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Review

Application of Fly Ash Obtained from the Incineration of Municipal Solid Waste in Agriculture

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Abstract: In the current context of the increase in the amount of municipal solid waste as a result of the development of urbanization, in this paper we have analyzed the impact of the use of fly ash obtained from the incineration of municipal solid waste in agriculture on the development of plants as an improver of acidic soils due to the nutrients it contains. We presented ash treatment methods to reduce the content of heavy metals and salts. Based on the studies in the literature, it was found that by adding certain concentrations of fly ash to degraded soils, the quality, porosity, and texture of the soil are improved; the yield of certain crops increases; the water retention capacity of the soil and soil aeration are improved; the density of the soil bulk; the compactness of the soil is reduced; the pH value is optimized; the electrical conductivity of the soil is increased; the crust formation is reduced; and it provides micronutrients to the soil. In the context of the circular economy, by using fly ash as an organic fertilizer in agriculture, the amount of chemical fertilizers harmful to agricultural crops is reduced, the problem of ash storage is solved, and thus it no longer pollutes the environment.

Keywords: municipal solid waste; incineration; fly ash; fertility; agriculture; acid soil; waste management

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Citation: Rusănescu, C.O.; Rusănescu, M. Application of Fly Ash Obtained from the Incineration of Municipal Solid Waste in Agriculture. *Appl. Sci.* **2023**, *13*, 3246. https://doi.org/10.3390/app13053246

Academic Editors: Vanja Jurišić and Tomislav Ivankovic

Received: 27 January 2023
Revised: 24 February 2023
Accepted: 1 March 2023
Published: 3 March 2023

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1. Introduction

The developments of the global economy and urbanization have led to increased amounts of waste worldwide [1,2]. The daily amount of waste produced in cities is 1.2 kg/capita/day and annually 1.3 billion tons per year; 15% of the entire amount is incinerated [3]. Considering the large volume of waste and people's opposition to landfills due to environmental pollution, over time, researchers have sought solutions to the problem of municipal solid waste management. In this paper, we analyze the possibility that the ash obtained from the incineration of this waste can be used to remediate degraded soils due to the nutrients it contains (phosphorus, potassium, calcium, and magnesium), making it a fertilizer for increasing the yield of agricultural plants [4].

MSW (municipal solid waste) can be processed by biological treatment, thermal treatment, or storage (Figure 1) [1,5]. Through heat treatment, the mass of waste is reduced and biofuel is obtained. The decomposition of organic matter in waste by microbes is a biochemical treatment.

Biochemical conversion is recommended in the case of waste with high moisture content and a high percentage of biodegradable organic matter. The residues obtained from these processes are stored [5]. Thermal treatment of waste is carried out by gasification, pyrolysis, and incineration [6]. Through gasification, waste is transformed into combustible gases by thermal decomposition in an oxygen-poor atmosphere to prevent complete combustion. Through pyrolysis, waste is chemically decomposed at high temperatures in the absence of air [5].

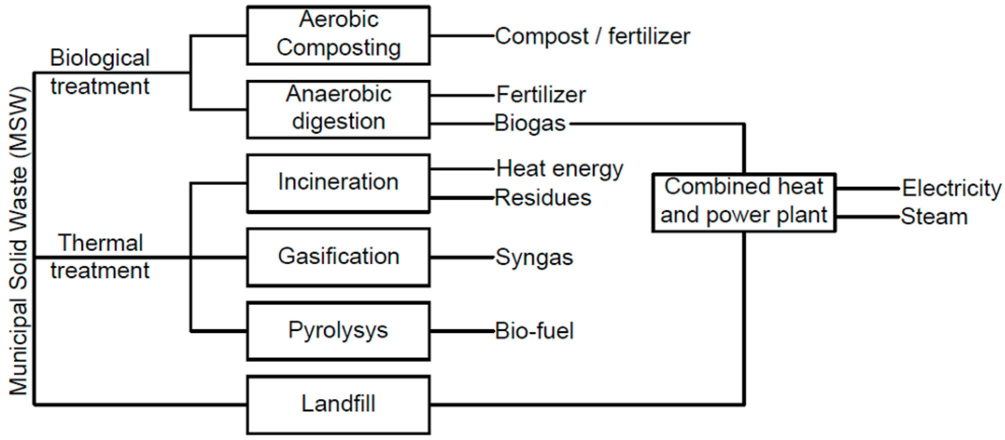

Figure 1. Municipal solid waste treatment methods (adapted from [6]).

By incinerating municipal solid waste, the fuel is burned in the furnace, where heat is produced and carried by the combustion gases at 800–1000 °C. The flue gases are cooled in the boiler with high-pressure water feed, where the steam is raised. This steam can be used to produce electricity [7].

The high cost of landfills, lack of land availability, stricter regulations, and people's opposition to siting new landfills [6] that pollute the soil, groundwater, and air by generating methane gas from waste degradation have led to municipal waste management by incineration (MSWI) [8,9].

MSWI has the following advantages: the volume of waste is reduced by 85–90% and the mass of waste is reduced by approximately 70%, thus avoiding land occupation; heat and electricity are generated; and waste is eliminated faster than through biological decomposition [10,11].

1.1. Description of the Municipal Solid Waste Incineration Process

Incineration is a method of disposal of waste by burning it. After incineration, we obtain heat that is recovered and used as such or converted in electricity, gases, steam and ash [1,12].

