SP (0.5:1 N:P ratio, Soil 1) and PoM+PiS (1:1 N:P ratio, Soil 2) led to plant yields similar to those obtained with the MFs 07:14:14 and 10:10:10, respectively. This suggests that it is possible to apply MBFs for basal fertilization of oat and obtain similar plant yields as with the correspondent MFs. However, only the plants fertilized with PoM+SP obtained a relative yield increase similar to that observed with the respective MF (07:14:14). It might be expected that N-enrichment of PoM with urea would lead to similar yields as PoM+SP and the mineral option (13:06:18) [29], but the urea in this experiment did not stimulate oat production to a yield equal to that observed for the 13:06:18 fertilizer. This can be attributed to the solid nature of PoM and the fast enzymatic hydrolysis of urea. Urea hydrolysis releases two ammonia molecules, which might result in a N loss due to the fact that PoM has an alkaline pH, stimulating ammonia volatilization. Therefore, urea may not be the most adequate N source to combine with PoM.

The highest yields were obtained on soil 3 (ratio N:P 2:1), when PiS+PiS-LIQ, and a 13:06:18 mineral fertilizer were applied, but for this soil the control also led to higher total yield compared to controls of the 2 other soils. Consequently, the values of relative yield increase obtained in soil 3 were the lowest among all MBFs tested. PiS+PiS-LIQ led to the highest yield of the 2:1 N:P MBFs tested, but still with lower values than the corresponding MF (13:06:18). This effect could be attributed to the fact that, even applying a higher amount of N_{Total}, a fraction of N in the MBFs is bound in organic molecules, which need to be mineralized to be available to the crop [30].

This may have created a nutrient deficiency and thus reduced crop yield. Hence, application of MBFs in rich sandy soils may not be the best option and several alternatives should be considered: (i) top-dressing fertilizer at an earlier growth stage, (ii) using 2:1 MBFs in crop species less nutrient demanding, or (iii) intercropping with legumes to assimilate some of the N byrhizobium to support, healthy crop growth [31].

4.2. N Uptake and Apparent N Recovery

Another important feature that MBFs should meet in order to be considered by farmers is plant N uptake, which can be used to prove that the N supplied via MBFs was sufficient for the plants' needs. Oat's N uptake in treatments with MBFs was similar, or even higher, relative to the use of an equivalent mineral fertilizer. Hence, the results suggest that it is possible to replace MFs with MBFs. In the 0.5:1 N:P ratio (soil 1) the yields obtained with PoM+SP and MF 7:14:14 resulted in equivalent N concentrations in the aboveground plant part. Indeed, a positive correlation between the yield and the N uptake is usually observed [32]. For the combination of PoM with SP the N_{av} apparent recovery was equal to the one obtained after the application of 07:14:14 (Figure 2).This may suggest that the combination of PoM with SP stimulated the N mineralization, which is also confirmed by the similar N uptake for PoM+SP and MF 07:14:14 (Table 4). The apparent stimulation of N mineralization by PoM+SP could be attributed to an increase in the microbial activitiy. Indeed, microorganisms need both N and P, and adding a MBF rich in nutrients to a poor P soil may have stimulated their activity and increased N mineralization, as reported by Heuck et al. [33]. Furthermore, the application of PoM+PiS (1:1 N:P ratio) to soil 2 led to a N uptake similar to the MF 10:10:10, and, consequently, the plants presented an equal N concentration. The apparent N recovery from plants fertilized with PoM+PiS was much lower than when applying MF 10:10:10, especially when expressed in terms of N_{Total}. This indicates that organically bound N from MBFs requires longer periods to become plant available and that approximately 70% of N_{Total} in MBFs remained in the soil for the next crops. Nevertheless, the use of MBFs did not limit N use by plants, as N uptake values did not appear to be a limitation. Furthermore, since N will be mineralized and nitrified at a lower rate, the risk of nitrate leaching following MBFs application should be lower [34].

