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ORIGINAL PAPER

Meat and bone meal (MBM) as a source of phosphorus for crop plants*

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Abstract

In the era of sustainable economy and the European Green Deal, a strong emphasis is placed on a better balance between nature, food systems, and biodiversity. Bio-based fertilizers are recovered from various by-products and biomass types to close nutrient cycles and reuse nutrients in food systems. Meat and bone meal (MBM) can be a viable alternative to organic fertilizers because it is a relatively rich source of nitrogen, phosphorus and calcium. A four-year pot experiment was conducted in Poland. The aim of this study was to evaluate the effect of meat and bone meal (MBM) on the yields of four crops, the content of nitrogen (N) and phosphorus (P) in plants, and selected chemical properties of soil. Four fertilization treatments were established: 1) NPK (mineral N, P, K fertilization); 2) 0.2% MBM; 3) 0.4% MBM, and 4) 0.8% MBM per 10 kg of soil per pot. Each year, MBM was applied before sowing as a substitute for NP fertilizer. Intensive MBM fertilization (0.8% MBM) contributed to increased crop yields, N and P concentrations and uptake by plants relative to the lowest MBM dose. The values of the analyzed parameters were comparable in the treatments fertilized with higher doses of MBM and with mineral NPK. The only exception was the highest total P content in the seeds of oilseed rape fertilized with the lowest dose of MBM. Soil mineral N and plant-available P concentrations increased with increasing MBM doses. The results of the study indicate that MBM can completely replace mineral P fertilizers and partially replace mineral N fertilizers, and its dose should be adjusted to meet the nutrient requirements of crops.

Keywords: triticale, oilseed rape, wheat, maize, mineral nitrogen, available P, soil pH, animal meal

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INTRODUCTION

The European Green Deal aims to decrease energy consumption in production processes, including mineral fertilizer production, to protect the natural environment, and to move towards a clean, circular economy. Fertilization is a key determinant of crop yields and one of the main indicators of the intensity and efficiency of agricultural production. After the use of meat and bone meal (MBM) as a feed additive had been banned in the European Union, researchers began to search for alternative strategies to manage this waste product. Military conflicts and the resulting threats to food security have led to an increase in fertilizer prices and supply shortages in global markets. These challenges encourage the use of organic raw materials, including food production waste, as fertilizers. Meat and bone meal is a waste product derived from various animal sources. It is abundant in nitrogen (N), phosphorus (P), and calcium (Ca), and can be applied as a valuable source of these nutrients in crop plants. Meat and bone meal is also a rich source of organic compounds, including amino acids, that improve the C:N ratio in soil (Jeng et al. 2006, Ylivainio et al. 2008, Liu et al. 2019, Haberecht et al. 2020). It stabilizes soil pH, thus inhibiting the growth of pathogenic microorganisms and protecting crops against disease (Lazarovits 2010, Qian et al. 2018, Dang et al. 2021). When applied as fertilizer in the production of food crops (Jeng et al. 2004, 2006, Chaves et al. 2005, Ylivainio et al. 2008, Chen et al. 2011, Kivelä et al. 2015, Nogalska 2016, Jatana et al. 2022) and energy crops for bioethanol and biodiesel production, MBM contributes to rational waste management, provides essential nutrients to plants, and reduces the demand for fossil fuels and mineral resources (Jankowski, Nogalska 2022). As part of sustainable agricultural practices, mineral and organic fertilizers can be combined to improve NPK use efficiency and reduce fertilizer use in crop production (Jatana et al. 2020, Nogalska, Załuszniewska 2020, Załuszniewska, Nogalska 2020, Nogalska, Załuszniewska 2021, Załuszniewska, Nogalska 2022).

The aim of this four-year pot experiment was to evaluate the effect of three increasing doses of MBM on the yields of four crops (spring triticale, spring oilseed rape, spring wheat, silage maize), N and P content and uptake by plants, and selected chemical properties of soil (pH_{KCl}, mineral N and plant-available P content) in comparison with mineral fertilizers.

MATERIALS AND METHODS

Experimental site

The four-year pot experiment was conducted in a greenhouse at the University of Warmia and Mazury in Olsztyn, in north-eastern (NE) Poland.