In the period 1995–2020, the amount of waste stored in the countries of the European Union decreased from 121 to 52 million tons, increasing the amount of incinerated waste and reaching 61 million tons in 2020 [13]. A total of 48% of the 505 kg of municipal waste generated for each member living in the countries of the European Union in 2020 was recycled [14].

From the burning of 1000 kg of waste, which requires the introduction of 4000–4500 m^3 of air, the following are obtained: 220 kg of bottom ash, 30 kg of fly ash, and 30 kg of metals (which means a reduction of 280 kg of the initial waste mass) [14]. The volume of combustion gases varies between 4600 and 6000 Nm^3/ton of waste, and the recovered energy is 400–700 kWh in the form of electricity and 1205 kWh in the form of heat [14].

At the exit of the chimney, the combustion gases contain 800–900 g of nitrogen oxides, 40–50 g of sulfur dioxide, 30–40 g of hydrochloric acid, 5–40 mg of mercury, and 11–19 g of dust [13,15,16].

An incineration plant must ensure that the level of total organic carbon, slag, and bottom ash is below 3% and that their share of calcinations does not exceed 5% of the dry matter of the incinerated material. By incinerating MSW, bottom ash is obtained, which represents approximately 20–30% of the amount of waste and is made up of mineral fraction (80–85%), ferrous metals (5–10%), non-ferrous metals (2–5%), and organic matter unburned [17,18]. Wet bottom ash can form new mineral phases and hardening processes, leading to the solidification of the bottom ash and the immobilization of heavy metals. Recoverable metals are bound in the mineral matrix [19]. Incineration can be practiced in small, individual installations or on an industrial scale. Solid, liquid, or gaseous waste, municipal, non-hazardous, and hazardous industrial waste, sewage sludge, waste from hospitals, and from the paper and wood industries can be incinerated. Incineration installations are ovens equipped with hearths with grills with direct or inverted thrust, rotary ovens, vertical ovens, and hearths with combustion in a fluidized layer or with combustion in suspension.

The amount of fly ash (3–5% of the amount of waste before it is incinerated) depends on the waste types, incineration conditions, incinerator types, and flue gas treatment methods. Heavy metals are separated from MSWI with chemical and biological reagents. Chemical stabilization is done with organic chelating reagents or inorganic chemicals to reduce the leaching of heavy metals from fly ash [18–20].

Through solidification and stabilization treatment, the negative effect of pollutants is reduced [19], and through thermal processes, the volume of waste is reduced [21]. Considering the high cost of landfills, the lack of land availability, people's opposition to the location of new landfills that pollute the soil, groundwater, and air, and the increase in the amount of municipal solid waste, solutions for the management of this waste must be found.

In this work, we analyze the management of municipal solid waste through incineration, a method by which the mass and volume of waste are reduced, electricity is generated, and we analyze the impact of using this ash as an amendment for acid soils. Due to the content of nutrients: iron, boron, manganese, zinc, copper, cobalt, molybdenum, phosphorus, potassium, calcium, sulfur, and magnesium, by adding ash obtained from the incineration of waste on degraded soils, the goal is to obtain a fertile soil and to replace chemical fertilizers, which, if continuously applied, can damage the soil and decrease the productivity of crops [22]. According to Sahu et al. [23], the use of ash obtained from municipal solid waste incineration in agriculture improves soil quality and crop yield due to the nutrients it contains. The lime content in the ash releases the following beneficial nutrients for agricultural crops: boron, sulfur, and molybdenum in the soil where it is added. Since ash is alkaline, adding it to degraded soils can increase the soil's pH. The electrical conductivity of the soil increases with the application of fly ash [23]. In this paper, we will analyze the possibility that the ash obtained from the incineration of municipal solid waste can be used as an improver of acidic soils.

1.2. Description of the Technological Flow of Municipal Solid Waste Incineration

Fly ash is captured by electrostatic precipitators and bag filters [1,24]. Municipal solid waste (MSW) is household waste, market waste, yard waste, and street sweeping waste which can be in solid, liquid, or gaseous form and is generated by commercial companies and residential complexes [25]. According to the EPA [7], the MSW material structure generated is: paper and cardboard 23.05%, food 21.59%, plastics 12.2%, yard trimmings 12.11%, metals 8.76%, wood 6.19%, textiles 5.83%, glass 4.19%, rubber and leather 3.13%, inorganic waste 1.39%, and other 1.56% [7].

The burning of solid waste consists of the following phases:

- drying and degassing of volatile substances (hydrocarbons and water) [26];
- pyrolysis of organic substances at temperatures of 250–700 °C and gasification of coal residues at temperatures between 500–1000 °C.

The transition of organic matter from the solid phase to the gaseous phase is favored by the presence of water, steam, and oxygen [26].

In the exothermic oxidation process, the moisture in the waste turns into water vapor, and the organic substances into volatile substances, flue gases, slag, and ash [26].

The technological flow of the incineration of animal and non-animal waste in an incinerator includes the following stages: collection of waste from generators and transport to the incineration plant; reception of waste on site; temporary storage of waste if applicable; waste incineration; and collection of ashes from the room incineration and their temporary storage [13].

Incineration includes the following stages, as shown in Figure 2: incineration, energy recovery, and air pollution control [13].

