energies

MDPI

Article

Impact of the Fly Ashes from Biomass Combustion on the Yield and Quality of Green Forage of Corn (*Zea mays* L.)

Andrzej Cezary Żołnowski [1,*], Karol Janeczek [1], Elżbieta Rolka [1] and Beata Żołnowska [2]

[1] Department of Agricultural and Environmental Chemistry, Faculty of Agriculture and Forestry, University of Warmia and Mazury in Olsztyn, Łódzki 4 Sq., 10-721 Olsztyn, Poland; kjaneczek15@gmail.com (K.J.); elzbieta.rolka@uwm.edu.pl (E.R.)

[2] Department of Agroecosystems and Horticulture, Faculty of Agriculture and Forestry, University of Warmia and Mazury in Olsztyn, Łódzki 3 Sq., 10-721 Olsztyn, Poland; beata.zolnowska@uwm.edu.pl

* Correspondence: andrzej.zolnowski@uwm.edu.pl; Tel.: +48-89-523-35-47

Abstract

Energy production from burning biomass in bioheat plants involves the production of biomass fly ash (BFA). Due to its rich chemical composition, in the era of a circular economy, it should be reused, for example, for environmental purposes as a secondary raw material containing valuable macro- and micronutrients. Due to its alkaline nature, it can also be an alternative to commercial agricultural lime (CAL) for neutralizing the acidic reaction of agricultural soils. The basis for the presented research was a pot experiment with corn (*Zea mays* L.) as a test plant and increasing doses of BFA (16.20, 32.40, and 48.60 g pot^{-1}), which is equal to 6.99, 13.98, and 20.97 g of CAL pot^{-1}. The above doses were determined based on the neutralization value (NV) of BFA and CAL, calculated to neutralize the hydrolytic acidity of the soil (Hh) to 0.5, 1.0, and 1.5 Hh. The study analyzed the effect of BFA on the leaf greenness index (SPAD), plant height, yield, and chemical composition of corn, as well as macronutrient content. The observations indicate that BFA application positively modified the yield of both fresh mass and dry mass of corn and height of plants, and reduced the dry matter content compared to the effect obtained after CAL use. BFA caused a decrease in the total N and Ca content and a significant increase in P, K, and Na compared to the CAL-fertilized treatments. BFA significantly contributed to a narrowing of the Ca:P, Ca:Mg ratios, and a widening of the K:(Ca + Mg), and K:Ca ratios compared to the ionic balance observed in the CAL-fertilized corn. The obtained results allow us to conclude that fly ash from biomass combustion can be a valuable alternative to conventional soil deacidification agents used till now in agriculture.

Keywords: biomass fly ash (BFA); corn; yield; SPAD; macronutrients; ion balance

check for updates

Academic Editor: Albert Ratner

Received: 10 September 2025
Revised: 23 October 2025
Accepted: 29 October 2025
Published: 30 October 2025

Citation: Żołnowski, A.C.; Janeczek, K.; Rolka, E.; Żołnowska, B. Impact of the Fly Ashes from Biomass Combustion on the Yield and Quality of Green Forage of Corn (*Zea mays* L.). *Energies* **2025**, *18*, 5714. https://doi.org/10.3390/en18215714

Copyright: © 2025 by the authors. Licensee MDPI, Basel, Switzerland. This article is an open access article distributed under the terms and conditions of the Creative Commons Attribution (CC BY) license (https://creativecommons.org/licenses/by/4.0/).

1. Introduction

Growing energy demand, dwindling fossil fuel resources, and the desire to reduce CO_2 emissions from combustion are driving the search for new sources of energy. Scientists are particularly interested in so-called renewable energy sources (RES). According to McKendry [1] and Basu et al. [2], the use of RES plays an important role in combating global warming by replacing fossil fuels, which is important for sustainable development [3]. One of the energy sources considered as a CO_2-neutral fuel is biomass [3,4]. Currently, biomass accounts for about 70% of renewable energy, meaning that bioenergy accounts for 9% of the global energy supply, which amounts to 622 exajoules (EJ) (1EJ = 10^{18}J) [5]. Globally, 83% of the energy consumed (422 EJ) comes from fossil fuels and 9.2% from biofuels, with

the remainder coming from other sources, including hydropower, wind energy, and solar energy [6]. Biomass is an increasingly important RES worldwide. Currently, it covers 14% and 38% of the primary energy demand of developed and developing countries, respectively [7]. Biomass, through thermal combustion and gasification, is mainly used to produce heat and electricity. The end product of this production is biomass ash (BA) [8]. Biomass can be used as a standalone fuel or co-combusted with hard coal [9]. Also in the Polish energy sector, biomass is currently one of the primary sources of renewable energy. According to Poland's Energy Policy, the share of renewable energy in all energy sources used by 2050 is planned to increase to 20% [9].

The growing use of biomass for energy purposes results in the generation of increasing amounts of ash [10]. BA generated from thermal processes, in accordance with the Regulation of the Minister of Climate of 2 January 2020, on the waste catalog in Poland [11], as in European Union countries, is treated as waste and should be disposed of in landfills. However, this solution is expensive and, in the case of BA, leads to the loss of valuable resources [10]. The use of BA in agriculture is an important issue related to nutrient cycling and the conservation of mineral fertilizers [12]. In the context of the growing demand for mineral fertilizers, greater attention should be paid to mineral wastes as BA, with significant fertilization and liming potential. It is this high lime potential that makes BA an attractive alternative to commercial calcium fertilizers. The vast majority of cultivated crops are pH-sensitive, and low soil pH impacts yields [13,14]. Unfortunately, approximately 40% of the world's agricultural soils [15] and approximately 58% of Polish soils are affected by acidification [16,17]. This is particularly noticeable in areas with light and very light soils, low carbonate levels, and a predominance of precipitation over evaporation. Acidification processes are further exacerbated by the use of artificial fertilizers and other anthropogenic factors [18–20]. Therefore, BA is becoming a material that, when used appropriately, can contribute to enriching soils with alkaline elements and thus mitigate the effects of soil acidification. Ashes from biomass combustion used in agricultural production are also a very good source of potassium [21,22]. According to Jian et al., BA's are particularly beneficial for soils low in this element [23]. Used in the cited authors' research, ash enhanced the availability of essential nutrients such as K, Ca, Mg, P, and Mo in both the soil solution and crops. In addition, BA, according to Johansen et al. [24], improves nutrient availability, pH stability, and nitrogen mineralization, leading to better crop growth. The potential for using ash is constantly increasing because BA is also recommended as a soil conditioner [25] and as a raw material for fertilizer production [26]. Such use would allow for closing the cycle of elements and their reintroduction into the environment, thus contributing to the integration of biomass-to-energy processes and sustainable energy production. Although the European Union's soil protection strategy has emphasized the importance of promoting soil improvement through nutrient recycling [27], and some Member States have already recognized the value of BA in the context of the circular economy, recycling this material at the European Union level, and the potential use of ash as fertilizer are still not adequately addressed within EU legislation. Appropriate regulations regarding BA from the energy sector are considered to be the most important thing as a driving force towards implementing proper management and valorization of ash as a raw material [10]. In addition to the above-mentioned components, this waste contains a high level of organic carbon, which, if used in agriculture, will promote carbon sequestration [28]. However, the composition of ash varies greatly depending on the type of biomass from which it was derived. Unfortunately, waste resulting from biomass combustion often contains toxic trace metals, which can reduce crop yields and the quality of food or feed, and can also lead to soil contamination [29–31]; therefore, the effects of BFA on crop growth and soil quality should be carefully evaluated. At the same time, some sources state that the use of biomass

ash may contribute to reducing the bioavailability of elements such as Zn, Mn, Ni, and Cd in the soil solution [23], This effect may be related to the presence of divalent calcium and magnesium ions in the BA, which increase the buffering properties of soils and thus increase the sorption capacity.

The cited literature data indicate many beneficial effects of BA on soil and plant yield. In addition to their rich chemical composition, BAs are also characterized by their alkaline nature, which may make them effective soil liming agents. However, the literature lacks comparative studies demonstrating how, or to what extent, BAs could replace calcium fertilizers. Therefore, the presented study aimed to investigate how the use of BA as a liming agent in corn cultivation would affect the yield and quality of the crop. The null hypothesis was that BA represents an interesting alternative to the commonly used agricultural lime as a soil liming agent and does not negatively impact plant yield or quality. The alternative hypothesis in the study was that ash would have a negative impact, resulting in reduced yield and deterioration in yield quality.

2. Materials and Methods

2.1. Description of the Experiment

A two-factor pot experiment was conducted in the greenhouse of the Faculty of Agriculture and Forestry, University of Warmia and Mazury in Olsztyn, Poland. The study assessed the effect of biomass fly ash (BFA) on plant yield and quality, as well as the potential use of BFA as a material to neutralize acidic soil pH. The effects of BFA were compared with those obtained after applying commercial agricultural lime (CAL) in doses equivalent in terms of neutralizing value (NV). The test plant used in the study was corn (*Zea mays* L.). In the presented study, the primary factor was the type of neutralizing materials used (BFA and CAL), while the secondary factor was the dose of neutralizing materials, which was intended to neutralize soil acidity equivalent to 0.5, 1.0, and 1.5 of the hydrolytic acidity value (Hh). The effects of the applied neutralizing materials were compared with those of the control object without the neutralizers.

The doses of neutralizing materials used in the experiment were calculated based on the neutralizing value (NV) [32] of BFA and CAL.

The determined NV was 21.98% for BFA and 50.88% for CAL, meaning that 100 kg of BFA or CAL can replace 21.98 and 50.88 kg of CaO, respectively. Based on this neutralization value and the value of hydrolytic acidity of the soil, the following doses of neutralizers equal to 0.5, 1.0, and 1.5 Hh were used: for BFA: 16.20, 32.40, and 48.60 g pot^{-1}, which correspond to: 5.40, 10.80, 16.20 Mg ha^{-1}, and for CAL: 6.99, 13.98, and 20.97 g pot^{-1}, which correspond to: 2.33, 4.66, 6.99 Mg ha^{-1}.

The experiment was performed in 3 repetitions. NPK mineral fertilization was applied once at doses of 111 mg N in the form of urea 46% N (Police Chemical Plant S.A., Szczecin, Poland), 66 mg P in the form of potassium dihydrogen phosphate (EUROCHEM BGD Sp. z o.o., Tarnów, Poland), and 139 mg K kg^{-1} of soil in the form of potassium dihydrogen phosphate (EUROCHEM BGD Sp. z o.o., Tarnów, Poland) and potassium sulfate pure p.a. (PPH "POCh" SA, Gliwice, Poland). The assessed neutralizing materials and mineral fertilizers (NPK) were applied to the soil and mixed thoroughly during the setup of the experiment. BFA and CAL were used as a powder, while NPK fertilizers were used as a water solution. The experiment was carried out in plastic pots. The pots used in the experiment had the following dimensions: top diameter 22 cm, height 24 cm, base diameter 18 cm. The calculated volume of the pots is 7.564 dm^{-3}. The pots were filled with 9 kg of soil. 12 corn seeds were sown in each pot. After emergence, the number of seedlings was thinned to 5 plants. The experiment was established on 21 May 2024, after emergence,

which occurred 24 May 2025 r., the number of seedlings was thinned to 5 plants, which were cultivated for 60 days. The experiment was completed on 23 July 2024.