Overall, PoM+PiS appears as one of the best options for the MBFs with the 1:1 N:P ratio and may support the replacement of MFs for N basal fertilization. For the 2:1 N:P ratio (Soil 3), the application of PiS+PiS-LIQ induced a higher N uptake, meaning that the N_{av} applied was more promptly assimilated by the plants (Figure 1). The percentage of N apparent recovery considering N_{Total} was ~78%, which indicates that 22% was in an organic form in the soil, available for a slow mineralization, while a major part of the N was released rapidly. In previous works, incorporation of a pig slurry liquid fraction into soil induced an enhancement in the N use efficiency, compared to the incorporation of pig slurry [35], which is in agreement with the present results. Therefore, enriching PiS in N with its liquid fraction appears as an optimal solution to overcome the imbalance N:P ratio of manure in specific situations where more N is required by a crop. However, when combining two liquid materials, the quantity of material needed to supply the same amount of nutrients as a solid material is much higher.

One of the features of MBFs is that they may improve soil health and close the nutrient cycles [2]. The lower percentage of the applied N_{Total} recovered by the plants when the MBFs were used, indicates a slower N mineralization. However, compared to the control, N uptake was always significantly higher in plants amended with MBFs regardless of the MBF used. That might be due to the different N fractions contained in MBFs compared to the readily available N in MFs. Furthermore, the complex mixture of macro- and micronutrients contained in MBFs could also have stimulated the utilization of N by plants.

4.3. Phosphorus Uptake

One of the major disadvantages of manure application as fertilizer is the nutrient imbalance relative to the crops' requirements, which, in many cases, led to the overapplication of P [8]. Designing MBFs with different P contents is important to overcome this problem, but it is crucial to bear in mind that P is a macronutrient essential for crop growth and physiology [35,36]. To consider MBFs as substitutes for P mineral fertilizers in basal fertilization, it is imperative that: (i) Oat P concentration and P uptake are at least equal to the value obtained with MFs; (ii) The amount of P applied is not too high in relation to the crops demands to avoid P accumulation in the soil that reaches environmental harmful values.

PoM+SP was the 0.5:1 N:P MBF that led to P concentration in oat plants similar to the values observed with the MF 07:14:14 application. The amount of P applied with PoM+SP was equal to that applied with 7:14:14 (Table 3). However, P uptake by oat plants after PoM+SP application was lower than that after applying MF. Therefore, P availability was lower with PoM+SP than with MF, but this did not affect P assimilation by oat. This indicates that the addition of P from a mineral source to the manure was not expected to cause P deficiencies for the plants.

The present results are coherent with Iqbal et al. [1] stating, that the application of MBFs tended to release nutrients more slowly. At the end of the experiment, the soil extractable P in the PoM+SP treatment was statistically similar to MF 7:14:14 (Supplemment Table S1). This could indicate that if a second crop was sown on that soil, there would be P remaining to meet this P demand. In addition, the soils' extractable P concentration in the PoM+SP treatment was similar to the other two MBFs applications and to the control. The lower P availability can be attributed to the material present in solid manures, which is rich in fibers and lignin, and may hinder the mineralization of the organic compounds [37]. Manure or MBFs contain P bound in organic forms, which require mineralization as mentioned before. Mineralization can be a prolonged process, which consequently can lead to P deficiencies after applying MBFs, especially in soils poor in P, like soil 1. Nevertheless, the combination of PoM with SP appeared to be sufficient to overcome this constraint. The application of MBFs like CaM+PiS or CaM+PoM, without the addition of a P mineral source, may have resulted in P deficiency for oat, even if these were the MBFs with higher P application (Table 3). Also, P availability depends on the presence of certain ions in the soil, such as iron (Fe) or aluminum (Al), that can bind P into Fe or Al oxides [38]. Azevedo et al. [39] stated that soil with lower clay content has a diminished P adsorption capacity, increasing its availability. Since a sandy soil was used in this experiment, the formation of oxidesshould not play a relevant role, and the P was not adsorbed as much, making it more available to the plant. MBFs like CaM+PiS and CaM+PoM were tailored for situations where there would be a necessity of applying high P contents or in soils with a P deficiency. Based on the results of our pot experiment it can be concluded that the application of CaM+PiS or CaM+PoM might be reasonable for winter crops, when the potential of P leaching especially on sandy soils is higher due to higher precipitation, diminishing the risk of P leaching [38]. It is important to keep in mind that if P was not immediately available for oat, it may be available for the next crop in the rotation. Nevertheless, the application of such MBFs needs to be also assessed in soils with different properties.