The experiment had a completely randomized design, with four replications. Modified polyethylene Kick-Brauckmann pots were filled with 10 kg of soil. The soil was developed from loamy sand, Dystric Cambisol (IUSS-WRB 2015), and it was characterized by the following chemical properties: pH in 1 mol dm^{-3} KCl – 6.61 (neutral), moderate levels of plant-available P (64 mg kg^{-1}), available K (120 mg kg^{-1}), and available magnesium Mg (32 mg kg^{-1}). The tested crop species were spring triticale cv. Kargo, spring oilseed rape cv. Landmark, spring wheat cv. Bombona, and silage maize cv. San. In the pot experiment, MBM was used as a substitute for slow-release NP fertilizer; it was thoroughly mixed with soil and applied in a single dose prior to planting each of the crops. Meat and bone meal was purchased from the Animal By-Products Disposal Plant Saria Poland in Długi Borek near Szczytno, and it had the following composition: 97% DM, 714 g organic matter, 280 g crude ash, 137 g crude fat, 75.2 g N, 47.5 g P, 3.42 g K, 100.3 g Ca, 6.8 g Na and 2.0 g Mg kg^{-1} DM on average.

Experimental design

Four fertilization treatments were established: 1) NPK (mineral N, P, and K fertilization); 2) 0.2% MBM; 3) 0.4% MBM, and 4) 0.8% MBM per 10 kg of soil per pot. Increasing doses of MBM (0.2%, 0.4%, and 0.8%) supplied the following amounts of N and P: 1.5, 3.0, and 6.0 g N pot^{-1} and 1.0, 2.0, and 4.0 g P pot^{-1}. Due to the low K content of MBM, K was supplied by mineral fertilizers, at a dose corresponding to K fertilizer levels in the NPK treatment. In the NPK treatment, mineral NPK fertilizer was applied in the following amounts per pot: N – 3.0 g as $CO(NH_2)_2$ in three equal doses of 1.0 g each (one pre-sowing application, followed by two top dressing applications in different growth stage of crops grown). Top dressing of plants with mineral nitrogen was as follows: spring triticale and spring wheat at the stem elongation (BBCH 30) and flag leaf stage (BBCH 47), spring rape at the fourth leaf stage (BBCH 15) and ninth leaf stage (BBCH 19), and maize at the fourth leaf stage (BBCH 14) and eighth leaf stage (BBCH 19). Phosphorus and potassium were applied pre-sowing, respectively 1.0 g P pot^{-1} in the form of KH_2PO_4 and 2.5 g K pot^{-1} in the forms of KH_2PO_4 and KCl.

Chemical composition of plants

Spring triticale, spring wheat, and spring oilseed rape were harvested in the fully ripe stage, while silage maize was harvested in the milk-dough stage. Plant samples from each pot were weighed and air-dried to dry matter, weighed, ground, and wet mineralized in concentrated sulfuric(VI) acid with hydrogen peroxide (H_2O_2) as the oxidizing agent. Mineralized plant samples were analyzed for the content of total N – by the Kjeldahl method using a KjelFlex K-360 distillation unit (BÜCHI Labortechnik AG, Flavil, Switzerland), P – by the vanadium-molybdenum method (UV-1201 V spectrophotometer, Shimadzu Corporation Kyoto, Japan). Nutrient uptake by plants (g pot^{-1}) was calculated based on the aerial biomass yields and N and P content of the analyzed crop species.

Chemical composition of soil

Soil samples were collected from pots after each crop had been harvested. Fresh samples were analyzed for the content of ammonium N (N-NH_4^+) – by colorimetry with the use of Nessler's reagent, nitrate N(N-NO_3^-) – by colorimetry with the use of phenoldisulfonic acid (UV-1201 V spectrophotometer, Shimadzu Corporation Kyoto, Japan), and available P – by the Egner-Riehm (DL) method (UV-1201 V spectrophotometer, Shimadzu Corporation Kyoto, Japan). Soil pH in 1 M KCl dm^{-3} was determined by the potentiometric method (CP-505 pH-meter, Elmetron Sp. j. Zabrze, Poland).