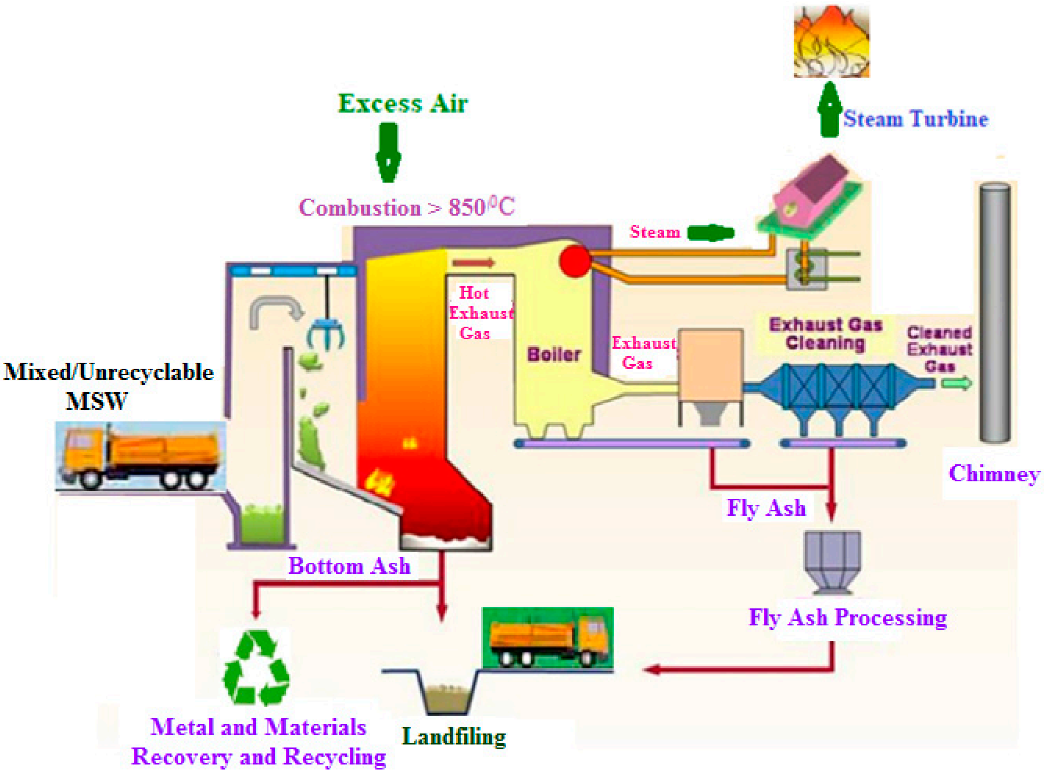

Figure 2. Scheme of the incineration process (adapted from [13]).

Solid waste is discharged into bunker storage, and then it is introduced into the oven with tongs. Air is injected into the furnace, traversing the layers of waste so as to optimize combustion.

The combustion processes are carried out through the following stages:

(a) The drying period: under the action of the heat radiated in the hearth, the air introduced, which in the vast majority of cases preheated, as well as the recirculated hot combustion gases, turn a large part of the moisture into water vapor, which is then removed in the mixture with combustion gases;

(b) The transformation period: through the uniform application of heat, volatile substances and semicoke gases, which are in relatively large quantities, are removed from the waste. The characteristic of these gases is that they ignite at relatively low temperatures (250 °C). The combustion of waste will begin after igniting the released gases;

(c) The burning period: if the appropriate conditions are met, the waste will burn continuously without the addition of auxiliary fuel. The combustion speed of the released gases depends on the thermal conductivity, the load capacity of the combustion grill, and the amount of air introduced into the hearth. The burning speed can be increased by reducing the amount of material on the burning grate and by preheating the air introduced into the incinerator;

(d) The post-combustion period represents the last part of the combustion process in which the particles of matter falling from the combustion grate continue their combustion on an additional grate (post-combustion grate) mounted in the extension of the main one or are introduced into a vertical well mounted at the lower end of the combustion grate, and through the layer of material a current of air is introduced from the bottom up, possibly with the addition of steam. In some cases, a solution can be used in which the slag (matter subjected to post-combustion) is introduced into a rotating post-combustion drum with a very low rotation speed (4–8 rot/h).

The hearth ensures continuous, well-regulated, and complete combustion of waste. An amount of air must be provided, introduced under the combustion grate, and its proper adjustment made. The firing temperature should be maintained at 850–1100 °C, and the hearths should be large and tall to ensure good air turbulence for proper combustion. For start-up ignition, it is necessary to use the support flame [26,27].

2. The Chemical Composition of Fly Ash from the Incineration of Municipal Solid Waste

The fly ash obtained from municipal solid waste incineration contains the following elements: silicon, aluminum, iron, magnesium, calcium, phosphorus, potassium, and chlorine (Table 1), and the following oxides: aluminum oxide, silicon oxide, sodium oxide, calcium oxide, potassium oxide, and iron oxide (Table 2) [26]. SiO_2 and CaO are in a higher concentration (Table 2). The fly ash obtained from the incineration of municipal solid waste is characterized by particles that are moved with the help of combustion gases, which are subsequently eliminated [28,29]. The nutrients that the soil needs are contained in the ash obtained from the incineration of municipal solid waste (Table 1) [30,31]. The chemical composition of fly ash obtained from the incineration of municipal solid waste is diverse and depends on the quality of the burned materials and the fly ash treatment methods.

Table 1. Components of fly ash (FA) from incineration units and soil (mg/kg) (data from [30–32]).