The best options regarding P fertilization using MBFs (e.g., the one that released P more quickly) were PoM+PiS for the 1:1 N:P ratio (soil 2), and PiS+PiS-LIQ for the 2:1 N:P ratio (soil 3). Indeed, both treatments allowed P concentrations in the plant similar to those obtained with MF, indicating equivalent agronomic value in terms of P, which is important to achieve quality yields and healthy crops to meet human nutritional demands [37]. With the application of these MBFs, P is released at a rate that allowed oat plants to assimilate this nutrient as required: (i) the different P uptakes observed indicates that some MBFs are more suitable for plants with high P requirements, while others should be more adapted to plants with low P requirements, and (ii) the release of these nutrients is highly dependent on the materials blend. Tailoring MBFs, like those suggested in the 2:1 ratio for soils with higher P concentrations, (e.g., PiS+PiS-LIQ), is important to avoid P overapplication [40].

Oat fertilized with the 2:1 MBFs (Soil 3) presented no P deficiency, which can be attributed to: (i) The high extractable P content in the soil; (ii) The extractable P forms found in PiS more easily used by plants [39]; (iii) The richness of LIQ in available P [19], which enhanced P uptake. Indeed, the single use of pig slurry liquid fraction has proven to result in higher P uptake in oat forage [41]. Therefore, when considering the application of PoM+PiS or PiS+PiS-LIQ, two aspects should be considered: (i) The fact that P becomes available more quickly, which means it will be more susceptible to leaching; (ii) These MBFs should be considered for crop species with a higher P need.

MBFs with 1:1 and 2:1 ratios may have helped to retrieve P from manure to plants, meaning a more efficient P cycle and the adoption of sustainable agriculture practices with MBFs application.

In a previous study, where granulated poultry manure was used to fertilize wheat, spring rapeseed and potato, the soil P content for treatments with the organic fertilizerapplication was the same as that of the the soil with MFs at the end of the production cycle, after the harvest of the last crop [15]. Indeed, other authors pointed out that an increase in soil P content was more frequent after the second year of manure application [42].

4.4. Practical Implications of MBFs Application

Manure is produced all year, but it is used as organic fertilizer in specific periods, e.g., before the sowing of crops or eventually all year round in permanent grassland. Hence, the use of MBFs as those designed for this study mainly for the on-farm solution, may require farmers to increase the storage capacity of manures and/or the produced MBFs. It is known that the storage of manure has effects on the manure composition and, therefore it would impact their agronomic value [43]. This aspect of manure storage time should be considered because it will be important for the design of some specific MBFs to achieve more stabile compositions. Similarly, it is expected that the storage of MBFs after production will have an effect on nutrients (namely N and P) availability for plants, so this point should be considered by farmers. Regarding the so-called "central-solution", it may not require an increase of manure storage at farm scale, but will need the transportation of large amounts of manures to one central plant, with environmental and economic impacts, especially when transporting slurries due to their high water content [44]. Independently of the scenarios considered in this study, it will be necessary to rent or acquire specific equipment to produce and/or apply MBFs to soil.

The application of MBFs can become an economic advantage for farmers. Within the on-farm scenario, the cost would be the acquisition of mineral fertilizer to be used in the blend, but in a considerably lower amount than that required when using only MFs. Therefore, the costs of fertilization are expected to decrease. On the other hand, for the centralized solution, an economic analysis is essential to understand the price difference between the production of these MBFs and the MF. Farmers might be willing to pay more for this type of fertilizer but they might also expect it to be an excellent product [3].

Some other important features of manure that need to be considered before the implementation of MBFs are the odours associated with manure handling, as well as the potential risks of viable weeds seeds. In future studies, these aspects should be considered.

5. Conclusions

Tailoring MBFs with different N:P ratios demonstrated the relevance of combining livestock and crop production sectors to better respond to the crops' nutrient needs, while contributing to a sustainable agriculture. The results determined the potential of applying MBFs as partial substitutes for MFs in basal fertilization, which established their agronomic efficiency independently of the scenario analyzed. The application of PoM+SP (0.5:1 ratio), PoM+PiS (1:1 ratio) and PiS+PiS-LIQ (2:1 ratio), led to the production of oat plants with similar characteristics to the plants fertilized with the MFs. The lower DM yield obtained with the MBFs was the result of i) their slow nutrient release, which can be interesting for winter crops to avoid nutrient losses, and ii) the fact that high nutrient availability in soil 3 impaired the results in the 2:1 ratio. This indicates that these MBFs need to be futher refined. Overall the application of MBFs is a viable solution to recycle nutrients while promoting sustainable agricultural practices by partially substituting MFs.