2.2. Characteristics of the Tested Plant

The Garantio FAO 190-210 corn variety (KWS Polska Sp. z o.o., Poznań, Poland) was used as the test crop. This variety is a versatile grain and silage variety. In the COBORU 2020–2021 registration trials, the Garantio variety achieved 106% grain yield, meaning it yielded 0.73 Mg ha^{-1} higher than the reference average. According to the breeder, this variety can cope well with short-term drought conditions and mosaic soils [33].

2.3. Characteristics of the Initial Soil Used in the Pot Experiment

For the presented research, the soil collected from the arable-humus level (0–25 cm) of a field owned by the Bałdy Educational and Research Station of the University of Warmia and Mazury, located in Tomaszkowo, near Olsztyn, Poland, was used. The soil was described as loamy sand (72% of sand 0.05–2.00 mm, 27% of silt 0.002–0.05 mm, and 1.0% of clay < 0.002 mm) [34], and characterized by an acidic reaction, low electrical conductivity, and a rather poor sorption complex Table 1.

Table 1. Physicochemical properties of the soil used in the experiment.

Soil Properties	Unit	Value
Sand 0.05–2.00 mm	%	71.0
Silt 0.002–0.05 mm	%	28.0
Clay $\leq$ 0.002 mm	%	1.0
Electrical conductivity (EC)	dS m^{-1}	0.33
Reaction (pH_{H2O})	$-\log_{10}[H^+]$	4.81
Sum of base cations (SBC)	mM(+) kg^{-1}	45.33
Hydrolytic acidity (Hh)	mM(+) kg^{-1}	28.25
Cation exchange capacity (CEC)	mM(+) kg^{-1}	73.58
Base saturation of the soil sorption complex (BS)	%	61.59
Total nitrogen (N)	g kg^{-1}	0.54
Total carbon (TC)	g kg^{-1}	4.38
C/N	ratio	8.11
Heavy metals—total forms		
Copper (Cu)	mg kg^{-1}	3.35
Zinc (Zn)	mg kg^{-1}	28.05
Lead (Pb)	mg kg^{-1}	11.99
Cadmium (Cd)	mg kg^{-1}	0.77
Iron (Fe)	mg kg^{-1}	9232.38
Nickel (Ni)	mg kg^{-1}	6.46
Cobalt (Co)	mg kg^{-1}	2.72
Manganese (Mn)	mg kg^{-1}	305.46
Chromium (Cr)	mg kg^{-1}	20.63

2.4. Characteristics of Biomass Fly Ash (BFA) and Commercial Agricultural Lime (CAL) Used in the Pot Experiment

The biomass fly ash (BFA) used in the experiment was obtained as a waste product of the biomass combustion process from the bioheating plant of the Thermal Energy Company (ENERGA Kogeneracja Sp. z o.o., Elbląg, Poland). The biofuel used in the heating process was a biopellet (Figure 1), the dominant part of which was straw from commonly cultivated plants (wheat, rye, rapeseed).



Figure 1. (**a**) Biomass pellet used as a biofuel for the heating process; (**b**) Biopellet size shown on a millimeter grid.

BFA (Figure 2) was in a black-gray powdery form with a specific gravity of 0.35 kg dm^{-3}, and very high total carbon (TC) content (300.2 g kg^{-1}). The literature indicates that the average carbon content in fly ash from biomass combustion varies. According to Shibaoka, this level ranges from 2.3 to 25.3 wt% [35], while according to Eberhardt and Pan, the carbon contents of fly ash from the processing of biomass typically range from 10% to 60% [36]. Polish research indicates that the content of unburned carbon in biomass ash, depending on the place of ash formation, ranges from 47% for fly ash to 1.62% for bottom ash with slag [37]. Previous research conducted by Rolka et al. on the agricultural use of ash from burning wood chips showed that the content of unburned carbon reached 20.8% [38]. Kilpimaa et al., on the other hand, indicate that the unburned coal content in the ashes analyzed by the authors ranged from 1.3 to as much as 89.4%, depending on the type of boiler used and the combustion temperature [39]. The properties of ash and agricultural lime are presented in Table 2.

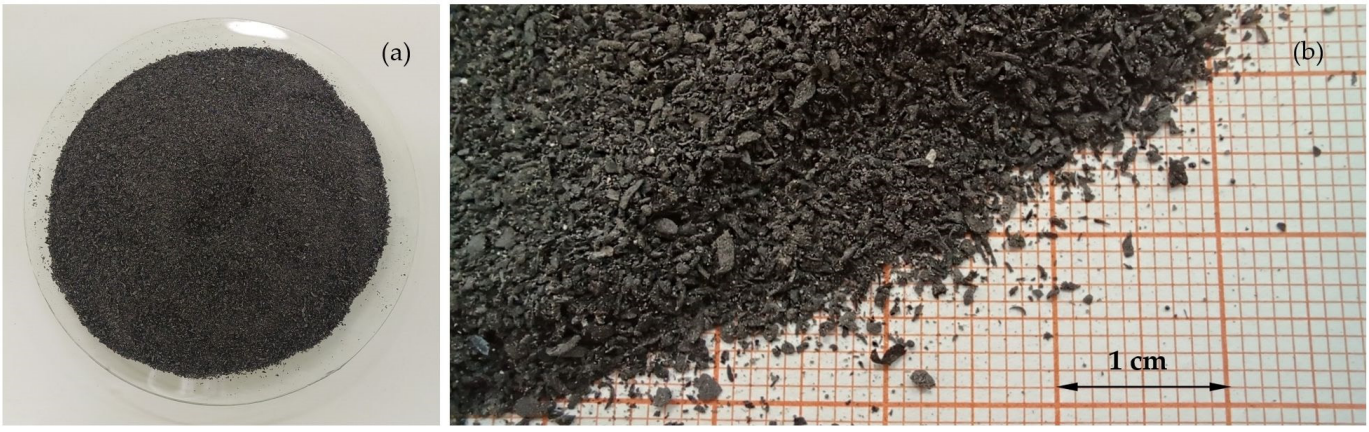


Figure 2. (**a**) BFA used in the experiment; (**b**) BFA particle size shown on a millimeter grid.

Table 2. Physicochemical properties of the neutralizing materials (BFA and CAL) used in the experiment.

Neutralizing Material Properties	Unit	BFA	CAL
		Value	
Dry matter content (DM)	%	98.88	92.74
Electrical conductivity (EC)	dS m^{-1}	12.35	0.08
Neutralizing value (NV)	% CaO	22.17	50.87
Macronutrients—total forms			
Nitrogen (N)	g kg^{-1}	0.20	0.02
Phosphorus (P)	g kg^{-1}	8.28	0.35
Potassium (K)	g kg^{-1}	41.61	0.23
Calcium (Ca)	g kg^{-1}	112.28	389.50
Magnesium (Mg)	g kg^{-1}	12.27	8.40
Sodium (Na)	g kg^{-1}	6.84	4.39
Carbon forms			
Total Carbon (TC)	g kg^{-1}	300.2	108.53
Inorganic carbon (IC)	g kg^{-1}	1.56	106.80
Total organic carbon (TOC)	g kg^{-1}	298.60	1.73
Heavy metals—total forms			
Copper (Cu)	mg kg^{-1}	59.09	9.99
Zinc (Zn)	mg kg^{-1}	331.50	69.70
Lead (Pb)	mg kg^{-1}	29.17	34.31
Cadmium (Cd)	mg kg^{-1}	1.38	1.99
Iron (Fe)	mg kg^{-1}	4198.61	1506.39
Nickel (Ni)	mg kg^{-1}	74.71	87.51
Cobalt (Co)	mg kg^{-1}	99.19	137.30
Manganese (Mn)	mg kg^{-1}	4155.57	289.35
Chromium (Cr)	mg kg^{-1}	93.28	34.26
Cr^{6+}	mg kg^{-1}	n.m.	n.m.
Mercury (Hg)	mg kg^{-1}	n.m.	n.m.
Arsenic (As)	mg kg^{-1}	n.m.	n.m.

EU limits for liming materials: Cu 300 mg kg^{-1}; Zn 800 mg kg^{-1}; Pb 120 mg kg^{-1}; Cd 2 mg kg^{-1}; Fe—not limited, Ni 90 mg kg^{-1}; Co—not limited; Mn—not limited; hexavalent Cr^{6+} 2 mg kg^{-1} (not measured in the presented studies); mercury (Hg) 1 mg kg^{-1} (not measured in the presented studies); arsenic (As) 40 mg kg^{-1} (not measured in the presented studies) [40]; ±standard error; n.m.—not measured.

The CAL used in the experiment was purchased at Wap-Pol Trade, Service and Transport Company (WAP-POL, Radoszewice, Poland). The highly reactive, granulated calcium fertilizer (Figure 3a) contains 55% CaO, with a granule size of 3–6 mm representing at least 90% by weight, according to ISO 3310-1:2016 [40] (Figure 3b).

The content of the marked forms of heavy metals in the compared neutralizing materials did not exceed the permissible standards specified in EU [40] and national regulations [41].



Figure 3. (**a**) Commercial agricultural lime (CAL) used in the experiment; (**b**) CAL particle size shown on a millimeter grid.

2.5. Chemical Analyses

One of the parameters indicating plant nutritional status is chlorophyll content, which can be calculated based on extinction measurements of extracts obtained from plant leaves or based on absorption of visible radiation in the 400–500 nm (blue light) and 600–700 nm (red light) ranges by leaf tissue. The presented study utilized a chlorophyllmeter, which allows for the measurement of leaf greenness using a non-destructive method, unlike the previously mentioned methods, which require maceration of leaves with an organic solvent to extract chlorophyll pigments. Leaf greenness index (SPAD) was measured with Chlorophyll meter SPAD–502Plus (Konica–Minolta, Osaka, Japan) [42]. Leaf greenness was expressed in SPAD (Leaf-Plant Analysis Development) units developed by Konica-Minolta. Numerous studies in the scientific literature confirm a strong correlation between SPAD readings and chlorophyll content in acetone extracts, subsequently measured spectrophotometrically [43–46]. The measurements were made three times during the experiment: 20, 40, and 60 days after plant emergence (DAE), i.e., on 13 June, 3 July, and 23 July. The individual development stages of maize plants were determined based on a standardized system for describing the phenological stages of plant development (BBCH—Biologische Bundesanstalt, Bundessortenamt und Chemische Industrie), i.e., the key growth stages that plants go through from sowing to maturity [47]. The first measurement of the leaves' greenness was made at the BBCH 15 stage (five unfolded leaves) on the third leaf, the second on the fifth leaf at the BBCH 17 stage (seven unfolded leaves), and the third on the seventh leaf at the BBCH 61 stage (beginning of pollination). Measurements were taken five times on each of the five plants, and the resulting readings were presented as averages.