Element	Unit	FA [30]	Soil [30]	Soil [31]	Soil [32]
Ca	%	0.11–22.2	0.7–50	-	-
S	%	0.1–1.5	0.01–2.0	-	-
Al	%	0.1–17.3	4–30	-	-
Si	%	-	-	-	-
Na	%	0.01–2.03	0.04–3.0	-	-
K	%	0.15–3.5	0.04–3.0	-	-
Cl	%	-	-	-	-
Mg	%	0.04–7.6	0.06–0.6	-	-
Fe	%	36–1333	0.7–55	-	-
As	mg/kg	2.3–6300	0.1–40	5–15	20
Ba	mg/kg	-	-	200–400	-
Cd	mg/kg	0.7–130	0.01–7.0	1–3	1–3
Co	mg/kg	7–520	1–40	15–30	-
Cr	mg/kg	10–1000	5–3000	30–100	100
Cu	mg/kg	14–2800	2–100	20–100	50–140
Mo	mg/kg	7–160	0.2–5.0	2–5	-
Ni	mg/kg	6.3–4300	10–1000	20–75	30–75
Pb	mg/kg	3.1–5000	2–100	20–100	50–300
Sr	mg/kg	-	-	-	-
V	mg/kg	-	-	50–100	-
Zn	mg/kg	10–3500	10–300	100–300	150–300
Sb	mg/kg	-	-	5–20	-
P	mg/kg	0.004–0.8%	0.005–0.2%	-	-
Hg	-	0.02–1.0	-	0.1–1	1–5
Mn	-	58–3000	100–4000	900–1500	-
TOC	g/kg	-	-	-	-
Ti	%	-	-	-	-
Ag	-	-	-	2–20	-
B	-	10–618	2–100	1–2	-
Se	-	0.2–134	0.1–2.0	1–3	-

TOC—total organic carbon.

According to Table 1, the concentration of some elements necessary for the growth of plants in the ash is higher than in the soil, such as potassium, phosphorus, copper, iron, molybdenum, zinc, and boron. The minimum values of the concentration of heavy metals do not exceed the standardized limits.

According to Khan et al. [33], the permissible limit of metals in the soil may vary depending on the type and characteristics of the soil. Heavy metals at high concentrations in the soil can have a negative impact on crops, inhibiting their growth. An alkaline soil pH can restrict metal mobilization in the soil matrix, thus controlling metal uptake by crops and reducing the risk of metal toxicity [34,35].

Many types of residues are generated during the waste combustion stage in the combustion chamber or in the flue gas purification part. In the waste incineration stage in the combustion chamber, residues such as bottom ash result in the second part, depending on the type of installation, boiler ash from the area of the heat recovery economizer and other types of residues result [36].

Oxides contained in fly ash are presented in Table 2. In fly ash, the highest concentration is SiO_2, and the content of calcium oxide (CaO) in fly ash can reduce soil acidity [37].

Table 2. Oxide compositions in fly ash (FA) (wt%) (data from [35,38–40]).

Element	[35]	[38]	[39]	[40]
SiO_2	20.33–44.90	13.60	44.40	4.48–24.84
Al_2O_3	9.26–17.0	0.92	27.50	1.56–12.43
CaO	10.36–18.20	45.42	11.50	16.6–39.9
Fe_2O_3	1.72–6.29	3.83	6.21	0.85–5.04
MgO	1.83–3.15	3.16	2.36	0.67–3.76
K_2O	1.44–5.28	3.85	0.99	3.76–15.24
Na_2O	2.03–7.70	4.16	1.38	2.71–9.17
SO_3	-	6.27	1.01	7.03–14.30
P_2O_5	0.01–0.06	1.72	1.37	1.76
MnO	0.10–0.25	-	-	-
TiO_2	1.14–2.34	3.12	1.79	1.06
Cr_2O_3	-	0.19	-	-
CuO	-	0.25	-	-
ZnO	-	2.32	-	0.71–3.11
PbO	-	0.57	-	-
BaO	-	-	0.42	-

3. MSWI Treatment Methods

The treatments applied to the ash obtained from the incineration of municipal solid waste to reduce the content of heavy metals [41,42] and salts are presented in Figure 3.

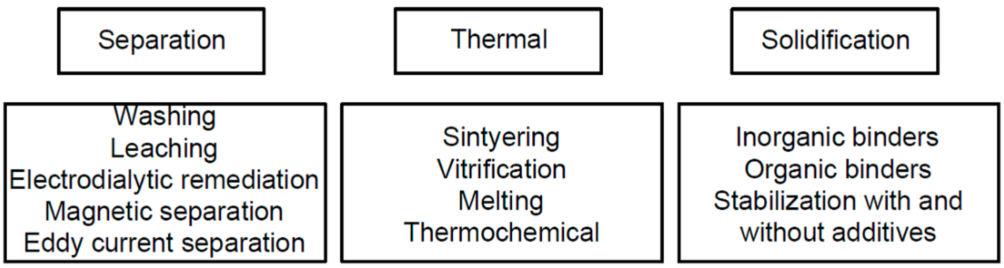

Figure 3. Fly ash treatment methods (adapted from [1]).

The treatment of fly ash is done through separation, solidification, stabilization, and thermal methods.

3.1. Separation Processes

Separation is done to reduce heavy metals, salts, and chloride from MSWI ash. According to [1], 90–95% of chlorides are removed by washing with water. Heavy metals (Cu, Pb, and Zn) are removed by washing with sulfuric and phosphoric acid [1].

