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THE POTENTIAL OF HUMAN URINE AND BIOCHAR INTEGRATION FOR SOIL HEALTH AND MAIZE PRODUCTIVITY: A REVIEW

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ABSTRACT

The decline in soil fertility and the excessive increase in the cost of in-organic inputs in sub-Saharan Africa, including Malawi, necessitate the need for integrated soil fertility management that includes organic inputs. Human urine and biochar have recently been promoted as sustainable sources of essential nutrients for maize production, especially for the resource-constrained smallholder farmers. Studies conducted have reported that human urine contains essential nutrients such as nitrogen (N), ranging from 3 to 12 g/l, available phosphorus (P), ranging from 1.25 to 2.8 g/l, and potassium (K), ranging from 0.65 to 3g/l. Urine has also been reported to increase maize grain yield, biomass, grain weight, and plant growth parameters. Urine can increase maize grain yield up to 6.82 t/ha which is above average maize grain yield (2000 kg/ha) produced by small holder farmers in Malawi. Human urine may contain traces of pharmaceuticals such as ampicillin, ciprofloxacin, ibuprofen, and trimethoprim sulfamethoxazole, especially if the individual is on medication, which can be harmful to soil microbes, plants and humans if urine is used untreated or in excessive amounts. However, fresh urine from healthy individuals is generally sterile, it should be properly treated and diluted before agricultural use to minimize health and environmental risks. Similarly, biochar has also been reported with large surface areas, high porosity, high carbon content, high conductivity. Additionally, biochar contains essential plant nutrients such as phosphorus, potassium, magnesium and calcium but in low concentrations which can be available for crop growth and development when it is applied in higher rates or when integrated with other sources of soil nutrient amendments. Furthermore, there is a lot of variations in the effects of both urine and biochar as influenced by inherent soil properties and materials they are integrated with during application. This review focuses on synthesis of information to provide clearly messages on the potential of urine, biochar and their combined effects on maize productivity and soil health.

Key words: biochar, maize productivity, urine, soil health, elements, phytochemical, rate, nutrients

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INTRODUCTION

Soil health is key to ensuring sustainable crop production. In Malawi and many countries in sub-Saharan Africa (SSA), soil degradation and imbalanced plant nutrition which limits agricultural productivity has been documented [1]. The continuous decline in soil health in the country is attributed to the loss of topsoil, loss of soil organic matter and acidification [2]. Small-scale farms in Malawi, have low soil nitrogen (N) and available phosphorus (P), additionally, the soil nutrients are also highly variable between farms [3, 4]. The soils are underprovided in essential nutrients such as nitrogen (N) and phosphorous (P) which limit the productivity of maize crop [5]. The study by Nalivata *et al*. [5], stated that the poor soil fertility and imbalanced plant nutrients as a result of soil degradation contribute to poor crop productivity in sub-Saharan Africa including Malawi. Integrated soil fertility management (ISFM) has been recommended for improving soil health through application of organic manure in combination with inorganic fertilizers, crop residue incorporation [6], and integration of legumes in cropping systems either as intercrops or crop rotations [3, 7]. Recently, some studies have reported that the use of human urine helps to supplement or replace inorganic sources of essential nutrients, especially N and boost maize crop productivity [8, 9].

Human urine, regardless of being rich in plant nutrients such as nitrogen (N), phosphorus (P), potassium (K), calcium (Ca), sulphur (S) and magnesium among others, however, some of these nutrients such as potassium (k) and phosphorus (P) are available in low concentrations [10]. Additionally, use of urine only encourages the export of cations from the soils since urine does not contain organic carbon and it is prone to leaching and volatilisation [11]. It may be beneficial to combine urine with other soil amendments like biochar for improved soil health and crop productivity. Biochar is carbonized biomass produced under oxygen-free conditions; a process referred to as pyrolysis [12, 13]. Biochar is overall negatively charged on the surface [10]. It can stabilize soil carbon, enhances the absorption of inorganic and organic compounds, has a large surface area and therefore is capable of holding and exchanging cations in soils. It provides an alkaline pH range and enriches the soil with organic matter [14, 15]. However, biochar is characterised by low plant macronutrients, especially nitrogen and cannot be used as a major nutrient source [13]. Hence, both biochar and human urine necessitate the need for their combination for sustainable maize crop production and improved soil health. This review is focused on further synthesis of the ability of human urine and biochar, separately and their integration in improving maize productivity, soil health and challenges associated with their use in agriculture.