During harvesting, the plant's height and the mass of the above-ground part of the plants (green forage) from each pot were measured. Harvested plants were cut into 2 cm pieces and dried with a FED 720 dryer (Binder, Tuttlingen, Germany) [48]. Drying was carried out at 60 °C until constant weight, and then the dry matter content was determined. The dried material was ground using a cutting mill SM 200 (Retsch; Haan, Germany) [49]. The ground plant samples were stored in polypropylene containers for further chemical analysis. Initial soil particle size distribution measured with particle size analyzer Mastersizer 3000 equipped with a Hydro EV module (Malvern Instruments, Worcestershire, UK) [50]. Soil reaction (pHH2O) measured according to the potentiometric method in a demineralized water, in the ratio of 1:2.5 (w/v), using a pH 538 laboratory pH meter and SenTix61 electrode (WTW, Wrocław, Poland) [51]. Soil EC was measured with the Hanna HI8733 conductivity meter (Hanna Instruments, Leighton Buzzard, UK) in a mixture of soil/deionized water in the 1:2 ratio (w/v) [51]. NV of BFA and CAL

were measured with the titrimetric method according to ISO 20978 [32]. Soil sum of base cations (SBC) and hydrolytic acidity (Hh) were measured with Kappen's method described by Ostrowska et al. 1991 [51]. Based on the obtained values of SBC and Hh, cation exchange capacity (CEC) (1) and base saturation (BS) (2) were calculated according to the following formulas:

$$\mathrm{CEC} = \mathrm{Hh} + \mathrm{SBC} \quad (1)$$

$$\mathrm{BS} = \mathrm{SBC}/\mathrm{CEC} \times 100 \quad (2)$$

The Total nitrogen (N) of soil, neutralizing materials, and plants was measured with the Kjeldahl method after prior mineralization of samples in pure concentrated sulphuric acid (H_2SO_4) (Chempur, Piekary Śląskie, Poland) in the presence of hydrogen peroxide (H_2O_2) (Stanlab, Lublin, Poland) as an oxidant. For wet digestion of the mentioned samples, we used a Speed Digester K-439 equipped with a scrubber K-415 (BÜCHI Labortechnik AG, Flawil, Switzerland). Nitrogen distillation was performed with a K-355 apparatus (BÜCHI Labortechnik AG, Flawil, Switzerland), and then titrated with TitroLine 7000 (Xylem Analytics, Weilheim, Germany) [52].

Total carbon (TC) content was determined with a Shimadzu TOC-L analyzer coupled with a module for solid samples SSM-5000A (Shimadzu Corporation, Kyoto, Japan). Chemically pure D-(+)-Glucose (Sigma-Aldrich Co., St. Louis, MO, USA) was used as a standard of carbon content (40% TC).

The C/N ratio was calculated based on TC content and N content.

Total forms of macroelements were determined in the same solutions in which total N was determined. The vanadium-molybdenum method was used for the colorimetric determination of total form of phosphorus (P) with UV-1900i Plus UV-Vis Spectrophotometer (Shimadzu Corporation, Kyoto, Japan) [51]. The potassium (K), calcium (Ca), and sodium (Na) were determined using flame atomic emission spectrometry (FAES) with a spectrophotometer SpectrAA-240FS (Varian Inc., Mulgrave, VIC, Australia). The magnesium (Mg) was determined with flame atomic absorption spectrometry (FAAS) using the same spectrometer.

Total forms of heavy metals (HMs), such as cadmium (Cd), cobalt (Co), chromium (Cr), copper (Cu), iron (Fe), manganium (Mn), nickel (Ni), lead (Pb), and zinc (Zn), were determined in the samples mineralized according to the US-EPA3051 protocol [53]. Microwave mineralization was performed using MARS 5 microwave oven (CEM Corporation, Matthews, NC, USA) in a mixture of acids: 65% HNO_3 (Chempur, Piekary Śląskie, Poland) and 38% HCl (Chempur, Piekary Śląskie, Poland) mixed in a 4:1 (v/v) ratio. The metals in soil samples were determined using flame atomic absorption spectrometry (FAAS) with an absorption spectrophotometer, SpectrAA-240FS (Varian Inc., Mulgrave, VIC, Australia), with reference standards (Merck, Darmstadt, Germany).

2.6. Statistical Analyses

A two-way ANOVA was processed using Statistica® v. 13.3 PL Software (TIBCO, Palo Alto, CA, USA) [54]. The correlation coefficients were established using a simple linear correlation model, with Microsoft Excel® for Microsoft 365 MSO v. 2206 (Microsoft, Redmond, WA, USA) [55]. The simple Pearson coefficient (r) was used to determine the relationship between the tested features. The significance of the (r) value was determined based on statistical tables [56].

3. Results

3.1. Soil Reaction

In the presented experiment, neutralizing materials were used in amounts intended to increase soil pH. Doses were calculated based on the neutralization value (NV) and hydrolytic acidity (Hh). The resulting pH increase is presented in Table 3.

Table 3. Soil reaction.

Doses of Neutralizing Materials Equal to Hh	Neutralizing Materials		Mean
	BFA	CAL	
	Reaction (pH_{H2O}) ($-\log_{10}[H^+]$)		
0	4.99 ± 0.06 ab	4.99 ± 0.06 ab	4.99 ± 0.03 A
0.5	4.89 ± 0.02 a	5.09 ± 0.08 b	4.99 ± 0.06 A
1.0	5.12 ± 0.06 b	5.29 ± 0.02 c	5.20 ± 0.05 B
1.5	5.52 ± 0.02 d	5.93 ± 0.06 e	5.73 ± 0.09 C
Mean	5.13 ± 0.08 *A*	5.33 ± 0.11 B	5.23 ± 0.07
r	0.82 **	0.90 **	0.82 **

Means followed by different letters are significantly different by the LSD $p \leq 0.05$ test (uppercase regular—show differences between doses of neutralizing materials; uppercase italic—show differences between types of neutralizing materials; lowercase—show interaction between doses of neutralizing materials and type of neutralizer); ±standard error; *r*—correlation coefficient: significant at ** $p \leq 0.01$; n = 12.

Indeed, increasing doses of CAL resulted in a significant linear increase in pH ($r = 0.90^{**}$), which for the dose equivalent to 1.5 Hh increased by 0.94 pH compared to the control. It should also be noted that equivalent doses of BFA also caused a significant increase in pH, by 0.53 pH ($r = 0.82^{**}$). In terms of deacidification power, soil fertilized with BFA had a slightly lower pH than soil fertilized with CAL. This indicates that BFA has a milder effect on the soil than CAL, which may be important in light soils with a lower sorption complex.

3.2. Leaves Greenness—SPAD Index

Corn leaf greenness was measured in the presented study three times: on 20, 40, and 60 days after emergence (DAE). Chlorophyll content, expressed as the SPAD index, varied during the growing season (Table 4). At the beginning of the growing season, i.e., on day 20 DAE, the studied corn plants were characterized by relatively high chlorophyll content. The average greenness was approximately 39.62 SPAD. In the second phase, on day 40 DAE, this index reached 32.86, and by 60 DAE, it was only approximately 25.47 units.

In each of the three study dates, no significant differences were found in the effect of BFA compared to CAL on chlorophyll content in the leaves of the analyzed plants. These neutralizing materials, applied at doses equivalent to Hh, had a very similar effect on the greenness of corn leaves. However, statistical analysis of the obtained results showed that leaf greenness was dependent on the dose of both neutralizing materials. This relationship was observed on the first and second dates of leaf analyses. On the first date (20 DAE), a significant linear decrease in leaf greenness was observed under the influence of BFA after the application of doses balanced with 0.5, 1.0. and 1.5 Hh ($r = -0.65^{*}$) (* correlation coefficient *r* significant at $p \leq 0.05$). Such a relationship was not observed with CAL. In this case, a downward trend ($r = -0.70^{**}$) (** correlation coefficient *r* significant at $p \leq 0.01$) was observed, which was not statistically proven. On the second date, i.e., at 40 DAE, the trends in the effect of the applied materials neutralizing soil acidity were reversed ($r = 0.68^{**}$). It was demonstrated that each of the BFA doses increased leaf greenness compared to the control, while for CAL, a significant increase in the SPAD index occurred after the dose equivalent to 0.5 Hh. Higher CAL doses, equivalent to 1 Hh and 1.5 Hh, had a similar effect. At the next measurement date—60 DAE—any differences in the effects of individual

doses of both BFA and CAL observed at earlier dates had disappeared, as evidenced by the insignificant LSD index value.

Table 4. Leaf greenness index of corn (SPAD units) (*Zea mays* L.).

Doses of Neutralizing Materials Equal to Hh	Neutralizing Materials		Mean
	BFA	CAL	
	20 DAE (BBCH 15)		
0	40.67 ± 1.05 bc	40.67 ± 1.05 bc	40.67 ± 0.66 A
0.5	40.12 ± 0.32 abc	41.47 ± 0.29 c	40.80 ± 0.36 A
1.0	38.51 ± 0.64 ab	39.97 ± 0.39 abc	39.24 ± 0.47 AB
1.5	38.05 ± 1.13 a	37.84 ± 0.33 a	37.94 ± 0.53 B
Mean	39.34 ± 0.49 *A*	39.99 ± 0.48 *A*	39.66 ± 0.34
r	−0.65 *	−0.70 **	−0.66 *
	40 DAE (BBCH 17)		
0	30.99 ± 0.68 a	30.99 ± 0.68 a	30.99 ± 0.43 A
0.5	32.23 ± 0.36 ab	34.68 ± 0.01 c	33.45 ± 0.57 B
1.0	33.34 ± 0.86 bc	33.71 ± 1.09 bc	33.53 ± 0.62 B
1.5	33.37 ± 0.66 bc	33.59 ± 0.34 bc	33.48 ± 0.34 B
Mean	32.48 ± 0.41 *A*	33.24 ± 0.50 *A*	32.86 ± 0.33
r	0.68 **	0.46 ^{ns}	0.54 ^{ns}
	60 DAE (BBCH 61)		
0	25.00 ± 0.70 a	25.00 ± 0.70 a	25.00 ± 0.44 A
0.5	24.67 ± 0.66 a	26.15 ± 0.26 a	25.41 ± 0.46 A
1.0	25.40 ± 0.61 a	26.07 ± 0.44 a	25.73 ± 0.37 A
1.5	26.13 ± 0.55 a	25.33 ± 0.85 a	25.73 ± 0.49 A
Mean	25.30 ± 0.32 *A*	25.64 ± 0.30 *A*	25.47 ± 0.21
r	0.44 ^{ns}	0.10 ^{ns}	0.27 ^{ns}

Means followed by different letters are significantly different by the LSD $p \leq 0.05$ test (uppercase regular—show differences between doses of neutralizing materials; uppercase italic—show differences between types of neutralizing materials; lowercase—show interaction between doses of neutralizing materials and type of neutralizer); ±standard error; *r*—correlation coefficient: significant at * $p \leq 0.05$, significant at ** $p \leq 0.01$, ns—not significant; n = 12.

3.3. Plant's Height

Plant appearance at 60 DAE is shown in Figure 4. The mean height of the tested corn plants in the presented study at 60 DAE was 208.43 cm (Table 5); however, no significant differences were found between the effects of BFA and CAL on corn plant height. Both neutralizing materials had very similar effects (Figure 4).

Table 5. Plant height of corn (*Zea mays* L.).