Nevertheless, more studies should be conducted to properly assess the application of these manure-based fertilizers and ascertain the viability of their application.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/agronomy13010140/s1, Table S1: Soil physicochemical properties at the end of the experiment (mean values, n = 4). Results for each ratio in each column followed by different letters differ significantly for $p < 0.05$ (Tukey test).

Author Contributions: Conceptualization, J.P., H.R., P.A. and D.F.; methodology, J.P., H.R, P.A. and D.F.; validation, J.P., H.R., P.A. and D.F.; formal analysis, J.P., H.R., P.A. and D.F.; investigation, J.P., H.R., P.A. and D.F.; resources, D.F.; data curation, J.P., H.R., P.A. and D.F.; writing—original draft preparation, J.P., H.R., P.A. and D.F.; writing—review and editing, J.P., H.R., P.A. and D.F.; visualization, J.P., H.R., P.A. and D.F.; supervision, D.F.; project administration, D.F.; funding acquisition, D.F. All authors have read and agreed to the published version of the manuscript.

Funding: The study was supported by the Project Nutri2Cycle: H2020-SFS-30-2017- "Transition towards a more carbon and nutrient efficient agriculture in Europe", funded by the European Union, Program Horizon 2020 (Grant Agreement No 773682), and by the logistic and institutional support of LEAF (Linking Landscape, Environment, Agriculture and Food Research Unit), funded by FCT (UID/AGR/04129/LEAF).

Data Availability Statement: Not applicable.

Conflicts of Interest: The authors declare no conflict of interest. The funders had no role in the design of the study; in the collection, analyses, or interpretation of data; in the writing of the manuscript, or in the decision to publish the results.