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Prospect of human urine as a sustainable source for maize plant nutrients

There are several factors which qualify human urine for improvement of both maize productivity and soil health. These factors are evidenced as follows:

Nutrient elements in human urine

Several studies have proven that human urine has a significant concentration of essential nutrients for crop growth and development including maize. The total nitrogen ranges from 0.21 to 0.83, phosphorus from 0.13 to 0.26 and potassium from 0.12 to 0.25. It also has traces of calcium, magnesium, sulphur and micronutrients [10,16]. Another study reported that urine contains 6.668 gL^{-1} total nitrogen, 5.257 gL^{-1} ammoniac nitrogen, 0.002 gL^{-1} nitrate, 0.325 gL^{-1} soluble orthophosphate (P-PO_4^{-3}), 1.558 gL^{-1} potassium, 2.509 gL^{-1} sodium, 0.034 gL^{-1} total hardness (Ca+Mg) and pH of 9.12 [17]. Studies conducted in Niger showed that human urine contains 0.5%, 0.25% and 0.65 % of N, P and K, respectively [18]. This was complemented by other experiments which reported that human urine is a potential source of nitrogen, potassium, phosphorus and other trace elements essential for plant growth [19, 20]. It has a lower content of heavy metals compared to other organic fertilizers. The quantity of nutrients in human urine is influenced by individual food intake (diet) [13], with the urine collected from non-vegetarian diets having slightly higher concentrations of some nutrients compared to a vegetarian diet [20]. The quality of urine justifies its potential for improved crop productivity. Additionally, urine is more beneficial compared to the in-organic sources of plant nutrients since it contains a number of both macro and micro essential nutrients (Table 1), while inorganic sources of nutrients mostly contain a maximum of five essential nutrients such as NPK + 4S. Additionally, the in-organic sources mostly do not count for micro-essential nutrients, hence human urine is an appropriate source of plant nutrients.

Human urine concentration for maize crop production

Studies have recommended best concentration or dilution rates for optimal performance of maize in response to human urine. The on-station laboratory experiment conducted at Kogi state University in Nigeria looked at the effects of gender and concentrations (50ml, 100ml, 150ml and 200ml) in making one litre urine + water product, on maize growth and phytochemicals [14]. Both male and female urine increased the rate of maize growth and phytochemical constituents of the *zea mays* for 50ml, 100ml, 150 ml and 200ml in 1000 ml urine: water, respectively. High concentration of urine (200ml) inhibited growth of maize [14]. This is contrary, to a pot experiment conducted by Kumar [20] at Arba Min, in Ethiopia on treated human urine diluted at the ratio of 1:3 and applied at 500 ml, 800ml, 1000ml and 1200 ml per maize plant. A non-significant difference was reported between the 500ml application per plant and the rest of application rate. This makes urine to be similar with all other sources of nutrients which need to be applied in the right amount in

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order to maximise the crop yield. The recommended amount of nitrogen for maize crop in Malawi is 92 kg N ha^{-1} [21], hence urine should be applied in the right amount to meet nitrogen requirement in order to optimise maize productivity.

Maize performance in response to human urine

There are several studies that have reported maize response to urine as a source of crop nutrients. For example, the on farm field experiment conducted in Marondra district in Chihota communal land in Zimbabwe discovered that urine in combination with faecal matter produced higher maize grain yield of 3.6t ha^{-1}, seconded by sole urine treatment with mean of 3.2 t ha^{-1}, then inorganic NPK (7:18:7) with the mean of 2.5 t ha^{-1} and the least was negative control (No application treatment) with the mean of 1.5 t/ha^{-1} [22]. Similar results were reported by Sridevi *et al*. [16], that a combination of 40% recommended dose of nitrogen through farm yard manure (FYM) as basal plus 60% human urine increased maize grain yield compared to the inorganic fertilizer (positive control) with mean values of 6.89 t ha^{-1}and 3.89 t ha^{-1} , respectively, while sole human urine had maize grain yield of 6.65 t ha^{-1}.