Statistical analysis

The results were processed by one-way analysis of variance (ANOVA), using Statistica 13.3 software (2020). The experimental factor was the MBM dose. The significance of differences between means was determined by the Newman-Keuls test at p<0.01.

RESULTS AND DISCUSSION

The yields of the tested crops were influenced by MBM dose and species (Table 1), and they were as follows: spring triticale – 38.90 g to 50.76 g grain pot^{-1}, spring oilseed rape – 16.97 g to 62.22 g seeds pot^{-1}, spring wheat – 25.45 g to 34.47 g grain pot^{-1}, silage maize – 121.33 g to 249.05 g herbage pot^{-1}. No significant differences in spring triticale yield were found between the NPK treatment and the treatments supplied with the lowest (0.2%) and medium (0.4%) doses of MBM per 10 kg of soil per pot. The yields of spring

Table 1

Effect of meat and bone (MBM) meal doses on the yields (g pot^{-1}) of the tested crops (grain moisture content – 14.0%, seed moisture content – 6%, herbage moisture content – 15%)

Treatment	Spring triticale (grain)	Spring oilseed Rape (seeds)	Spring wheat (grain)	Maize (herbage)
NPK^{+}	47.67^{bc}	62.22^{d}	34.47^{b}	249.05^{c}
0.2% MBM^{++}	39.27^{ab}	16.97^{a}	25.45^{a}	121.33^{a}
0.4% MBM^{++}	50.76^{c}	30.15^{b}	32.25^{b}	159.97^{b}
0.8% MBM^{++}	38.90^{a}	50.07^{c}	33.52^{b}	226.22^{c}

$^{+}$ NPK – mineral nitrogen, phosphorus, and potassium fertilization, $^{++}$ MBM – meat and bone meal applied at 0.2%, 0.4%, and 0.8% per 10 kg of soil per pot; *a,b,c,d* – significant differences between means (in columns) are marked with different small letters, according to the Newman-Keuls test (p<0.01) wheat fertilized with the medium and highest doses of MBM (0.4% and 0.8%, respectively) and maize fertilized with the highest dose of MBM (0.8%) were comparable to the results obtained from objects fertilized only with mineral NPK. Jatana et al. (2022) also demonstrated that the grain yields of maize fertilized with MBM and conventional fertilizers were similar, and N leaching losses were reduced. In the present study, spring rapeseed oil responded differently than cereals, and its yields were significantly higher in the NPK treatment (62.22 g seeds pot^{-1}) than in all MBM treatments, regardless of MBM dose (16.97-50.07 g seeds pot^{-1}). The yields of oilseed rape, wheat, and maize tended to increase with increasing MBM doses. Triticale yields peaked (50.76 g grain pot^{-1}) in response to the medium dose of MBM, whereas its highest dose decreased the grain yield by more than 23% relative to the medium dose. In the field experiment, increasing the MBM dose from 1.5 to 2.5 t ha^{-1} did not significantly increase the yields of triticale, rapeseed oil, wheat, and silage maize (Nogalska et al. 2014). In the current study, the medium dose of MBM and NPK fertilizer provided the same amount of N and exerted a comparable yield-forming effect on spring triticale. A beneficial influence of MBM on crop yields (spring wheat, spring barley, ryegrass and oat) has been observed by many authors (Jeng et al. 2004, 2006, Chaves et al. 2005, Ylivainio et al. 2008, Chen et al. 2011, Nogalska 2016).

Nitrogen content and uptake by plants

The N content and uptake by the tested crops were significantly modified by fertilization (Table 2). All plants (excluding oilseed rape) fertilized with the medium and highest doses of MBM (0.4% and 0.8%, respectively) were more abundant in total N than those fertilized with the lowest dose of MBM.