References

1. Iqbal, A.; He, L.; Khan, A.; Wei, S.; Akhtar, K.; Ali, I.; Ullah, S.; Munsif, F.; Zhao, Q.; Jiang, L. Organic Manure Coupled with Inorganic Fertilizer: An Approach for the Sustainable Production of Rice by Improving Soil Properties and Nitrogen Use Efficiency. *Agronomy* **2019**, 651. [CrossRef]
2. Luo, H.; Robles-Aguilar, A.A.; Sigurnjak, I.; Michels, E.; Meers, E. Assessing Nitrogen Availability in Biobased Fertilizers: Effect of Vegetation on Mineralization Patterns. *Agriculture* **2021**, 870. [CrossRef]
3. Hills, K.; Yorgey, G.; Cook, J. Demand for Bio-Based Fertilizers from Dairy Manure in Washington State: A Small-Scale Discrete Choice Experiment. *Renew. Agric. Food Syst.* **2021**, *36*, 207–214. [CrossRef]
4. Spiegal, S.; Kleinman, P.J.A.; Endale, D.M.; Bryant, R.B.; Dell, C.; Goslee, S.; Meinen, R.J.; Flynn, K.C.; Baker, J.M.; Browning, D.M.; et al. Manuresheds: Advancing Nutrient Recycling in US Agriculture. *Agric. Syst.* **2020**, 182. [CrossRef]
5. Hayashi, S.; Hara, M.; Katoh, M. Improvement on Plant Uptake of Inorganic Nutrients Fertilized by Migration of Water-Soluble Organic Matter From Animal Manure-Based Compost. *J. Soil Sci. Plant Nutr.* **2022**, *22*, 3399–3413. [CrossRef]
6. Rayne, N.; Aula, L. Livestock Manure and the Impacts on Soil Health: A Review. *Soil Syst.* **2020**, *4*, 64. [CrossRef]
7. Fangueiro, D.; Pereira, J.L.S.; Fraga, I.; Surgy, S.; Vasconcelos, E.; Coutinho, J. Band Application of Acidified Slurry as an Alternative to Slurry Injection in a Mediterranean Double Cropping System: Agronomic Effect and Gaseous Emissions. *Agric. Ecosyst. Environ.* **2018**, *267*, 87–99. [CrossRef]
8. Sigurnjak, I.; Brienza, C.; Snauwaert, E.; De Dobbelaere, A.; De Mey, J.; Vaneeckhaute, C.; Michels, E.; Schoumans, O.; Adani, F.; Meers, E. Production and Performance of Bio-Based Mineral Fertilizers from Agricultural Waste Using Ammonia (Stripping-) Scrubbing Technology. *Waste Manag.* **2019**, *89*, 265–274. [CrossRef] [PubMed]
9. Pahalvi, H.N.; Rafiya, L.; Rashid, S.; Nisar, B.; Kamili, A.N. Microbiota and Biofertilizers, Ecofriendly Tools for Reclamation of Degraded Soil Environs. In *Chapter I*; Dar, G., Bhat, R.A., LMehmood, M.A., Hakeemm, K.R., Eds.; Springer Nature: Cham, Switzerland, 2022; Volume 2, ISBN 9783030610098.
10. Keskinen, R.; Suojala-Ahlfors, T.; Sarvi, M.; Hagner, M.; Kaseva, J.; Salo, T.; Uusitalo, R.; Rasa, K. Granulated Broiler Manure Based Organic Fertilizers as Sources of Plant Available Nitrogen. *Environ. Technol. Innov.* **2020**, *18*, 100734. [CrossRef]
11. Valentinuzzi, F.; Cavani, L.; Porfido, C.; Terzano, R.; Pii, Y.; Cesco, S.; Marzadori, C.; Mimmo, T. The Fertilising Potential of Manure-Based Biogas Fermentation Residues: Pelleted vs. *Liquid Digestate. Heliyon* **2020**, *6*. [CrossRef]
12. Oenema, O.; Lesschen, J.P.; Rietra, R.; Rieger, J.; Hendriks, C.D. Driving Forces of Farming Systems and Their Impacts on CNP Ratios and Flows. 2021; pp. 1–91. Available online: http://nutri2cycle.eu/driving-forces-of-farming-systems-and-their-impacts-on-cnp-ratios-and-flows/ (accessed on 26 March 2022).