The other experiment conducted on khumal (yellow) maize variety in India reported the equivalent maize grain yield of 1.05 t ha^{-1} for inorganic fertilizer, 1t ha^{-1} for human urine and 0.45 t ha^{-1} for no application treatments [18]. The experiment conducted in a green house in which the maize was treated by various sources of nutrients such as no application, inorganic NPK, sole human urine and human urine + cassava water among others discovered that at 9 weeks after planting (WAP) the inorganic NPK, urine and urine in combination with cassava water treatments performed statistically equally at p-value of 0.05 with mean values of 169 cm, 176 cm and 177.5 cm, respectively in terms of plant height. However, the non-application treatment significantly reduced the maize plant height with mean value of 129.75cm [17]. The pot experiment conducted in Ethiopia through which the human urine was applied at a rate of 500ml, 800ml, 1000ml and 1200ml discovered that human urine treatments increased maize plant height compared to no application treatment. These urine treatments had plant height mean values of 136cm ± 9.1, 146cm ± 10.4, 147cm ±10.4, 147.8cm ± 10.7 and 153.3 cm ± 13.6, respectively compared to non-treated maize which had a mean value of 87cm ± 8.04 [7].

All these studies proved that urine has potential to boost maize growth and yield but the results are significantly improved when urine is combined with other soil amendments. Figure 1 and 2 are the summaries of the average maize yield and plant height in response to urine products analysed from the secondary data. The good maize performance in response to urine over in-organic fertilizer and no application is justified by additional essential nutrients present in human urine (Zn, Ca and Mg) (Table 1) [17], which are not available in-organic fertilizer.

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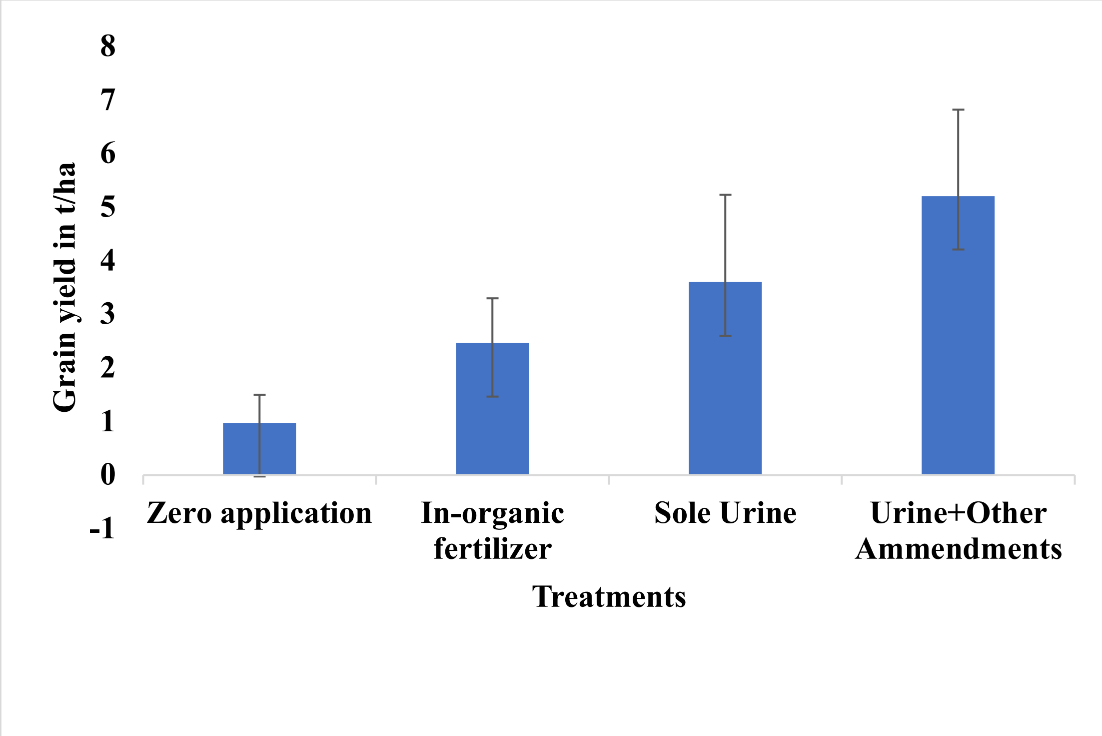