Table 2

Effect of meat and bone (MBM) meal doses on the total nitrogen (N) content of grain/seeds/herbage and N uptake by the aboveground biomass of the tested crops

Treatment	Spring triticale	Spring oilseed rape	Spring wheat	Maize herbage
	N content (g kg^{-1} DM)			
NPK	21.22^{a}	30.79^{c}	23.62^{b}	7.10^{a}
0.2% MBM	20.77^{a}	28.85^{abc}	13.42^{a}	6.59^{a}
0.4% MBM	26.45^{b}	25.13^{a}	15.57^{a}	7.46^{ab}
0.8% MBM	27.87^{b}	30.75^{bc}	20.75^{b}	9.05^{b}
	N uptake (g pot^{-1})			
NPK	2.33^{ab}	6.07^{d}	1.27^{d}	1.77^{b}
0.2% MBM	1.95^{a}	2.17^{a}	0.51^{a}	0.80^{a}
0.4% MBM	2.96^{b}	3.13^{b}	0.73^{b}	1.19^{a}
0.8% MBM	2.44^{ab}	5.60^{c}	1.06^{c}	2.05^{b}

Explanations as in Table 1

This indicates that the MBM dose of 0.2% per 10 kg of soil per pot was insufficient to fully meet the N requirements of triticale, wheat, and maize. The only exception was oilseed rape whose seeds had the lowest N content when MBM was applied at the medium dose, but the difference between the medium and lowest doses was not significant. It should be stressed that the N content of triticale grain and maize herbage fertilized with high doses of MBM was significantly higher than in the object with NPK treatment. A pot experiment conducted by Atemni et al. (2023) revealed that an increase in the soil pH in response to high doses of bone meal was positively correlated with N concentrations in the tested plants. The response of crops to organic fertilizers depends on the dose of N mineralization during plant growth and the C:N ratio in MBM (Abalos et al. 2016). Meat and bone meal is characterized by a narrow C:N ratio (4.6-5.6), and the rate of plant growth is similar after the application of 2-4 t ha^{-1} MBM and conventional fertilizers (Jatana et al. 2020, Nogalska, Zalewska 2013, Nogalska et al. 2017). In MBM, most N is in the form of protein and amino acids, which rapidly undergo mineralization and ammonification to NH_4. In the present study, oilseed rape seeds and wheat grain supplied with the highest dose of MBM and mineral fertilizer had comparable N concentrations. Similar results were obtained in a previous field trial (Nogalska, Zalewska 2013).

Nitrogen uptake by the aerial biomass of the analyzed crop species was more dependent on yield than on N content (Table 2). Nitrogen uptake was lowest in the soil fertilized with the lowest MBM dose (0.2%), which provided 1.5 g N pot^{-1}, i.e. twice less than in the NPK treatment. Nitrogen uptake by oilseed rape and wheat was significantly higher in the soil fertilized with mineral NPK than with MBM. In turn, N uptake by triticale and maize was comparable in the treatments with high MBM doses and in the NPK treatment. Nitrogen uptake by oilseed rape, wheat, and maize tended to increase with increasing MBM doses. It should be noted that spring rapeseed uptake twice as much N from the NPK treatment than the applied rate. The 3.0 g N pot^{-1} was likely too low for rapeseed, which has high N requirements and therefore draws this nutrient from soil reserves. In field experiments conducted by Nogalska et al. (2012) and Nogalska (2013), N uptake by winter triticale, winter wheat, and silage maize was higher in treatments with high MBM doses than in the mineral NPK treatment. The lowest MBM dose (1.0 t ha^{-1}) was insufficient to meet the N requirements of the cultivated plants. An analysis of the simplified N balance revealed that plants with high nutrient requirements fertilized with MBM require supplemental N fertilization. However, mineral N added to MBM, which accounted for 25% and 50% of the total N rate, had no significant effect on the N content of maize herbage, wheat grain, and winter oilseed rape seeds (Załuszniewska, Nogalska 2020, Nogalska, Załuszniewska 2021, Załuszniewska, Nogalska 2022).