13. Lesschen, J.P.; Ros, M.; Sigurnjak, I.; Aguilar, A.R.; Michels, E.; Hajdu, Z.; Prado, J.; Guerra, H.P.; Lesschen, J.P. Effects of Current Techniques and Management Systems on CNP Flows in Europe. 2020. Available online: https://www.nutri2cycle.eu/effects-of-current-techniques-and-management-systems-on-cnp-flows-in-europe/ (accessed on 26 March 2022).
14. Chojnacka, K.; Moustakas, K.; Witek-Krowiak, A. Bio-Based Fertilizers: A Practical Approach towards Circular Economy. *Bioresour. Technol.* **2020**, *295*, 122223. [CrossRef] [PubMed]
15. Mažeika, R.; Arbačiauskas, J.; Masevičienė, A.; Narutytė, I.; Šumskis, D.; Žičkienė, L.; Rainys, K.; Drapanauskaite, D.; Staugaitis, G.; Baltrusaitis, J. Nutrient Dynamics and Plant Response in Soil to Organic Chicken Manure-Based Fertilizers. *Waste Biomass Valor* **2021**, *12*, 371–382. [CrossRef]
16. Powers, S.M.; Chowdhury, R.B.; MacDonald, G.K.; Metson, G.S.; Beusen, A.H.W.; Bouwman, A.F.; Hampton, S.E.; Mayer, B.K.; McCrackin, M.L.; Vaccari, D.A. Global Opportunities to Increase Agricultural Independence Through Phosphorus Recycling. *Earth's Futur.* **2019**, *7*, 370–383. [CrossRef]
17. Huygens, D.; Orveillon, G.; Lugato, E.; Tavazzi, S. Technical Proposals for the Safe Use of Processed Manure above the Threshold Established for Nitrate Vulnerable Zones by the Nitrates Directive (91/676/EEC). *JRC Ispra* 2020. [CrossRef]
18. Wang, Z.; Jiang, H.; Shen, Y. Forage Production and Soil Water Balance in Oat and Common Vetch Sole Crops and Intercrops Cultivated in the Summer-Autumn Fallow Season on the Chinese Loess Plateau. *Eur. J. Agron.* **2020**, *115*, 126042. [CrossRef]
19. Prado, J.; Ribeiro, H.; Alvarenga, P.; Fangueiro, D. A Step towards the Production of Manure-Based Fertilizers: Disclosing the Effects of Animal Species and Slurry Treatment on Their Nutrients Content and Availability. *J. Clean. Prod.* **2022**, *337*, 130369. [CrossRef]
20. Rodrigues, J.; Alvarenga, P.; Silva, A.C.; Brito, L.; Tavares, J.; Fangueiro, D. Animal Slurry Sanitization through PH Adjustment: Process Optimization and Impact on Slurry Characteristics. *Agronomy* **2021**, 517. [CrossRef]
21. MADRP, Ministério Da Agricultura Do Desenvolvimento Rural E Das Pescas Diário Da República No25/2018; 2 Series: Lisboa. 2018. Available online: https://files.dre.pt/2s/2018/02/025000000/0413204170.pdf (accessed on 9 December 2021).
22. Rodríguez-García, M.F.; Huerta-Espino, J.; Villaseñor-Mir, H.E.; Rivas-Valencia, P.; González-González, M.; Hortelano-Santa Rosa, R.; Robles-Yerena, L.; Aranda-Ocampo, S. Chemical Treatment to Wheat Seed to Reduce the Incidence of Bacteria. *Rev. Mex. Fitopatol. Mex. J. Phytopathol.* **2020**, *38*, 239–249. [CrossRef]
23. Veloso, A.; Sempiterno, C.; Calouro, F.; Rebelo, F.; Pedra, F.; Castro, I.V.; Gonçalves, M.d.C.; Marcelo, M.d.E.; Pereira, P.; Fareleira, P.; et al. *Manual de Fertilização Das Culturas*; Instituto Nacional de Investigação Agrária e Veterinária, Ed.; INIAV—Instituto Nacional de Investigação Agrária e Veterinária, I.P.: Oeiras, Portugal, 2022; ISBN 978-972-579-063-2.
24. FAO, Food and Agriculture Organization of United Nations. *Standard Operating Procedure for Soil Nitrogen Kjeldahl—Dumas Dry Combustion Method*; FAO: Rome, Italy, 2021.