Doses of Neutralizing Materials Equal to Hh	Neutralizing Materials		Mean
	BFA	CAL	
	Plants' Height (cm)		
0	208.07 ± 2.66 a	208.07 ± 2.66 a	208.07 ± 1.68 A
0.5	204.40 ± 9.20 a	213.40 ± 3.00 a	208.90 ± 4.77 A
1.0	209.33 ± 7.22 a	203.33 ± 3.54 a	206.33 ± 3.84 A
1.5	218.10 ± 6.07 a	202.53 ± 4.09 a	210.43 ± 4.82 A
Mean	210.03 ± 3.26 *A*	206.83 ± 1.94 *A*	208.43 ± 1.88
r	0.37 ^{ns}	−0.46 ^{ns}	0.06 ^{ns}

Means followed by different letters are significantly different by the LSD $p \leq 0.05$ test (uppercase regular—show differences between doses of neutralizing materials, uppercase italic—show differences between types of neutralizing materials, lowercase—show interaction between doses of neutralizing materials and type of neutralizer); ±standard error; *r*—correlation coefficient: ^{ns}—not significant; n = 12.



Figure 4. Effect of increasing neutralization of soil acidity with BFA and CAL on the appearance of corn plants (*Zea mays* L.). Control—without neutralizing material; BFA0.5 (16 g of BFA pot^{-1} equal to 0.5 Hh); BFA1.0 (32 g of BFA pot^{-1} equal to 1.0 Hh); BFA1.5 (48 g of BFA pot^{-1} equal to 1.5 Hh); CAL0.5 (7 g of CAL pot^{-1} equal to 0.5 Hh); CAL1.0 (14 g of CAL pot^{-1} equal to 1.0 Hh); CAL1.5 (21 g of CAL pot^{-1} equal to 1.5 Hh).

3.4. Green Forage Yield, Dry Mass Content, and Yield of Dry Mass of the Corn (Zea mays L.)

The average green forage yield of corn from the treatments fertilized with BFA was 0.84 kg·pot^{-1} and was significantly higher than the yield obtained from the treatments fertilized with CAL by 5.95% (Table 6). A significant effect of the applied BFA dose, as a neutralizing agent for soil acidity, on yield was demonstrated. Detailed analysis, taking into account the interaction, showed that each of the applied BFA doses: 0.5, 1.0, and 1.5 Hh, linearly affected green forage yield (r = 0.95**), increasing it by 3.8, 11.5, and 16.6%, respectively, compared to the control treatment. With respect to CAL, a targeted effect cannot be considered, as only the first dose of this material slightly increased green fodder yield, and otherwise all treatments (including the control treatment) were statistically homogeneous.

The average dry matter content in green forage for the BFA-fertilized treatments was 22.81%. This value was significantly lower than that obtained for the treatments fertilized with CAL by 0.55% (Table 6). The results also revealed a significant effect of the dose of soil deacidification materials used on the mean dry matter content in green forage of corn. This effect was caused by the specific effect of BFA. For each of the BFA doses, a linear decrease in dry matter content was noted; doses of 0.5, 1.0, and 1.5 reduced this parameter by 0.74%, 1.69%, and 1.76%, respectively (r = −0.77**). Regarding CAL, a directed effect on dry matter content in green forage of corn cannot be clearly determined, as doses equal to 0.5 and 1.0 Hh reduced dry matter content and occurred at similar levels. For the highest dose of CAL equal to 1.5 Hh, no significant changes were observed compared to the control treatment.

Determined by aboveground mass yield and dry matter content, the average dry matter yield of the forage for the BFA-fertilized treatments was 0.191 kg·pot^{-1}. This

value was significantly higher than that obtained from the CAL-fertilized treatments by 7.3 g·pot^{-1} (Table 6). A significant effect of the increasing dose of BFA on the average dry matter yield was also demonstrated. Each of the BFA doses used: 0.5, 1.0, and 1.5 Hh, caused a linear increase (r = 0.85**) in dry matter yield of corn, increasing it relative to the control treatment by 2.2, 8.3, and 15.5 g·pot^{-1}, respectively. Regarding CAL, no effect on the dry matter yield of corn was observed for any of the applied doses. All CAL-fertilized treatments (including the control treatment) formed a statistically homogeneous group.

Table 6. Green forage yield, dry mass content, and dry mass yield of the corn (*Zea mays* L.).

Doses of Neutralizing Materials Equal to Hh	Neutralizing Materials		Mean
	BFA	CAL	
Yield of green forage (kg of FM pot^{-1})			
0	0.78 ± 0.01 a	0.78 ± 0.01 a	0.78 ± 0.00 A
0.5	0.81 ± 0.02 b	0.80 ± 0.00 ab	0.80 ± 0.01 B
1.0	0.87 ± 0.01 c	0.79 ± 0.01 ab	0.83 ± 0.02 C
1.5	0.91 ± 0.00 d	0.79 ± 0.01 ab	0.85 ± 0.03 C
Mean	0.84 ± 0.02 *B*	0.79 ± 0.01 *A*	0.81 ± 0.01
r	0.95 **	0.31 ^{ns}	0.59 *
Dry matter content (DM %)			
0	23.86 ± 0.22 a	23.86 ± 0.22 a	23.86 ± 0.14 A
0.5	23.12 ± 0.56 ab	22.96 ± 0.37 ab	23.04 ± 0.30 A
1.0	22.17 ± 0.23 b	23.21 ± 0.20 ab	22.69 ± 0.27 A
1.5	22.10 ± 0.42 b	23.40 ± 0.32 a	22.75 ± 0.37 B
Mean	22.81 ± 0.27 *B*	23.36 ± 0.16 *A*	23.08 ± 0.16
r	−0.77 **	−0.24 ^{ns}	−052 *
Yield of dry matter (g of DM pot^{-1})			
0	184.9 ± 1.07 a	184.9 ± 1.07 a	184.9 ± 0.68 A
0.5	187.1 ± 1.27 a	183.0 ± 1.95 a	185.1 ± 1.38 A
1.0	193.2 ± 1.81 a	183.8 ± 2.74 a	188.5 ± 2.57 A
1.5	200.4 ± 4.06 a	184.8 ± 0.23 a	192.6 ± 3.92 A
Mean	191.4 ± 2.08 *A*	184.1 ± 0.79 *A*	187.8 ± 1.32
r	0.85 **	0.02 ^{ns}	0.47 ^{ns}

Means followed by different letters are significantly different by the LSD $p \leq 0.05$ test (uppercase regular—show differences between doses of neutralizing materials; uppercase italic—show differences between types of neutralizing materials; lowercase—show interaction between doses of neutralizing materials and type of neutralizer); ±standard error; *r*—correlation coefficient: significant at * $p \leq 0.05$, significant at ** $p \leq 0.01$, ^{ns}—not significant; n = 12.

3.5. Chemical Composition of Plants

The total N content in the dry matter of the corn in the BFA-fertilized treatments was 6.053 g·kg^{-1}, and was significantly lower than that obtained in the CAL-fertilized treatments by 0.48 g·kg^{-1} (Table 7). BFA fertilization, even at a dose equivalent to 0.5 Hh, caused a significant decrease in the N content in the dry matter of the corn compared to the control treatment. However, subsequent BFA doses did not cause changes in the content of this element, and the results obtained for each BFA dose were statistically homogeneous. The addition of CAL did not significantly change the total N content in the dry matter of the corn.

Table 7. Content of macroelements (N, P, and K) in corn (*Zea mays* L.) yield.

Doses of Neutralizing Materials Equal to Hh	Neutralizing Materials		Mean
	BFA	CAL	
	N (g kg^{-1} DM)		
0	6.35 ± 0.09 b	6.35 ± 0.09 b	6.35 ± 0.06 A
0.5	5.97 ± 0.09 a	6.61 ± 0.09 b	6.29 ± 0.15 A
1.0	5.88 ± 0.00 a	6.63 ± 0.09 b	6.25 ± 0.17 A
1.5	6.01 ± 0.15 a	6.53 ± 0.09 b	6.27 ± 0.14 A
Mean	6.05 ± 0.07 *A*	6.53 ± 0.05 *B*	6.29 ± 0.06
r	−0.54 ^{ns}	0.37 ^{ns}	−0.09 ^{ns}
	P (g kg^{-1} DM)		
0	2.18 ± 0.02 a	2.18 ± 0.02 a	2.18 ± 0.01 A
0.5	2.35 ± 0.24 a	1.99 ± 0.47 a	2.17 ± 0.25 A
1.0	2.76 ± 0.21 a	2.09 ± 0.11 a	2.43 ± 0.18 A
1.5	2.76 ± 0.49 a	2.32 ± 0.29 a	2.54 ± 0.27 A
Mean	2.51 ± 0.15 *A*	2.15 ± 0.13 *A*	2.33 ± 0.10
r	0.50 ^{ns}	0.13 ^{ns}	0.30 ^{ns}
	K (g kg^{-1} DM)		
0	7.61 ± 0.06 b	7.61 ± 0.06 b	7.61 ± 0.04 A
0.5	8.36 ± 0.04 c	7.71 ± 0.28 b	8.04 ± 0.19 B
1.0	9.15 ± 0.13 d	7.38 ± 0.05 b	8.26 ± 0.40 BC
1.5	9.66 ± 0.08 e	6.96 ± 0.09 a	8.31 ± 0.61 C
Mean	8.70 ± 0.24 *B*	7.42 ± 0.11 *A*	8.06 ± 0.18
r	0.98 **	−0.71 **	0.29 ^{ns}

Means followed by different letters are significantly different by the LSD $p \leq 0.05$ test (uppercase regular—show differences between doses of neutralizing materials; uppercase italic—show differences between types of neutralizing materials; lowercase—show interaction between doses of neutralizing materials and type of neutralizer); ±standard error; *r*—correlation coefficient: significant at ** $p \leq 0.01$, ^{ns}—not significant; n = 12.

In the presented study, the mean P content in dry matter of corn for the BFA-fertilized treatments was 2.51 g·kg^{-1} (Table 7). This value was significantly higher than the value obtained from the CAL-fertilized treatments by 0.36 g·kg^{-1}. Increasing BFA doses did not significantly increase the P content in the dry matter of corn. Also, no significant differences in P content in the dry matter of corn were observed with increasing CAL doses.

The K content in dry matter of corn for the BFA-fertilized treatments was 8.70 g·kg^{-1}. This value was significantly higher by 1.28 g·kg^{-1} than the value obtained from the CAL-fertilized treatments (Table 7). It was shown that each of the applied BFA doses: 0.5, 1.0, and 1.5 Hh, caused a linear increase in the K content in dry matter of corn (r = 0.98**), increasing it compared to the control treatment by 0.75, 1.54, and 2.05 g·kg^{-1}, respectively. In the CAL cases, a downward trend was demonstrated (r = −0.71**); doses of CAL equivalent to 0.5 and 1.0 Hh had no significant effect on the K content, while the highest dose, equal to 1.5 Hh, significantly reduced the K content compared to the control treatment.

The Ca content in dry matter of corn for the BFA-fertilized treatments was 1.12 g·kg^{-1}. This value did not differ statistically from the value obtained for the treatments fertilized with CAL (Table 8). However, it was shown that BFA and CAL act differently depending on the applied doses. Using BFA as an agent to reduce soil acidity resulted in a decrease in Ca content in the dry matter of corn (r = −0.80**). However, this decrease proved significant only after applying a dose equal to 1.5 Hh. CAL, as a soil deacidification additive, caused an initial decrease (0.5 Hh) in Ca content in the dry matter of corn, followed by a gradual increase at the highest CAL dose. However, Pearson's simple analysis of correlation did not demonstrate the linearity of this effect.