Phosphorus content and uptake by plants

Meat and bone meal applied at three increasing doses induced differences in the P content and uptake by plants (Table 3). Significant changes in total P content were noted in oilseed rape seeds and wheat grain. The seeds of

Table 3

Effect of meat and bone (MBM) meal doses on the total phosphorus (P) content of grain/seeds/ herbage and P uptake by the aboveground biomass of the tested crops

Treatment	Spring triticale	Spring oilseed rape	Spring wheat	Maize herbage
	P content (g kg^{-1} DM)			
NPK	2.30^{a}	4.29^{a}	4.14^{b}	3.04^{a}
0.2% MBM	2.31^{a}	5.12^{b}	3.40^{ab}	3.21^{a}
0.4% MBM	2.30^{a}	5.06^{b}	2.79^{a}	3.73^{a}
0.8% MBM	2.35^{a}	4.53^{a}	3.47^{ab}	3.68^{a}
	P uptake (g pot^{-1})			
NPK	0.25^{a}	0.85^{c}	0.22^{b}	0.76^{cd}
0.2% MBM	0.22^{a}	0.39^{a}	0.13^{a}	0.39^{a}
0.4% MBM	0.26^{a}	0.63^{b}	0.13^{a}	0.60^{bc}
0.8% MBM	0.21^{a}	0.83^{c}	0.18^{ab}	0.83^{d}

Explanations as in Table 1

oilseed rape fertilized with the lowest and medium doses of MBM (0.2% and 0.4%, respectively) were most abundant in P, and the observed differences were significant compared with the other treatments. Wheat grain had the highest P content in the NPK treatment, and the increase in P content was significant relative to the 0.4% MBM treatment. In a four-year field experiment conducted by Nogalska and Zalewska (2013), the P content of winter wheat grain and winter triticale grain was higher after the application of MBM than mineral fertilizer. Many authors have found that MBM can be a source of P for oilseed rape, maize, other cereals and grasses, and root crops both immediately after application and in the long term (Jeng et al. 2004, 2006, Ylivainio et al. 2008, Venegas 2009, Chen et al. 2011, Brod et al. 2012, Nogalska et al. 2012, Simoes et al. 2012, Nogalska, Zalewska 2013, Nogalska et al. 2014, Brod et al. 2015, Kivelä et al. 2015, Foereid 2017, Nogalska et al. 2017). The mineralization of MBM and, consequently, P availability to plants, are determined by soil type and pH, weather conditions, duration of the trial, and the type and amount of animal meal. According to Jeng et al. (2006), 50% of P from MBM is available to plants already in the first year after application.

Phosphorus uptake by the tested crop species was comparable in the 0.8% MBM and NPK treatments (Table 3). It should be noted that the highest dose of MBM provided four times more P (4.0 g pot^{-1}) than the mineral fertilizer. Such a high amount of biogenic element may pose a threat to the environment, especially in acidic soils where sparingly soluble P is more rapidly converted to soluble forms (Jeng et al. 2006, Ylivainio et al. 2008). Phosphorus uptake by oilseed rape and maize increased significantly with increasing MBM doses. Załuszniewska and Nogalska (2022) also reported that P uptake by the studied crop species was similar after the application of mineral fertilizer and MBM, but P utilization by plants gradually decreased from 35.6% to 14.6% with increasing MBM doses. These authors showed that phosphorus supplied by the lowest dose of MBM was most efficiently utilized by plants, and P uptake and balance in this treatment were comparable with those in the NPK treatment, which is an important consideration. These findings indicate that P from MBM and granular triple superphosphate was equally efficiently utilized by the tested crops.

Soil pH

In comparison with the mineral fertilizer, MBM usually decreased the soil pH (Table 4). Increasing doses of MBM supplied increasing amounts of Ca: 2.06, 4.12, and 8.24 g kg^{-1}, and the soil pH decreased steadily. However, the soil pH changed from neutral to slightly acidic only when the highest MBM dose was applied to spring triticale. The initial soil pH was neutral (pH_{KCl}=6.61) and it remained neutral after harvest (pH_{KCl}=6.62-6.91), regardless of the fertilizer applied to the crops. Slight acidification could be caused by the activity of nitrifying microorganisms whose growth is promoted by the application of organic wastes and under high sulfate concentrations (Bohacz, Korniłowicz-Kowalska 2005). The results of previous studies are inconclusive and contradictory due to the presence of various factors such as soil type, type of animal waste and processing method, weather conditions, and duration of the experiment. Stępień and Mercik (2002) noted a decrease in the pH of soil amended with MBM, horn meal and feather meal, whereas Spychaj-Fabisiak et al. (2007) found no differences in this parameter after the application of a conditioner based on poultry offal. In contrast, Valenzuela et al. (2000), Unagwu et al. (2023) and Atemni et al. (2023) observed an increase in the soil pH.