25. Shah, G.M.; Shah, G.A.; Groot, J.C.J.; Raza, M.A.S.; Shahid, N.; Lantinga, E.A. Maize Nitrogen Recovery and Dry Matter Production as Affected by Application of Solid Cattle Manure Subjected to Various Storage Conditions. *J. Soil Sci. Plant Nutr.* **2016**, *16*, 591–603. [CrossRef]
26. Cai, A.; Xu, M.; Wang, B.; Zhang, W.; Liang, G.; Hou, E. Manure Acts as a Better Fertilizer for Increasing Crop Yields than Synthetic Fertilizer Does by Improving Soil Fertility. *Soil Tillage Res.* **2019**, *189*, 168–175. [CrossRef]
27. Singh, J.P. A Rapid Method for Determination of Nitrate in Soil and Plant Extracts. *Plant Soil* **1988**, *110*, 137–139. [CrossRef]
28. Egnér, H.; Riehm, H.; Domingo, W. Untersuchungen Über Die Chemische Bodenanalyse Als Grundlage Für Die Beurteilung Des Nährstoffzustandes Der Böden. II. Chemische Extraktionsmethoden Zur Phospor Und Kaliumbestimmung. *K. Lantbrukshögskolan Ann.* **1960**, *26*, 199–215.
29. Iqbal, A.; He, L.; Ali, I.; Ullah, S.; Khan, A.; Khan, A.; Akhtar, K.; Wei, S.; Zhao, Q.; Zhang, J.; et al. Manure Combined with Chemical Fertilizer Increases Rice Productivity by Improving Soil Health, Post-Anthesis Biomass Yield, and Nitrogen Metabolism. *PLoS One* **2020**, *15*, 1–24. [CrossRef]
30. Reuland, G.; Sigurnjak, I.; Dekker, H.; Sleutel, S.; Meers, E. Assessment of the Carbon and Nitrogen Mineralisation of Digestates Elaborated from Distinct Feedstock Profiles. *Agronomy* **2022**, *12*, 456. [CrossRef]
31. Lindström, K.; Mousavi, S.A. Effectiveness of Nitrogen Fixation in Rhizobia. *Microb. Biotechnol.* **2020**, *13*, 1314–1335. [CrossRef]
32. Prather, R.M.; Castillioni, K.; Kaspari, M.; Souza, L.; Prather, C.M.; Reihart, R.W.; Welti, E.A.R. Micronutrients Enhance Macronutrient Effects in a Meta-Analysis of Grassland Arthropod Abundance. *Glob. Ecol. Biogeogr.* **2020**, *29*, 2273–2288. [CrossRef]
33. Heuck, C.; Weig, A.; Spohn, M. Soil Microbial Biomass C: N: P Stoichiometry and Microbial Use Oforganic Phosphorus. *Soil Biol. Biochem.* **2015**, *85*, 119–129. [CrossRef]
34. Fangueiro, D.; Chadwick, D.; Bol, R. Assessment of the Potential N Mineralization of Different Particle-Size Fractions in Two Dairy Cattle Slurries. *J. Plant Nutr. Soil Sci.* **2008**, *171*, 313–315. [CrossRef]
35. de Bang, T.C.; Husted, S.; Laursen, K.H.; Persson, D.P.; Schjoerring, J.K. The Molecular–Physiological Functions of Mineral Macronutrients and Their Consequences for Deficiency Symptoms in Plants. *New Phytol.* **2021**, *229*, 2446–2469. [CrossRef]
36. Wang, X.; Xiong, J.; He, Z. Activated Dolomite Phosphate Rock Fertilizers to Reduce Leaching of Phosphorus and Trace Metals as Compared to Superphosphate. *J. Environ. Manag.* **2020**, *255*, 109872. [CrossRef]
37. Bhogal, A.; Williams, J.R.; Nicholson, F.A.; Chadwick, D.R.; Chambers, K.H.; Chambers, B.J. Mineralization of Organic Nitrogen from Farm Manure Applications. *Soil Use Manag.* **2016**, *32*, 32–43. [CrossRef]
38. Tiecher, T.L.; Lourenzi, C.R.; Girotto, E.; Tiecher, T.; De Conti, L.; Marques, A.C.R.; Silva, L.O.S.; Marchezan, C.; Brunetto, G.; Ceretta, C.A. Phosphorus Forms Leached in a Sandy Typic Hapludalf Soil under No-Tillage with Successive Pig Slurry Applications. *Agric. Water Manag.* **2020**, *242*, 106406. [CrossRef]
39. Azevedo, R.P.; Salcedo, I.H.; Lima, P.A.; da Silva Fraga, V.; Lana, R.M.Q. Mobility of Phosphorus from Organic and Inorganic Source Materials in a Sandy Soil. *Int. J. Recycl. Org. Waste Agric.* **2018**, *7*, 153–163. [CrossRef]
40. Ashworth, A.J.; Chastain, J.P.; Moore, P.A. Nutrient Characteristics of Poultry Manure and Litter. In *Animal Manure: Production, Characteristics, Environmental Concerns, and Management*; Waldrip, H.M., Pagliari, P.H., He, Z., Eds.; American Society of Agronomy: Madison, WI, USA, 2020; pp. 63–87. ISBN 9780891183716.
41. Fangueiro, D.; Pereira, J.L.S.; Macedo, S.; Trindade, H.; Vasconcelos, E.; Coutinho, J. Surface Application of Acidified Cattle Slurry Compared to Slurry Injection: Impact on NH_3, N_2O, CO_2 and CH_4 Emissions and Crop Uptake. *Geoderma* **2017**, *306*, 160–166. [CrossRef]
42. Antoniadis, V.; Koutroubas, S.D.; Fotiadis, S. Nitrogen, Phosphorus, and Potassium Availability in Manure- and Sewage Sludge–Applied Soil. *Commun. Soil Sci. Plant Anal.* **2015**, *46*, 393–404. [CrossRef]
43. Ali, B.; Shah, G.A.; Traore, B.; Shah, S.A.A.; Shah, S.u.S.; Al-Solaimani, S.G.M.; Hussain, Q.; Ali, N.; Shahzad, K.; Shahzad, T.; et al. Manure Storage Operations Mitigate Nutrient Losses and Their Products Can Sustain Soil Fertility and Enhance Wheat Productivity. *J. Environ. Manag.* **2019**, *241*, 468–478. [CrossRef] [PubMed]
44. Silva, A.A.; Fangueiro, D.; Carvalho, M. Slurry Acidification as a Solution to Minimize Ammonia Emissions from the Combined Application of Animal Manure and Synthetic Fertilizer in No-Tillage. *Agronomy* **2022**, 265. [CrossRef]