Table 8. Content of macronutrients (Ca, Mg, and Na) in corn (*Zea mays* L.) yield.

Doses of Neutralizing Materials Equal to Hh	Neutralizing Materials		Mean
	BFA	CAL	
	Ca (g kg^{-1} DM)		
0	1.38 ± 0.13 c	1.38 ± 0.13 c	1.38 ± 0.08 B
0.5	1.25 ± 0.05 bc	0.77 ± 0.01 a	1.01 ± 0.11 A
1.0	1.00 ± 0.15 abc	1.04 ± 0.17 b	1.02 ± 0.10 A
1.5	0.85 ± 0.07 ab	1.28 ± 0.18 c	1.07 ± 0.13 A
Mean	1.12 ± 0.08 *A*	1.12 ± 0.09 *A*	1.12 ± 0.06
r	−0.80 **	0.02 ^{ns}	−0.37 ^{ns}
	Mg (g kg^{-1} DM)		
0	0.67 ± 0.02 a	0.67 ± 0.02 a	0.67 ± 0.01 A
0.5	0.73 ± 0.01 bcd	0.79 ± 0.04 ab	0.76 ± 0.02 B
1.0	0.75 ± 0.03 d	0.83 ± 0.01 bc	0.79 ± 0.02 BC
1.5	0.82 ± 0.01 d	0.84 ± 0.03 cd	0.83 ± 0.01 C
Mean	0.74 ± 0.02 *B*	0.78 ± 0.02 *A*	0.76 ± 0.02
r	0.84 **	0.79 **	0.78 **
	Na (g kg^{-1} DM)		
0	0.55 ± 0.03 ab	0.55 ± 0.03 ab	0.55 ± 0.02 A
0.5	0.53 ± 0.02 ab	0.49 ± 0.02 ab	0.51 ± 0.02 A
1.0	0.61 ± 0.06 b	0.41 ± 0.04 a	0.51 ± 0.06 A
1.5	0.65 ± 0.10 b	0.39 ± 0.04 a	0.52 ± 0.08 A
Mean	0.58 ± 0.03 *A*	0.46 ± 0.02 *B*	0.52 ± 0.02
r	0.43 ^{ns}	−0.77 **	−0.08 ^{ns}

Means followed by different letters are significantly different by the LSD $p \leq 0.05$ test (uppercase regular—show differences between doses of neutralizing materials; uppercase italic—show differences between types of neutralizing materials; lowercase—show interaction between doses of neutralizing materials and type of neutralizer); ±standard error; *r*—correlation coefficient: significant at ** $p \leq 0.01$, ^{ns}—not significant; n = 12.

The mean Mg content in the dry matter of the green forage of the corn for the BFA-fertilized treatments was 0.742 g kg^{-1}. This value is statistically lower by 0.04 g kg^{-1} than the mean value obtained from the CAL-fertilized treatments (Table 8). The analysis showed that each of the BFA doses: 0.5, 1.0, and 1.5 Hh, caused a linear increase in the Mg content in dry mass compared to the control treatment by 0.07, 0.08, and 0.15 g kg^{-1}, respectively (r = 0.84**). The use of the CAL doses also showed an effect on the Mg content in the dry matter of the corn. In this case, there was also a linear increase in the Mg content in the dry matter of corn (r = 0.79**).

In the presented study, the mean Na content in the dry matter of green forage of corn for the BFA-fertilized treatments was 0.59 g·kg^{-1} and was statistically higher by 0.13 g·kg^{-1} than the value obtained for the CAL-fertilized treatments (Table 8). For both BFA and CAL, increasing doses of these agents neutralizing acidic soil pH were not shown to cause significant changes in the Na content in the dry matter of corn.

The mean ionic Ca:P ratio in corn for the BFA-fertilized treatments was 0.36. This index did not differ significantly from the mean Ca:P ratio in the treatments fertilized with CAL (Table 9). The study demonstrated an interaction between the neutralizer dose and the neutralizer type. It was shown that each of the BFA doses used: 0.5, 1.0, and 1.5 Hh, caused a linear decrease in the ionic Ca:P ratio (r = −0.82**) in corn forage, lowering it by 0.07, 0.21, and 0.24, respectively, compared to the control treatment, which was not observed for CAL.

Table 9. Ca:P, Ca:Mg, and K:(Ca + Mg) ratios in the dry mass of tissue of corn (*Zea mays* L.).

Doses of Neutralizing Materials Equal to Hh	Neutralizing Materials		Mean
	BFA	CAL	
Ca:P (molar ratio)			
0	0.49 ± 0.05 b	0.49 ± 0.05 b	0.49 ± 0.03 B
0.5	0.42 ± 0.04 ab	0.34 ± 0.09 ab	0.38 ± 0.05 AB
1.0	0.28 ± 0.05 a	0.38 ± 0.05 ab	0.33 ± 0.04 A
1.5	0.25 ± 0.04 a	0.45 ± 0.10 ab	0.35 ± 0.07 A
Mean	0.36 ± 0.04 *A*	0.42 ± 0.04 *A*	0.39 ± 0.03
r	−0.82 **	−0.07 ^{ns}	−0.42 ^{ns}
Ca:Mg (meq(+) ratio)			
0	1.25 ± 0.07 d	1.25 ± 0.07 d	1.25 ± 0.05 B
0.5	1.04 ± 0.05 cd	0.59 ± 0.02 a	0.81 ± 0.10 A
1.0	0.81 ± 0.10 abc	0.76 ± 0.12 ab	0.78 ± 0.07 A
1.5	0.63 ± 0.05 a	0.92 ± 0.13 bc	0.78 ± 0.09 A
Mean	0.93 ± 0.08 *A*	0.88 ± 0.08 *A*	0.91 ± 0.06
r	−0.92 **	−0.32 ^{ns}	−0.60 *
K:(Ca + Mg) (meq(+) ratio)			
0	1.58 ± 0.10 ab	1.58 ± 0.10 ab	1.58 ± 0.06 A
0.5	1.74 ± 0.03 b	1.90 ± 0.10 bc	1.82 ± 0.06 AB
1.0	2.13 ± 0.18 cd	1.59 ± 0.11 ab	1.86 ± 0.15 B
1.5	2.25 ± 0.08 d	1.36 ± 0.13 a	1.81 ± 0.21 AB
Mean	1.93 ± 0.10 *B*	1.61 ± 0.07 *A*	1.77 ± 0.07
r	0.86 **	−0.44 ^{ns}	0.25 ^{ns}

Means followed by different letters are significantly different by the LSD $p \leq 0.05$ test (uppercase regular—show differences between doses of neutralizing materials; uppercase italic—show differences between types of neutralizing materials; lowercase—show interaction between doses of neutralizing materials and type of neutralizer); ±standard error; *r*—correlation coefficient: significant at * $p \leq 0.05$, significant at ** $p \leq 0.01$, ^{ns}—not significant; n = 12.

The ionic Ca:Mg ratio in the green corn forage for the BFA-fertilized treatments was 0.93 and statistically did not differ significantly from the Ca:Mg ratio recorded in the CAL treatments (Table 9). In this case, it was also shown that each of the applied ash doses equivalent to 0.5, 1.0, and 1.5 Hh caused a linear decrease in the ionic Ca:Mg ratio in the green corn forage, lowering it compared to the control treatment by 0.21, 0.44, and 0.62 ($r = -0.92$**), respectively. The use of CAL had the opposite effect; the Ca:Mg ratio decreased at a dose of 0.5 Hh of this additive, and increased with increasing CAL dose.

One of the most important ionic ratios indicative of forage quality is the K:(Ca + Mg) ionic ratio. In the presented study, in the corn forage fertilized with BFA, this ratio was 1.93, and was by 0.32 higher than that obtained in the CAL-fertilized treatments (Table 9). Each of the BFA doses used equal to 0.5, 1.0, and 1.5 Hh caused a linear increase in the K:(Ca + Mg) ionic ratio in the corn forage, raising it relative to the control treatment by 0.16, 0.55, and 0.68 ($r = 0.86$**), respectively. The use of CAL as an additive had the opposite effect to that of BFA. The K:(Ca + Mg) ratio increased at a dose of 0.5 Hh, and decreased with increasing doses.

The ionic K:Mg ratio in the corn forage in the BFA-fertilized treatments was 3.64, and significantly higher than that obtained in the CAL-fertilized treatments by 0.66 (Table 10). The neutralizing materials used were shown to affect this ionic ratio differently. Each of the CAL doses used: 0.5, 1.0, and 1.5 Hh, caused a linear decrease ($r = -0.89$**) in the ionic K:Mg ratio in the corn forage, lowering its value relative to the control treatment by

0.52, 0.77, and 0.96, respectively. In this case, increasing BFA doses did not demonstrate a significant effect on changes in the ionic K:Mg ratio in the corn forage.

Table 10. K:Mg, K:Ca, and K:Na ratios in the dry mass of tissue of corn (*Zea mays* L.).

Doses of Neutralizing Materials Equal to Hh	Neutralizing Materials		Mean
	BFA	CAL	
K:Mg (meq(+) ratio)			
0	3.54 ± 0.10 c	3.54 ± 0.10 c	3.54 ± 0.06 B
0.5	3.54 ± 0.04 c	3.03 ± 0.17 b	3.29 ± 0.14 A
1.0	3.82 ± 0.13 c	2.78 ± 0.02 ab	3.30 ± 0.24 A
1.5	3.67 ± 0.08 c	2.59 ± 0.10 a	3.13 ± 0.25 A
Mean	3.64 ± 0.05 *B*	2.99 ± 0.12 *A*	3.31 ± 0.09
r	0.42 ^{ns}	−0.89 **	−0.31 ^{ns}
K:Ca (meq(+) ratio)			
0	2.86 ± 0.25 a	2.86 ± 0.25 a	2.86 ± 0.16 A
0.5	3.43 ± 0.12 a	5.12 ± 0.22 bc	4.28 ± 0.39 B
1.0	4.90 ± 0.74 bc	3.84 ± 0.57 ab	4.37 ± 0.48 B
1.5	5.89 ± 0.47 c	2.94 ± 0.52 a	4.41 ± 0.73 B
Mean	4.27 ± 0.41 *A*	3.69 ± 0.33 *A*	3.98 ± 0.26
r	0.87 **	−0.11 ^{ns}	0.42 ^{ns}
K:Na (meq(+) ratio)			
0	8.24 ± 0.38 ab	8.24 ± 0.38 ab	8.24 ± 0.24 A
0.5	9.24 ± 0.31 ab	9.37 ± 0.40 ab	9.30 ± 0.23 A
1.0	8.97 ± 1.02 b	10.75 ± 0.834 a	9.86 ± 0.71 A
1.5	9.21 ± 1.32 b	10.72 ± 1.19 a	9.96 ± 0.86 A
Mean	8.91 ± 0.39 *A*	9.77 ± 0.46 *B*	9.34 ± 0.31
r	0.23 ^{ns}	0.65 *	0.43 ^{ns}

Means followed by different letters are significantly different by the LSD $p \leq 0.05$ test (uppercase regular—show differences between doses of neutralizing materials; uppercase italic—show differences between types of neutralizing materials; lowercase—show interaction between doses of neutralizing materials and type of neutralizer); ±standard error; *r*—correlation coefficient: significant at * $p \leq 0.05$, significant at ** $p \leq 0.01$, ^{ns}—not significant; n = 12.