Heavy metals are extracted through the leaching process, and then they are recovered from the leach solutions using chelating agents.

To extract heavy metals, biological leaching is used with strains resistant to acids and heavy metals, such as autotrophic Thiobacillus species and heterotrophic Aspergillus niger [42].

The calcium oxalate precipitate loosens fly ash molecules, thus releasing the heavy metals. Bioleaching with thiobacillus species is effective in the extraction of metals depending on the pH value (less than 4), the ash content up to 8%, and the sulfide content. Through chemical leaching and bioleaching [43], metals such as Mg, Zn, Al, Mn, and Cr are removed from fly ash. Nd, Pb, and Co were leached with biological reagents, and Ni, Fe, and Cu were leached with chemical reagents [1].

According to Kanhar et al. [1], heavy metals from fly ash are removed by acid leaching.

3.2. Electrodialytic Remediation

For the removal of heavy metals from fly ash by electrodialysis, the ash is placed in a solution in electrodialytic cells, over which an electric current is applied that allows the metal ions to migrate to the electrodes according to their charge [1,44]. Heavy metals were separated by the two-compartment electrodialytic method [45].

By magnetic separation [45], ferrous metals are separated based on their magnetic properties up to 83% [1,46]. By the eddy current separation method, non-ferrous metals are separated from the ash, and a high metal recovery efficiency was found for the fine fractions < 5 mm [1].

3.3. Solidification/Stabilization Process

It immobilizes heavy metals with the help of binders [1]. Stabilization/Solidification (S/S) MSWI ash treatment processes by stabilization/solidification are very often used. Additives or binders (cement) are used for the physical or chemical immobilization of heavy metals in fly ash to reduce the toxicity of pollutants and their drainability. After the chemical stabilization treatment, the waste is solidified [44,45].

By using washing-immobilization treatments, sulfates and chloride can be removed from the ash and the ash is stabilized in cement [1,13].

Through the cement solidification process, it is mixed with MSWI fly ash and water; after the cement is hydrated, the heavy metals are immobilized. The chemical stabilization of heavy metals is carried out using stabilizing agents such as gypsum, phosphate, bleach, sulfides (sodium thiosulfate, sodium sulfide), and polymeric organic stabilizers [1].

3.4. Thermal Methods

The thermal methods of stabilizing the metals in the ash are vitrification, sintering, fusion, and thermochemical treatment. Through the chemical processes of vitrification and sintering, hazardous waste and glass are melted. Fusion is a chemical process by which MSWI fly ash is melted at high temperature (1000–1600 °C), organic pollutants such as dioxins in fly ash can be decomposed, burned, and gasified, and inorganic ones are melted into glassy slag [1].

Through the thermal treatment of fly ash, the recovery of metals from the fly ash or the reduction of heavy metal leakage through stabilization is pursued [1]. The removal of heavy metals from fly ash can be achieved by using chlorination agents [1].

4. Physico-Chemical Properties of Fly Ash

The bulk density of fly ash (0.95–1.75 g/cm^3) decreases with decreasing ash separation temperature; fly ash has a specific gravity of 1.1–2.7 [47].

The higher the temperature, the more the structural aspect of the ash particles has a spherical shape, crystalline salts precipitate on the silicate spheres; at low temperatures, the particles have an irregular shape [48,49].

Spherical particles of ash have a diameter smaller than 10 µm, a low density, and a light texture. The ash contains the following nutrients for the soil: silicon, magnesium, calcium, iron, aluminum, sodium, and potassium.

Onions were planted on soil to which different concentrations of ash were added; no ash was added to the control soil, then ash was added from 1 t/ha to 15 t/ha (Table 3). When adding ash to the soil, the pH values increased from 7 to 8.2, the electrical conductivity of the soil increased, but the cation exchange capacity (CEC) remained almost unchanged. The values of organic carbon and organic matter increased slightly, the water holding capacity (WHC) of the soils also increased [50] (Table 3). The addition of fly ash to soil improves the physical [51], chemical, and biological properties of the soil, soil texture, bulk density, soil porosity, reduces soil compactness, changes particle size distribution, and can improve soil affected by mining activities [52,53]. Soil porosity and water retention capacity in sandy soils increased when a percentage of 40% fly ash was added to the soil, improving plant growth [51].

Table 3. Physical properties of soil mixed with ash (data from [50]).

Fly Ash (t/ha)	pH	EC	CEC	OC	OM	WHC
0	7.0	210	2.35	0.58	0.99	33.68
1	7.5	265	1.78	0.54	0.93	34.69
2.5	8.1	265	2.56	0.60	1.03	33.75
5	8.0	280	2.48	0.58	0.99	36.13
10	8.10	320	3.0	0.64	1.10	39.93
15	8.2	346	2.82	0.73	1.26	42.93

EC—electrical conductivity (EC), micro mhos cm^{-1}; CEC—exchange capacity cmols kg^{-1}; OC—organic carbon; OM—organic matter; WHC—water holding capacity.

Fly ash was added in the proportions of 10, 20, 30, 40, and 50% to the soil to see the variation of the pH and electrical conductivity of the soil where leguminous crops grow. The specific gravity of the fly ash sample was 2.21 g/cm^2 and the bulk density was 1.32 g/cm^2 in the dry state and 1.22 g/cm^2 in the wet state. It was observed that the pH of the fly ash sample was 7.56 and that of the soil was 6.65. With the increase in fly ash concentration in the soil, the pH increases, and the electrical conductivity also increases from 281 to 600 µs/cm [54] (Table 4).