Soil mineral nitrogen content

Excessive concentrations of mineral N remaining in the soil after harvest may pose a risk of soil and groundwater contamination. In the current study, only the highest MBM dose significantly (1.5 times on average) increased $N\text{-}NH_4$ levels in soil after the harvest of triticale, wheat, and maize, compared with the NPK treatment (Table 4). Such a relationship was observed in soil fertilized with a twofold higher dose of N (6.0 g pot^{-1}) provided by MBM, compared with soil supplied with mineral fertilizer (3.0 g N pot^{-1} as urea). In turn, $N\text{-}NO_3$ levels were significantly higher in soil amended with the medium and highest doses of MBM (triticale) and the highest MBM

Table 4

Effect of meat and bone meal (MBM) doses on pH in 1 mol KCl dm^{-3} of soil and the content of ammonium nitrogen (N-NH_4), nitrate nitrogen (N-NO_3), and plant-available phosphorus (P) (mg kg^{-1}) in soil after harvest

Treatment	Soil after the harvest of			
	Spring triticale	Spring oilseed rape	Spring wheat	Maize herbage
pH				
NPK	6.71^{b}	6.91^{a}	6.91^{c}	6.83^{b}
0.2% MBM	6.79^{b}	6.82^{a}	6.87^{bc}	6.71^{a}
0.4% MBM	6.62^{b}	6.84^{a}	6.81^{b}	6.66^{a}
0.8% MBM	6.30^{a}	6.84^{a}	6.72^{a}	6.65^{a}
N-N_H4				
NPK	7.20^{a}	5.24^{a}	1.78^{a}	2.58^{b}
0.2% MBM	7.21^{a}	4.86^{a}	1.78^{a}	1.65^{a}
0.4% MBM	8.01^{a}	5.04^{a}	1.99^{a}	2.73^{b}
0.8% MBM	12.30^{b}	6.27^{a}	2.76^{b}	3.65^{c}
N-NO_3				
NPK	3.55^{a}	3.55^{b}	4.03^{ab}	2.27^{b}
0.2% MBM	3.23^{a}	2.29^{a}	2.76^{a}	1.28^{a}
0.4% MBM	5.68^{b}	3.67^{b}	9.91^{b}	1.95^{a}
0.8% MBM	10.40^{c}	4.62^{b}	12.65^{c}	2.88^{b}
P				
NPK	77.78^{a}	86.33^{b}	63.83^{a}	87.72^{b}
0.2% MBM	67.06^{a}	79.26^{a}	63.31^{a}	80.40^{a}
0.4% MBM	72.16^{a}	85.15^{b}	69.93^{b}	87.24^{b}
0.8% MBM	76.26^{a}	88.55^{b}	75.91^{c}	95.92^{c}

Explanations as in Table 1

dose (wheat), with an increase of 1.6 to 3.1 times relative to the NPK treatment. It should be noted that the highest grain yield of triticale was not obtained in the 0.8% MBM treatment, in contrast to the other tested crop species. This suggests that mineral N was not effectively utilized by triticale. The lowest dose of MBM, which provided 1.5 g N pot^{-1} (twice less than in the NPK treatment), significantly reduced soil N-NO_3 concentrations after the harvest of oilseed rape, wheat, and maize, while N-NH_4 concentrations were comparable with those determined in the NPK treatment. Similarly to urea, MBM contributed to higher N-NH_4 than N-NO_3 levels in soil (except in soil after wheat harvest). Field experiments (Nogalska 2013, Nogalska, Zalewska 2013, Nogalska et al. 2017) revealed that due to its direct and residual effects, MBM applied at high doses (2.0 and 2.5 t ha^{-1}) increased soil mineral N levels, compared with the NPK treatment. The differences reached 6-9 kg N ha^{-1}, and N-NO_3 levels were very low. Soil amended with MBM was characterized by a higher proportion of N-NH_4 than N-NO_3. The N-NH_4 ion is relatively strongly sorbed by the soil sorption complex, indicating that MBM does not pose a threat to the soil environment when applied in adequate doses. According to Jeng and Vagstadt (2009), N leaching was approximately three times lower in soil amended with MBM than in soil supplied with mineral fertilizers. In MBM, N is present in organic compounds and is gradually released into the soil through mineralization, making it available to plants (Jeng et al. 2004, Nogalska 2013). In the work of Unagwu et al. (2023), bone meal positively influenced the chemical properties of degraded soil, increasing total N content by 78-111% relative to the initial soil status, and outperforming the NPK fertilizer in terms of measured soil parameters.