The K:Ca ratio in the corn forage in the BFA-fertilized treatments was 4.27 and did not differ significantly from the K:Ca ratio observed in the CAL-fertilized treatments (Table 10). However, increasing the BFA doses to 0.5, 1.0, and 1.5 Hh resulted in a linear widening of the ionic K:Ca ratio in the green corn forage, increasing it by 0.57, 2.04, and 3.03, respectively (r = 0.87**), compared to the control treatment. The use of agricultural lime as an additive had the opposite effect to that of biomass ash. The K:Ca ratio increased at a dose of 0.5 Hh of this additive, and decreased with increasing doses.

The mean value of the K:Na ionic ratio was 9.34. However, no significant differences were found between the effects of BFA and CAL on this parameter. Both additives had very similar effects (Table 10). No significant changes in the K:Na ionic ratio were observed with increasing doses of BFA and CAL, although a tendency towards widening of the K:Na ratio was demonstrated with CAL (r = 0.65*).

4. Discussion

The results of the presented study showed that, despite the lack of differences in plant height (Table 5) and reduced dry matter content (Table 6) compared to the treatments fertilized with agricultural lime and the control treatment, the addition of BFA significantly contributed to increasing both corn green forage and dry matter yield (Table 6). Green

forage yield was significantly higher after the application of BFA doses balancing the hydrolytic acidity of the soil within the range of 1.0 and 1.5 Hh than in the control treatment and the treatment fertilized with BFA at a dose equivalent to 0.5 Hh, ultimately contributing to an increase in dry matter yield. This result demonstrates the yield-enhancing potential of BFA. The BFA, as a waste generated during biomass combustion, in terms of the resulting corn yield, is a good alternative to CAL, which, in the presented case, had a lower yield-enhancing effect. This raises the question of why BFA might affect plant growth differently than CAL. The research presented in this paper showed that using equivalent doses of BFA and CAL in terms of liming effect, significantly higher corn green forage yields were achieved in treatments fertilized with BFA than with CAL. It is important to note that BFA, in addition to its neutralizing properties, which result primarily from the content of divalent cations, i.e., calcium and magnesium, contains a number of other components (macro- and micronutrients) (Table 2). These additional components determined the greater yield-enhancing effect of BFA than CAL. CAL, in turn, containing small amounts of additional components, was primarily responsible for regulating soil pH and, of course, the content of available calcium. It is safe to say that BFA is a good amendment that can be used to improve soil properties. An increase in yield after using BFA as a soil improver was also observed in studies conducted by other authors [57–61]. Among others, Ajala et al. showed that under the influence of ash, there was a significant increase in such indicators as plant height, leaf length, leaf area, and stem diameter, which resulted in an increase in plant weight and, consequently, in an increase in total biomass [57]. These beneficial changes are primarily due to the lime effect obtained after the use of ashes [62]. According to Baloch et al., biomass ash improves soil structure and water capacity, and also increases the availability of nutrients and the buffering capacity of soils, which has a beneficial effect on the physicochemical and biological properties of soils [63]. The introduction of biomass ash to the soil, resulting in increased soil fertility, is of significant importance not only in corn cultivation but also in the cultivation of other plants. Füzesi et al. [64] demonstrated a positive effect of biomass ash on the yield of perennial ryegrass (*Lolium perenne* L.) and white mustard (*Sinapis alba* L.). Gill et al., in their research, after using biomass ash as a soil improver, observed higher yields of rapeseed (*Brassica napus* L.), field pea (*Pisum sativum* L.), and barley (*Hordeum vulgare* L.) [65]. Romdhane et al. concluded that the increase in corn yield after using biomass ash may be related to reduced transpiration, making biomass ash one of the possible cost-effective options for counteracting drought periods in corn cultivation [59]. The research presented in this paper seems to confirm this thesis, taking into account the reduced dry matter content of corn as a result of the biomass ash.

Biomass ash affects not only plant growth and yield but can also cause changes in plant chlorophyll content, which is expressed as leaf greenness. The SPAD index, which is often measured at critical stages of corn growth, can be used as a method for determining the yield of plants intended for silage production [46]. The results presented in this study showed significant variability in chlorophyll content in corn plant leaves, depending not only on the material used to neutralize the acidic soil reaction but also on the vegetation stage. Young plants were characterized by a higher SPAD index than plants assessed at 40 and 60 days of vegetation. The study currently presented showed that the SPAD index measured on the 20 days after emergence (DAE) significantly decreased for both of the neutralizing materials used at the highest dose, equal to 1.5 Hh. During the next measurement (40th DAE), leaf greenness increased for each neutralizer to a similar extent; however, the last SPAD measurement showed no changes in leaf greenness for any of the neutralizing materials compared to the control. Ajala et al. [57] showed that both in solo corn cultivation and in the intercropping system with lima beans, regardless of the amount of beans, they always achieved an increase in the chlorophyll content in leaves

under the influence of the BA used. In turn, in the research conducted by Rolka et al. [66], also conducted on corn, the authors stated that the SPAD value steadily decreased under ash elevated doses. Similar fertilization was used in both experiments, suggesting that this discrepancy may be due to the use of BA with a different composition than the ash used in the above study. Cited earlier, Ajala et al. [57] connected the phenomenon of an increase in the leaf greenness under the use of BA with higher photosynthesis rates, which contributed to potentially higher yields. The leaf greenness index is influenced not only by soil properties and the specific doses of additives used, as shown in the present study, but also by the species of the tested plant, as demonstrated by Żołnowski et al. [67]. These studies demonstrated significantly higher leaf greenness in sunflower and rapeseed than in corn, and combined with the currently presented research, it can be concluded that this parameter also changes significantly depending on the plant's vegetation phase, which is also confirmed by the results obtained by Romdhane et al. [59] regarding the dynamics of SPAD values, especially at the end of the growing season of corn.

The content of individual macroelements in the tested green forage indicates the quality of the feed obtained from it [68]. According to Symanowicz [69], BA is a rich source of macronutrients and, when added to the soil, can introduce significant amounts of C (160 kg), N (6 kg), P (20 kg), K (98 kg), Ca (302 kg), Mg (39 kg), and S (18 kg). The current study showed that the content of macronutrients in corn green forage after the application of BA increased with increasing doses of this neutralizing material. The exceptions were Ca, whose content decreased with increasing ash doses, and N, whose content decreased after the application of BFA and did not increase with increasing doses. The results differ from those of Rolka et al. [66] conducted on corn, where the use of BA increased the content of components such as N, Ca, K, Mg, and Na, while the content of P decreased. Here, the situation regarding the content of Ca and P was completely different.

Results similar to those presented were obtained in the study by Meller and Bilenda [60]. Their study showed significantly higher uptake of most nutrients (P, K, Mg, Ca, Na) by corn, but in this case, the Ca content also increased. Iderawumi [58] believes that the increased content of macronutrients in the aboveground parts of plants is due to the increased solubility of P and K, which results from the liming properties of BA. Szostek et al. [70] believe that this phenomenon is also caused by the greater availability of soluble forms of these elements in the soil after the application of BA.

Among the basic cations, the most important role in shaping the quality of feed is attributed to potassium and sodium, which are the basic cations of body fluids and are of great importance for the proper functioning of animal organisms, because they influence the water-electrolyte and acid-base balance [71]. Hence, the ratios of potassium to other elements such as Ca, Mg, and Na are estimated. According to Czuba and Mazur [72], another important indicator of plant quality, in addition to the content of individual macronutrients, is their mutual ratio. This characterizes the proportions of these components in plant products. The values of the most important ratios in the green forage according to literature data should be as follows: K:(Ca + Mg) = 1.6–2.2; K:Mg = 6; K:Ca = 2; K:Na = 5–10; Ca:Mg = 2–3; K:Ca = 2; and Ca:P = 1.5–2 (molar ratio) [73–77]. Therefore, when applying fertilization, farmers should consider not only the yield but also the quality of the feed, determined by the content of macronutrients and their proper mutual relationships. In the presented study, the observed changes in ionic ratios induced by BFA and CAL fertilization mainly concerned the K:(Ca + Mg) ratio (Table 9) and K:Mg ratio (Table 10), for which the use of BFA determined a wider value. This fact resulted mainly from the higher potassium content in BFA compared to CAL (Table 2). As can be seen, the use of BFA at doses equivalent to CAL contributed not only to increased yield in treatments fertilized with BFA compared to those fertilized with CAL (Table 6) but also improved their ionic balance through better

supply of plants with potassium and sodium. In the current study, the K:(Ca + Mg) ratio was consistent with the recommended values [72]. However, the K:Mg ratio was narrow and the K:Ca ratio was wide, resulting from low magnesium and high calcium supply, respectively. In this case, additional magnesium fertilization should be considered. The current study also revealed a relatively narrow Ca:P ratio compared to the recommended values [72]. To improve it, additional fertilization with phosphate fertilizers should be considered. Supplemental doses of mineral fertilizers should be applied individually, as the literature indicates that the chemical composition of BA varies greatly and depends on many factors, including the type of biomass, the species of plants used, the type of organic waste, the type of boiler, the combustion temperature, etc. [78,79].

5. Conclusions

The use of BFA as an agent neutralizing the acidic soil reaction resulted in an increase in the green forage yield and a decrease in the dry matter content, which ultimately contributed to an increase in the dry matter yield compared to the treatments fertilized with CAL. The currently presented results indicate that leaf greenness (SPAD index) was much more dependent on the date of the tests than on the fertilization and BFA dose. Higher yields of plants from treatments fertilized with BFA may indicate a significant potential of this combustion by-product in shaping the yield, which may result from the other important macronutrients it contains, such as K, Mg, and Na. The obtained research results support the conclusion that biomass combustion ash can be an interesting alternative to conventional soil deacidification agents currently used in agriculture. Their use should be preceded by a neutralization value determination and analysis of macro- and micronutrient content. This will allow for the use of supplemental mineral fertilization. The aforementioned chemical analysis will also exclude ash containing potentially hazardous elements from agricultural use. The proven beneficial effects of biomass combustion ash on plant yield and quality should be the basis for its use in agriculture, which is consistent with the broadly understood sustainable development strategy and the concept of a circular economy.

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

Funding: The results presented in this paper were obtained as part of a comprehensive study financed by the University of Warmia and Mazury in Olsztyn, Faculty of Agriculture and Forestry, Department of Agricultural and Environmental Chemistry (grant no. 30.610.004-110).

Data Availability Statement: The original contributions presented in this study are included in the article. Further inquiries can be directed to the corresponding author.

Acknowledgments: We acknowledge the Staff of the Department of Agricultural and Environmental Chemistry of UWM Olsztyn for their assistance in conducting the experimental work in the greenhouse and the bioheating plant of the Thermal Energy Company (ENERGA Kogeneracja Sp. z o.o., Elbląg, Poland) for providing biomass fly ash samples used for this study.