Table 4. The values of pH and conductivity of the soil sample at different concentrations of ash added to the soil (data from [54]).

Fly Ash Concentration (%)	pH	EC µs/cm
0 (Soil only)	6.65	281
10	6.72	288
20	6.72	296
30	6.9	300
40	6.91	308
50	6.96	358
100 (Fly ash only)	7.56	600

5. The Impact of Using MSWI in Agriculture

Of the total amount of ash generated, approximately 1.38 billion tons are used in agriculture [55,56].

The application of fertilizers on the soil determined the degradation of agricultural lands over time (1.9×10^9 ha of land are degraded), their surface increasing in the period 1991–2011 from 15% to 25% [57].

Improving the quality of degraded lands can be done by using biofertilizers that are friendly to the soil and the environment [58,59]. The acidic pH of degraded soils can be alkalized by applying ash to the soil due to the hydroxides and carbonate salts of Ca and Mg contained in fly ash [47,52,56,57], thus replacing the lime used to reduce soil acidity, and CO_2 emissions and global warming are reduced [30,56,57,60]. One ton of fly ash could capture up to 26 kg of CO_2, i.e., 38.18 tons of fly ash per ton of sequestered CO_2 [30,61].

Adding fly ash to soil in different concentrations is useful for plant growth and for sustainable agriculture, and is a good soil amendment [61,62].

According to Thien et al. [63], the application of ash in sandy soil increased the amount of water available for plants.

Due to the content of nutrients in the soil: magnesium, calcium, phosphorus, potassium, and sulfur [22,64], ash can replace chemical fertilizers [5,16,37,58,65]. When applying the ash to the acid soil, the heavy metal content of the soil and fly ash mixtures was below the acceptable limits [59,66–70]. The amount of ash applied to the soil must be calculated according to the resistance of the plants, the plant species that grow on the respective soil, and the type of soil [71–73].

According to Ram [59], the salt content of an ash pond decreases after approximately 2–3 years, no longer being dangerous for soil and plants [74]. The concentration of salts in fresh ash decreases over time [59,75,76].

According to [73], it is recommended to apply an amount of MSWI fly ash lower than 5–10% to the soil, depending on its acidity and the plants growing on it.

Continuous application of chemical fertilizers on soils can decrease crop productivity [17,22,40]. At fly ash doses ranging from 20 tons/hectare to 100 tons/hectare, the yield increase was 20–30% [12].

Applying ash to the soil together with organic manure brings beneficial nutrients to agricultural crops, increases soil pH, and increases crop yields.

Adsorption of heavy metals is dependent on ash particle size, increasing with the decrease in bottom ash particle size [77–79].

The addition of a concentration of 5–10% fly ash increased the content of N, S, Ca, Na, and Fe of the soil; K uptake by plants was reduced; soil compaction was reduced; pH increased; the soil's bulk density decreased; water retention capacity increased; soil texture improved; soil fertility and productivity improved; and boron mobility and availability decreased [53,56].

The analysis of the soil to which different concentrations of ash were added showed an increase in the potassium content of the soil; the Fe content of the soil remained almost unchanged; the following microelements, manganese, calcium, nickel, copper, and zinc, had progressive increases with the increase in concentration of added ash. The potassium content of the soil gradually increased with the increase in the concentration of ash applied to the soil, from 45.5 (control) to 70.0 mg/kg [50] (Table 5) [50].

Table 5. The influence of fly ash obtained from the incineration of municipal solid waste on the elemental state of the soil (values in mg/kg) (data from [50]).

Fly Ash (t/h)	0	1	2.5	5	10	15
Na	1180	1215	1180	900	850	1025
K	3900	4280	6500	7050	8290	10,150
P	45.5	36.9	46.0	50.3	46.8	70.0
Fe	325	267	340	263	300	310
Mn	03	100	161	195	211	240
Ni	5.80	5.79	6.67	8.50	12.05	15.37
Co	5.15	6.10	6.68	7.36	10.22	17.31
Zn	36.0	39.6	46.0	49.8	51.0	67.0
Cu	5.06	5.73	5.97	7.50	10.0	14.38
Pb	8.3	9.50	13.46	12.97	17.58	20.00
Cr	0.0	0.02	0.20	1.06	1.39	1.89
Cd	0.0	0.0	0.0	0.005	0.02	0.06

According to Kishor et al. [78], with the increase in the concentration of ash applied to the soil, higher values of organic carbon, organic matter, phosphorus, and pH were obtained.

According to Srivastva's research, fly ash can be used as organic fertilizer at levels of 120 and 180 t ha^{-1}, due to the content of nutrients that the ash contains [54]. The addition of fly ash to clayey soil reduced bulk density and increased nutrient mobility due to increased soil porosity and soil drainage [79]. The main nutrients necessary for plant growth are phosphorus and potassium, elements found in the composition of ash, which can be used as a partial substitute for chemical fertilizers [80,81]. According to Charles et al. [13], Swiss chard and alfalfa had similar growth in soils to which ash was added to soils to which chemical fertilizers were added, due to the nutrients in MSWI ash.

Ash used in agriculture depends on the type of incinerated waste, the type of soil on which it is applied, the type of crops, the concentration of ash that is applied, and the treatment applied in order not to have a negative impact on the environment and agricultural crops [73,82,83].