Available phosphorus content of soil

The application of MBM significantly modified the plant-available P content of soil, except in the first year of the study when spring triticale was grown (Table 4). The highest dose of MBM, which supplied 4.0 g P pot^{-1}, induced a significant increase in the plant-available P content of soil after maize harvest, in comparison with the NPK treatment (1.0 g P pot^{-1}). Soil P concentrations also increased significantly in response to the medium and highest doses of MBM in the treatment where wheat was grown. An increase in the plant-available P content of soil amended with bone meal was also reported by Unagwu et al. (2023) and Atemni et al. (2023). In the present study, the accumulation of plant-available P in soil increased and the soil pH gradually decreased with increasing doses of MBM. A similar trend was observed by Nogalska and Zalewska (2013) who found that plant-available P concentrations in soil increased with increasing doses of MBM throughout the field experiment, regardless of the frequency of its application. Simoes et al. (2012) also confirmed that the amount of plant-available P in soil was affected by the dose of MBM. In MBM, P is present in organic form (meat fraction), which is readily available to plants, and as hydroxyapatite (bone fraction), from which P is released in an acidic environment in the presence of H^+ ions (Jeng et al. 2006, Ylivainio et al. 2008). The rate of plant-available P mobilization is difficult to explain because in the soil with moderate plant-available P levels, which was used in this study, the P requirements of plants can be met by obtaining P from soil reserves. According to Brod et al. (2012), the fertilizing effect of MBM is much higher in soils deficient in plant-available P. Kivelä et al. (2015) demonstrated that MBM can be a competitive alternative to mineral fertilizers and, as a recycled fertilizer, it is a good option for organic production. According to the cited authors, MBM should be applied to soils with low plant-available P status. Some researchers recommend soil acidification as an effective method to accelerate P release from MBM (Sica et al. 2023).

CONCLUSIONS

The results of the four-year pot experiment with spring cereals and spring oilseed rape indicate that MBM can completely replace mineral P fertilizers and partially replace mineral N fertilizers, and its dose should be adjusted to meet the nutrient requirements of crops. Intensive MBM fertilization contributed to increased crop yields, N and P concentrations and uptake by plants relative to the lowest MBM dose. The only exception was the highest total P content in the seeds of oilseed rape fertilized with the lowest MBM dose. The values of the analyzed parameters were comparable in the treatments fertilized with higher doses of MBM and with mineral NPK. Soil mineral N and plant-available P concentrations increased, and soil pH slightly decreased with increasing MBM doses. The proportion of $N\text{-}NH_4$ was higher than the proportion of $N\text{-}NO_3$ after the application of MBM, similarly to urea. Meat and bone meal should be used as an organic fertilizer, especially on farms where manure is not produced.

Author contributions

A.N. – conceptualization, A.N. – methodology, A.N., M.S. – chemical analysis, A.N., M.S. – data analysis, A.N. – investigation, A.N. – resources, A.N., M.S. – data curation, A.N., M.S. – writing, original draft preparation, A.N., M.S. – writing – review & editing, A.N., M.S. – visualization, A.N. – supervision, A.N. – project administration, A.N. – funding acquisition. All authors have read and agreed to the published version of the manuscript.

Conflicts of interest

The authors declare no conflicts of interest.

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