Conflicts of Interest: The authors declare no conflicts 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. McKendry, P. Energy Production from Biomass (Part 1): Overview of Biomass. *Bioresour. Technol.* **2002**, *83*, 37–46. [CrossRef] [PubMed]
2. Basu, M.; Pande, M.; Bhadoria, P.B.S.; Mahapatra, S.C. Potential Fly-Ash Utilization in Agriculture: A Global Review. *Prog. Nat. Sci.* **2009**, *19*, 1173–1186. [CrossRef]
3. Demirbas, F.M.; Balat, M.; Balat, H. Potential Contribution of Biomass to the Sustainable Energy Development. *Energy Convers. Manag.* **2009**, *50*, 1746–1760. [CrossRef]
4. James, A.K.; Thring, R.W.; Helle, S.; Ghuman, H.S. Ash Management Review-Applications of Biomass Bottom Ash. *Energies* **2012**, *5*, 3856–3873. [CrossRef]
5. Popp, J.; Kovács, S.; Oláh, J.; Divéki, Z.; Balázs, E. Bioeconomy: Biomass and Biomass-Based Energy Supply and Demand. *N. Biotechnol.* **2021**, *60*, 76–84. [CrossRef]
6. World Bionergy Association, W. *Global Bioenergy Statistics Report 2024*; World Bioenergy Association: Stockholm, Sweden, 2023; p. 58.
7. Mignogna, D.; Szabó, M.; Ceci, P.; Avino, P. Biomass Energy and Biofuels: Perspective, Potentials, and Challenges in the Energy Transition. *Sustainability* **2024**, *16*, 7036. [CrossRef]
8. Quirantes, M.; Calvo, F.; Romero, E.; Nogales, R. Soil-Nutrient Availability Affected by Different Biomass-Ash Applications. *J. Soil Sci. Plant Nutr.* **2016**, *16*, 159–163. [CrossRef]
9. Uliasz-Bocheńczyk, A.; Pawluk, A.; Pyzalski, M. Characteristics of Ash from the Combustion of Biomass in Fluidized Bed Boilers. *Gospod. Surowcami Miner./Miner. Resour. Manag.* **2016**, *32*, 149–162. [CrossRef]
10. Silva, F.C.; Cruz, N.C.; Tarelho, L.A.C.; Rodrigues, S.M. Use of Biomass Ash-Based Materials as Soil Fertilisers: Critical Review of the Existing Regulatory Framework. *J. Clean. Prod.* **2019**, *214*, 112–124. [CrossRef]
11. Ministry of Climate. Regulation of the Minister of Climate of January 3, 2020 on the Waste Catalog. Journal of Laws of the Republic of Poland. Available online: https://isap.sejm.gov.pl/isap.nsf/download.xsp/WDU20200000010/O/D20200010.pdf (accessed on 20 August 2025).
12. Schiemenz, K.; Eichler-Löbermann, B. Biomass Ashes and Their Phosphorus Fertilizing Effect on Different Crops. *Nutr. Cycl. Agroecosyst.* **2010**, *87*, 471–482. [CrossRef]
13. Li, Y.; Cui, S.; Chang, S.X.; Zhang, Q. Liming Effects on Soil PH and Crop Yield Depend on Lime Material Type, Application Method and Rate, and Crop Species: A Global Meta-Analysis. *J. Soils Sediments* **2019**, *19*, 1393–1406. [CrossRef]
14. Holland, J.E.; Bennett, A.E.; Newton, A.C.; White, P.J.; McKenzie, B.M.; George, T.S.; Pakeman, R.J.; Bailey, J.S.; Fornara, D.A.; Hayes, R.C. Liming Impacts on Soils, Crops and Biodiversity in the UK: A Review. *Sci. Total Environ.* **2018**, *610–611*, 316–332. [CrossRef]
15. Yadav, D.; Jaiswal, B.; Gautam, M.; Agrawal, M. Soil Acidification and Its Impact on Plants. In *Plant Responses to Soil Pollution*; Springer: Berlin/Heidelberg, Germany, 2020; pp. 1–26. [CrossRef]
16. Barczyk-Ciuła, J.; Dacko, M.; Kozielec, A.; Minta, S.; Nicia, P.; Oleksy, A.; Paluch, Ł.; Płonka, A.; Wojewodzic, T.; Zadrożny, P. Economic and Environmental Factors Determining Spatial Variation in Soil Liming in Poland. *Econ. Environ.* **2024**, *90*, 705. [CrossRef]
17. Pietr, S.J.; Krysztoforski, M. National Report on the Condition of Agricultural Land in Poland: Soil Acidification and Their Regeneration Through Liming—Current Status and Proposals for Systemic Solutions. Available online: http://phavi.wapno-info.pl/at/attachments/2022/0422/133556-spw-raport-zakwaszenie-gleb-wydanie-ii-luty-2022.pdf (accessed on 15 October 2025).
18. Mockeviciene, I.; Karcauskiene, D.; Slepetiene, A.; Vilkiene, M.; Repsiene, R.; Braziene, Z.; Anne, O. Influence of Liming Intensity on Fractions of Humified Organic Carbon in Acid Soil: A Case Study. *Sustainability* **2022**, *14*, 5297. [CrossRef]
19. Macías, F.; Camps-Arbestain, M. *A Biogeochemical View of the World Reference Base Soil Classification System: Homage to Ward Chesworth*, 1st ed.; Elsevier Inc.: Amsterdam, The Netherlands, 2020; Volume 160. [CrossRef]
20. Zhang, Y.; Ye, C.; Su, Y.; Peng, W.; Lu, R.; Liu, Y.; Huang, H.; He, X.; Yang, M.; Zhu, S. Soil Acidification Caused by Excessive Application of Nitrogen Fertilizer Aggravates Soil-Borne Diseases: Evidence from Literature Review and Field Trials. *Agric. Ecosyst. Environ.* **2022**, *340*, 108176. [CrossRef]
21. Maeda, N.; Katakura, T.; Fukasawa, T.; Huang, A.N.; Kawano, T.; Fukui, K. Morphology of Woody Biomass Combustion Ash and Enrichment of Potassium Components by Particle Size Classification. *Fuel Process. Technol.* **2017**, *156*, 1–8. [CrossRef]
22. Wang, J.; Katsumi, S.; Naganuma, H.; Makino, T.; Jian, C.; Ohori, Y.; Alviani, V.N.; Tsuchiya, N.; Watanabe, N. Converting Woody Biomass Ash and CO_2 into Valuable Resources via a Sustainable Chelation Approach. *Resour. Conserv. Recycl.* **2026**, *225*, 108606. [CrossRef]
23. Jian, C.; Hamamoto, T.; Inoue, C.; Chien, M.F.; Naganuma, H.; Mori, T.; Sawada, A.; Hidaka, M.; Setoyama, H.; Makino, T. Effects of Wood Ash Fertilizer on Element Dynamics in Soil Solution and Crop Uptake. *Agronomy* **2025**, *15*, 1097. [CrossRef]
24. Johansen, J.L.; Nielsen, M.L.; Vestergård, M.; Mortensen, L.H.; Cruz-Paredes, C.; Rønn, R.; Kjøller, R.; Hovmand, M.; Christensen, S.; Ekelund, F. The Complexity of Wood Ash Fertilization Disentangled: Effects on Soil PH, Nutrient Status, Plant Growth and Cadmium Accumulation. *Environ. Exp. Bot.* **2021**, *185*, 104424. [CrossRef]

25. Cruz, N.; Avellan, A.; Ruivo, L.; Silva, F.C.; Römkens, P.F.A.M.; Tarelho, L.A.C.; Rodrigues, S.M. Biomass Ash-Based Soil Improvers: Impact of Formulation and Stabilization Conditions on Materials' Properties. *J. Clean. Prod.* **2023**, *391*, 136049. [CrossRef]
26. Stankowski, S.; Chajduk, E.; Osińska, B.; Gibczyńska, M. Biomass Ash as a Potential Raw Material for the Production of Mineral Fertilisers. *Agron. Res.* **2021**, *19*, 1999–2012. [CrossRef]
27. European Commission. *Communication from the Commission to the European Parliament, the Council, the European Economic and Social Committee and the Committee of the Regions: EU Soil Strategy for 2030 Reaping the Benefits of Healthy Soils for People, Food, Nature and Climate*; European Commission: Brussels, Belgium, 2021; pp. 1–26.
28. Zhao, H.; Zhang, H.; Shar, A.G.; Liu, J.; Chen, Y.; Chu, S.; Tian, X. Enhancing Organic and Inorganic Carbon Sequestration in Calcareous Soil by the Combination of Wheat Straw and Wood Ash and/or Lime. *PLoS ONE* **2018**, *13*, e0205361. [CrossRef] [PubMed]
29. Rolka, E.; Żołnowski, A.C.; Wyszkowski, M.; Zych, W.; Skorwider-Namiotko, A. Wood Biomass Ash (WBA) from the Heat Production Process as a Mineral Amendment for Improving Selected Soil Properties. *Energies* **2023**, *16*, 5110. [CrossRef]
30. Maj, I.; Niesporek, K.; Płaza, P.; Maier, J.; Łój, P. Biomass Ash: A Review of Chemical Compositions and Management Trends. *Sustainability* **2025**, *17*, 4925. [CrossRef]
31. Munawar, M.A.; Khoja, A.H.; Naqvi, S.R.; Mehran, M.T.; Hassan, M.; Liaquat, R.; Dawood, U.F. Challenges and Opportunities in Biomass Ash Management and Its Utilization in Novel Applications. *Renew. Sustain. Energy Rev.* **2021**, *150*, 111451. [CrossRef]
32. *ISO 20978*; Liming Material—Determination of Neutralizing Value—Titrimetric Methods. International Organization for Standardization: Geneva, Switzerland, 2020.
33. KWS, P. Spring Crops KWS—Variety Catalog 2025. Available online: https://www.kws.com/pl/media/katalog-uprawy-jare.pdf (accessed on 20 August 2025).
34. US Department of Agriculture Natural Resources Conservation Service—Soils. Soil Texture Calculator. Available online: https://www.nrcs.usda.gov/sites/default/files/2022-11/MultiPointTriangle_v1.xlsm (accessed on 20 August 2025).
35. Shibaoka, M. Carbon Content of Fly Ash and Size Distribution of Unburnt Char Particles in Fly Ash. *Fuel* **1986**, *65*, 449–450. [CrossRef]
36. Eberhardt, T.L.; Pan, H. Elemental Analyses of Chars Isolated from a Biomass Gasifier Fly Ash. *Fuel* **2012**, *96*, 600–603. [CrossRef]
37. Ryłko, I. Environmental Impact of Waste Biochar and Biomass Recycling in Sustainable Cement Composites. Analysis. *Gaz Woda Tech. Sanit.* **2024**, *1*, 14–21. [CrossRef]
38. Rolka, E.; Wyszkowski, M.; Żołnowski, A.C.; Skorwider-Namiotko, A. Role of Woody Biomass Ash Material in Immobilization of Cadmium, Lead and Zinc in Soil. *Materials* **2024**, *17*, 2206. [CrossRef]
39. Kilpimaa, S.; Kuokkanen, T.; Lassi, U. Characterization and Utilization Potential of Wood Ash from Combustion Process and Carbon Residue from Gasification Process. *BioResources* **2013**, *8*, 1011–1027. [CrossRef]
40. European Parliament and the Council of the EU. Regulation (EU) 2019/1009 of the European Parliament and of the Council of 5 June 2019 Laying down Rules on the Making Available on the Market of EU Fertilising Products and Amending Regulations (EC) No 1069/2009 and (EC) No 1107/2009 and Repealing Regula. In *Official Journal of the European Union*; EU: Brussels, Belgium, 2019; pp. 1–114.
41. Ministry of Agriculture and Rural Development. Regulation of 18 June 2008 on the Implementation of Certain Provisions of Fertilizers and Fertilization. Journal of Laws of the Republic of Poland. Available online: https://isap.sejm.gov.pl/isap.nsf/download.xsp/WDU20100560344/O/D20100344.pdf (accessed on 20 August 2025).
42. Konica Minolta Optics. SPAD-502Plus A Lightweight Handheld Meter for Measuring the Chlorophyll Content of Leaves without Causing Damage to Plants. Available online: https://www.konicaminolta.com/instruments/download/instruction_manual/color/pdf/spad-502plus_instruction_eng.pdf (accessed on 20 August 2025).
43. Ghosh, M.; Roychowdhury, A.; Dutta, S.K.; Hazra, K.K.; Singh, G.; Kohli, A.; Kumar, S.; Acharya, S.; Mandal, J.; Singh, Y.K.; et al. SPAD Chlorophyll Meter-Based Real-Time Nitrogen Management in Manure-Amended Lowland Rice. *J. Soil Sci. Plant Nutr.* **2023**, *23*, 5993–6005. [CrossRef]
44. Nurbaiti, S.; Milasari, A.F.; Wibowo, W.A.; Nilamsari, E.I.; Rachmawati, D. Assessing Foliar Chlorophyll Content with SPAD-502 Chlorophyll Meter: A Comparison with Spectrophotometer Method in Various Plants. *J. Ris. Biol. Dan Apl.* **2025**, *7*, 50–56. [CrossRef]
45. Pacewicz, K.; Gregorczyk, A. Comparision Values of Chlorophyll Content by Chlorophyll Meter Spad-502 and N-Tester. *Agric. Aliment. Pisc. Zootech.* **2009**, *269*, 41–46.
46. Szulc, P.; Bocianowski, J.; Nowosad, K.; Zielewicz, W.; Kobus-Cisowska, J. SPAD Leaf Greenness Index: Green Mass Yield Indicator of Maize (*Zea mays* L.), Genetic and Agriculture Practice Relationship. *Plants* **2021**, *10*, 830. [CrossRef]
47. Meier, U.; Bleiholder, H.; Buhr, L.; Feller, C.; Hack, H.; Heß, M.; Lancashire, P.; Schnock, U.; Stauß, R.; Van den Boom, T.; et al. The BBCH System to Coding the Phenological Growth Stages of Plants-History and Publications. *J. für Kult.* **2009**, *61*, 41–52. [CrossRef]