The improvement in nutrients (sulfates, bicarbonates, carbonates, phosphorus, potassium, boron, calcium, zinc, magnesium, manganese) in acid soils was found after the application of an ash concentration of 5–10%, g/g [28,84–89]. The agronomic properties of the soil were improved [66–94], and the phosphorus retention capacity of the soil and phosphorus adsorption increased [59,95].

The water retention capacity and plant production were improved, and the acidity of the sandy clay soil was reduced by adding 200–400 t/ha of fly ash [28]. Raj and Mohan [96] found that the plants had an improvement in growth in the soil to which fly ash was added, the mobility of nutrients in the soil increased, and the chemical and physical properties were improved by applying the following amounts of fly ash: 0, 25, 75, and 100 tons/ha [28]. Table 6 shows the physical characteristics of the fly ash and the soil [30].

Table 6. Physical characteristics of fly ash and soil (data from [30]).

Physical Characteristics	Fly-Ash	Soil
Bulk density (g cc^{-1})	<1.0	1.33
Water-holding capacity (%)	35–40	<20
Porosity (%)	50–60	<25

According to Dwivedi and Jain [20], the use of fly ash in agriculture is also profitable from an economic point of view; 10 million hectares of land out of 150 million hectares of cultivated land can be safely occupied for fly ash application per year. At a fly ash dose of 20 mt per hectare, 200 million tons of fly ash per year would be consumed. Fields treated with fly ash would provide an additional yield of 5 million tons of grain per year [20].

6. The Effect of Using Fly Ash on Plant Development

Soil micronutrient deficiency can be improved by adding certain concentrations of MSWI to the soil, thus helping plant development [16,40,53,56,97]. The addition of a quantity of MSWI ash lower than 10% of the weight of the acid soil, changed the respiratory intensity of the soil, and the soil microbes were activated by the release of CO_2 [98]. Some elements such as As, B, Mo, Se, and V can accumulate in the plant tissue [96].

Alkaline pH fly ash applied to acidic soil helps the development of crops and provides the micronutrients and macronutrients needed by plants, vegetables, and grains [56]. Plant biomass increased in fly ash-applied soil by 11.6–29.2% at lower application rates (<25% of soil mass) and decreased by 45.8% at higher application rates (50–100%) due to heavy metal toxicity [56].

Grain growth in soils treated with ash was similar to that in soils treated with phosphorus and potassium fertilizers, indicating that ash from waste incineration can provide essential nutrients for plant growth [49]. Plant growth was twice as high in ash-applied soils as compared to ash-free soils [51,52]. At MSWI ash concentrations ranging from 20 ton/ha to 100 ton/ha, plant yield increases were 20–30% [21]. According to [66], the application of an amount of ash of 5–10% is recommended to have a positive effect on crops and acid soils. The addition of fly ash as a substitute for chemical fertilizer due to the content of phosphorus and potassium in sandy soils increased the production of clover, rye, barley, canola, rice, soybean, sunflower, wheat, tomato, and carrots [96]. According to [23], the addition of ash (125 MT ha^{-1}) on acid soils (pH 6.0) improved the yield of crops of alfalfa, millet, beans, corn, cabbage, onions, tomatoes, potatoes, sorghum, and lettuce. Onion leaves increased when a quantity of 5 t/h ash was added to the soil [51].

The production of rice and wheat was improved in the soils to which an amount between ash of 10 and 20 t ha^{-1} was added. The addition of ash to the soil led to a high growth yield after six months for the following crops: *Eucalyptus globulus*, *Neem* (*Azadirachta indica*), *Custard apple* (*Annona squamosa*), and *Jamun* (*Syzygium cumini*) [96]. High peanut yields were obtained when BA bottom ash was added at a rate of 15 kg/m^2 of soil [77]. Fly ash soil mixture concentrations from 5 to 10% were beneficial for chili plant growth and yield; this addition improved the soil with nutrients and improved soil texture and fertility, resulting in good plant development, water retention capacity, and soil pH improvement [73].

The application of a quantity of 20% ash (*w/w*) [59] led to an increase in the concentration of nutrients N, P, K, Ca, S, Mg, Na, and Zn in the soil and their absorption by rice; it was found that an improvement of Si content, an improvement of soil fertility, and the absorption of nutrients in oilseed crops helped plant roots develop better, according to Basu [30]; in soil to which ash was added [99], the yield of agricultural crops increased; the silicon content of rice plants [100] increased; and the yield of corn, sunflower, soybean, tomato, chili, and hot pepper crops increased [54]. The elemental analysis of the onion bulb showed that Na was unaffected, while the content of K and P gradually increased with the increase in the concentration of ash applied to the soil, and the concentration of iron remained unchanged due to the changes brought by the ash [50].

According to Lopareva-Pohu et al. [69], when applying fly ash to acidic soil, the concentration of metals Cu, Pb, and Ni did not exceed the limits provided in the standards [68]. The addition of ash to a soil polluted with heavy metals led to a decrease in the availability of heavy metals; at a quantity of 20 g/kg of ash, a reduction in metal absorption from rice was found; the concentration of nickel, zinc, cadmium, and copper in the acid soil decreased, thus remediating the acid soil polluted with heavy metals [101–103]. The rice culture absorbed more silicon, potassium, and phosphorus [58,100]. According to [4] Neina, no heavy metals were found in the edible parts of oats and rape grown on the soil to which the ash obtained from sewage sludge [101–103] was applied, which contained high concentrations of zinc, lead, manganese, chromium, and cadmium. The accumulation of metals depends on the type of plant and on the pH value of the soil [104–106].