48. Binder. Model FED 720 | Drying and Heating Chambers Avantgarde. Line with Forced Convection and Enhanced Timer Functions. BINDER Data Sheet. Available online: https://www.binder-world.com/int-en/products/drying-ovens/product/asset/643794 (accessed on 20 August 2025).
49. Retch. Cutting Mill SM200. Manual. Available online: https://www.retsch.com/files/9806/sm-200.pdf (accessed on 20 August 2025).
50. Panalytical Malvern. Mastersizer 3000. Brochure. Available online: https://www.malvernpanalytical.com/en/assets/mrk1872-07-en_ms3000_broch_brandupdate_lr_web_tcm50-17232.pdf (accessed on 20 August 2025).
51. Ostrowska, A.; Gawliński, S.; Szczubiałka, Z. *Methods of Analysis and Assessment of Soil and Plants Properties*, 1st ed.; Institute of Environmental Protection: Warsaw, Poland, 1991.
52. Bremner, J.M. Nitrogen—Total. In *Methods of Soil Analysis. Part 3. Chemical Methods*; Sparks, D.L., Page, A.L., Helmke, P.A., Loeppert, R.H., Soltanpour, P.N., Tabatabai, M.A., Johnston, C.T., Sumner, M.E., Eds.; Soil Science Society of America, Inc.: Madison, WI, USA; American Society of Agronomy, Inc.: Madison, WI, USA, 1996; pp. 1087–1123.
53. US Environmental Protection Agency. Method 3051 Microwave Assisted Acid Digestion of Sediments, Sludges, Soils, and Oils. Available online: https://www.epa.gov/sites/default/files/2015-12/documents/3051a.pdf (accessed on 10 February 2023).
54. Tibco. *Statistica Data Analysis Software System*; Tibco Software Inc.: Palo Alto, CA, USA, 2021.
55. Microsoft Corporation. *Microsoft 2021; Microsoft® Excel® for Microsoft 365 MSO*; Microsoft Corporation: Albuquerque, NM, USA, 2022.
56. Burdzy, J. *Statistical Tables*; Lublin University of Technology Publishing House: Lublin, Poland, 1995.
57. Ajala, R.; Awodun, M.; Oladele, S. Effects of Wood Ash Biomass Application on Growth Indices and Chlorophyll Content of Maize and Lima Bean Intercrop. *Turkish J. Agric. Food Sci. Technol.* **2017**, *5*, 614–621. [CrossRef]
58. Iderawumi, A.M. Effects of Ash on Soil Properties and Yield of Crops. *Agric. Obs.* **2020**, *1*, 61–66.
59. Romdhane, L.; Ebinezer, L.B.; Panozzo, A.; Barion, G.; Dal Cortivo, C.; Radhouane, L.; Vamerali, T. Effects of Soil Amendment with Wood Ash on Transpiration, Growth, and Metal Uptake in Two Contrasting Maize (*Zea Mays* L.) Hybrids to Drought Tolerance. *Front. Plant Sci.* **2021**, *12*, 661909. [CrossRef]
60. Meller, E.; Bilenda, E. Effects of Biomass Ash on the Physicochemical Properties of Light Soil. *Energy Policy J.* **2012**, *15*, 287–292.
61. Bilenda, E.; Meller, E. Effect of Biomass Combustion Ash on Reaction, Sorption Properties and Content of Available Forms of Macronutrients in Soil. *Przem. Chem.* **2018**, *97*, 678–681. [CrossRef]
62. Mbah, C.N.; Nwite, J.N.; Njoku, C.; Nweke, I.A. Response of Maize (*Zea Mays* L.) to Different Rates of Wood-Ash Application in Acid Ultisol in Southeast Nigeria. *Afr. J. Agric. Res.* **2010**, *5*, 580–583.
63. Baloch, S.B.; Ali, S.; Bernas, J.; Moudrý, J.; Konvalina, P.; Mushtaq, Z.; Murindangabo, Y.T.; Onyebuchi, E.F.; Baloch, F.B.; Ahmad, M.; et al. Wood Ash Application for Crop Production, Amelioration of Soil Acidity and Contaminated Environments. *Chemosphere* **2024**, *357*, 141865. [CrossRef] [PubMed]
64. Füzesi, I.; Heil, B.; Kovács, G. Effects of Wood Ash on the Chemical Properties of Soil and Crop Vitality in Small Plot Experiments. *Acta Silv. Lignaria Hung.* **2015**, *11*, 55–64. [CrossRef]
65. Gill, K.S.; Malhi, S.S.; Lupwayi, N.Z. Wood Ash Improved Soil Properties and Crop Yield for Nine Years and Saved Fertilizer. *J. Agric. Sci.* **2015**, *7*, 72. [CrossRef]
66. Rolka, E.; Żołnowski, A.C.; Wyszkowski, M.; Skorwider-Namiotko, A. Determination of the Possibilities of Using Woody Biomass Ash from Thermal Power Plants in Corn Cultivation. *Energies* **2024**, *17*, 2783. [CrossRef]
67. Żołnowski, A.C.; Bakuła, T.; Rolka, E.; Klasa, A. Effect of Mineral–Microbial Deodorizing Preparation on the Value of Poultry Manure as Soil Amendment. *Int. J. Environ. Res. Public Health* **2022**, *19*, 16639. [CrossRef]
68. Antonkiewicz, J. The Effect of Hard Coal Ashes on the Amount and Quality of Maize Yield. *Pol. J. Chem. Technol.* **2007**, *9*, 20–25. [CrossRef]
69. Symanowicz, B.; Becher, M.; Jaremko, D.; Skwarek, K. Possibilities for the Use of Wood Ashes in Agriculture. *J. Ecol. Eng.* **2018**, *19*, 191–196. [CrossRef]
70. Szostek, M.; Szpunar-Krok, E.; Jańczak-Pieniążek, M.; Ilek, A. Short-Term Effect of Fly Ash from Biomass Combustion on Spring Rape Plants Growth, Nutrient, and Trace Elements Accumulation, and Soil Properties. *Int. J. Environ. Res. Public Health* **2023**, *20*, 455. [CrossRef] [PubMed]
71. Górski, K.; Saba, L. Assessment of Sodium and Potassium Levels in Soil, Feeds and Hair of Dairy Cows in East-Central Poland/Ocena Poziomu Sodu i Potasu w Glebie, Paszach i Sierści Krów Mlecznych z Rejonu Środkowo-Wschodniej Polski. *Ochr. Sr. Zasobów Nat.* **2015**, *26*, 28–31. [CrossRef]
72. Czuba, R.; Mazur, T. *The Influence of Fertilization on Crop Quality*, 1st ed.; PWN: Warszawa, Poland, 1988.
73. Grzegorczyk, S.; Grabowski, K. The K:(Ca+Mg) Ratio in Meadow Sward Irrigated with Wastewater. *J. Elem.* **2019**, *24*, 953–959. [CrossRef]
74. Grzegorczyk, S.; Alberski, J.; Olszewska, M.; Grabowski, K.; Bałuch-Małecka, A. Content of Calcium and Phosphorus and the Ca:P Ratio in Selected Species of Leguminous and Herbaceous Plants. *J. Elem.* **2017**, *22*, 663–669. [CrossRef]
75. Żołnowski, A.C.; Sądej, W.; Suski, M.S.; Wyrwas, A.; Skrocki, D. Impact of Paper Mill Waste on Physicochemical Properties of Soil, Crop Yield, and Chemical Composition of Plants. *Clean—Soil Air Water* **2019**, *47*, 1900080. [CrossRef]

76. Żołnowski, A.C.; Wyszkowski, M.; Rolka, E.; Sawicka, M. Mineral Materials as a Neutralizing Agent Used on Soil Contaminated with Copper. *Materials* **2021**, *14*, 6830. [CrossRef]
77. Ciećko, Z.; Mierzejewska, A.; Żołnowski, A.C.; Szostek, R. Influence of Foliar Nitrogen and Magnesium Fertilization on Concentration of Ash Micronutrients in Potato Tubers. *Ecol. Chem. Eng. A* **2012**, *19*, 677–688. [CrossRef]
78. Puri, L.; Hu, Y.; Naterer, G. Critical Review of the Role of Ash Content and Composition in Biomass Pyrolysis. *Front. Fuels* **2024**, *2*, 1378361. [CrossRef]
79. Jakubus, M.; Graczyk, M. Quantitative Changes in Various Nutrient Ratios in Fodder Plants as an Effect of Compost and Fly Ash Application. *Int. J. Environ. Res. Public Health* **2022**, *19*, 8136. [CrossRef]

Disclaimer/Publisher's Note: The statements, opinions and data contained in all publications are solely those of the individual author(s) and contributor(s) and not of MDPI and/or the editor(s). MDPI and/or the editor(s) disclaim responsibility for any injury to people or property resulting from any ideas, methods, instructions or products referred to in the content.