In soils where an amount of ash of 3–5 Mg ha^{-1} (3000–5000 kg ha^{-1}) was applied, the production of trees increased, and the acidity of forest soils was reduced [96].

7. Discussion

Analyzing the studies in the specialized literature, we found that by applying certain amounts of ash to the degraded soils, the following characteristics of the soil were improved: electrical conductivity, physical, chemical, and biological properties; texture; bulk density; porosity; the compactness of the soil was reduced; increased organic carbon and organic matter values; water holding capacity [59] of sandy soils increased when 40% fly ash was added to the soil; improved plant growth; and increased soil pH value. The texture of sandy and clayey soils can be changed to a clayey texture, and soil encrustation on the surface was reduced [107–109].Adding certain amounts of ash to the sandy soil improved the growth of certain crops and increased the amount of water available for the plants. The analysis of the soil to which different concentrations of ash were added revealed an increase in the potassium and phosphorus content of the soil, and the following microelements:

manganese, calcium, nickel, copper, and zinc had progressive increases with the increase in the concentration of added ash.

Water holding capacity and plant production were improved, and the acidity of clay-sand soil was reduced by adding 200–400 t/ha fly ash [28].

The price of fly ash (AUS 2926) is lower than that of fertilizers (AUS 8800). Fly ash can be used to improve soil acidity by replacing agricultural lime, providing nutrients to plants, and improving the properties of sandy soil [107].

Since the application of chemical fertilizers on the soil led to its degradation, it is necessary to find some solutions to be able to use the degraded soils.

The use of fly ash in agriculture is profitable, and economically, 10 million hectares of land out of 150 million hectares of cultivated land can be safely occupied for fly ash application per year. At a fly ash dose of 20 mt per hectare, 200 million tons of fly ash would be consumed per year. Fields treated with fly ash would provide an additional yield of 5 million tons of grain per year [20]. Plant growth was twice as high in ash-applied soils compared to ash-free soils [51,52].

In soils where an amount of ash of 3000–5000 kg ha^{-1} was applied, tree production increased and the acidity of forest soils was reduced [96].

By applying a 5% amount of fly ash to the soil, peanut production increased from 0.19 to 2.3 t/ha [107].

The benefits brought by ash in agriculture depend on the type of incinerated waste, the type of soil on which it is applied, the type of crops, the concentration of ash that is applied, and the treatment applied so as not to have a negative impact on the environment and agricultural crops [73,82,83].

8. Conclusions

Adding fly ash to soil in different concentrations improves the physical, chemical, and biological properties of soil; improves soil quality, porosity, soil texture; helps plant growth; reduces soil bulk density; improves water retention capacity; optimizes the pH value; improves soil aeration; reduces crust formation provides micronutrients such as Fe, Zn, Cu, Mo, B, Mn, K, P, Ca, Mg, and S; and it works as a partial substitute for lime to restore alkaline soil.

Due to the addition of fly ash to sandy soils, the production of clover, rye, barley, rapeseed, rice, soybeans, sunflowers, wheat, tomatoes, and carrots increased.

The use of fly ash in agriculture is 1.38 billion tons, with up to 0.63% of all fly ash generated.

Soils that were mixed with up to 50% fly ash had lower bulk density and higher water holding capacity due to structural and textural changes. Soil water holding capacity is related to surface area, pore space volume, and pore space continuity. The hydraulic conductivity is lower than that of the plain soil, but the porosity and workability of the soil are better. The application of high rates of fly ash changed the texture of sandy and loamy soil. The analysis of the soil to which different concentrations of ash were added revealed an increase in the potassium and the phosphorus content of the soil, and the following microelements, manganese, calcium, nickel, copper, and zinc, had progressive increases with the increase in the concentration of added ash. Water holding capacity and plant production were improved, and the acidity of clay-sand soil was reduced by adding 200–400 t/ha of fly ash. Plants had an improvement in growth in the fly ash added to soil; soil nutrient mobility increased; and chemical and physical properties were improved by applying the following amounts of fly ash: 0, 25, 75, and 100 tons/ha.

The use of fly ash in agriculture is profitable, and economically, 10 million hectares of land out of 150 million hectares of cultivated land can be safely occupied for fly ash application per year. At a fly ash dose of 20 mt per hectare, 200 million tons of fly ash would be consumed per year. Fields treated with fly ash would provide an additional yield of 5 million tons of grain per year.

Considering the increase in the amount of municipal solid waste and climate change, we believe that by incinerating this waste we reduce its volume, protect the environment, and it can be used as a fertilizer for degraded soils, which favors plant development and helps the soil. This is the municipal solid waste management method. We have also presented the methods of treating the ash obtained from the incineration of municipal solid waste, so that if the ash contains heavy metals or salts by treating the ash, it can be used as a soil fertilizer.

The effects of applying certain concentrations of ash on different types of soil over long periods of time must be analyzed.

Author Contributions: Conceptualization: C.O.R.; methodology: C.O.R. investigation: C.O.R. and M.R.; resources: C.O.R. and M.R.; writing—review and editing: C.O.R. and M.R. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: Not applicable.

Conflicts of Interest: The authors declare no conflict of interest.

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