Figure 1: Maize grain yield in response to treatments. Analysed from secondary data (reviewed papers)

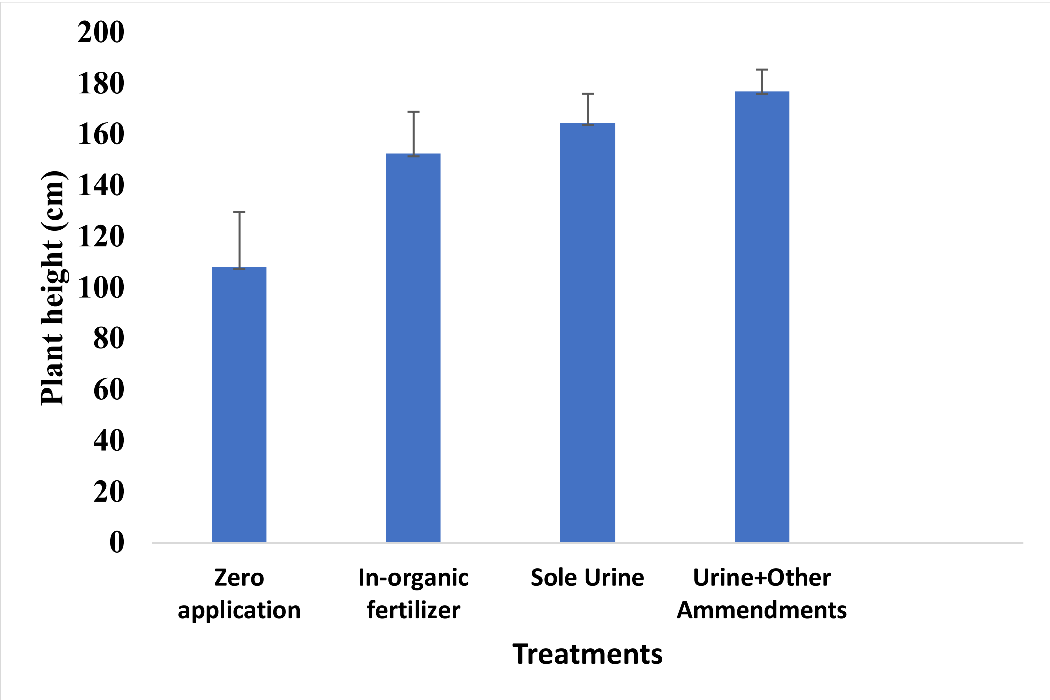

Figure 2: Maize plant height per treatment. Analysed from the secondary data (reviewed papers)

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Effects of Human Urine on Soil Health

The positive impact of human urine on soil properties was reported which includes the soil pH and salt content after harvest of crop. The treatment of urine recorded higher available nitrogen, available phosphorus and potassium when compared to inorganic source application [23]. The experiment conducted in pots in which urine was applied at the rate of 500ml, 800ml, 1000ml and 1200ml per plant as treatments observed that application of urine improved the phosphate concentration and soil conductivity which was directly proportional to the amount of urine applied especially on top and bottom soils, respectively. Both soil pH and nitrogen were not affected by the treatment [9]. The study by Yu *et al.* [24] reported that urine enriched both soil nutrients and enzymatic activities. Additionally, urine increased the soil electrical conductivity (104 ml kg^{-1}) by 840% compared to no application treatment. In this study, the activities of enzymes such as invertase, urase and catalase, increased by 7.30% to 58.75%, 0.93% to 47.77%, and 1.56 % to 16.62%, respectively.

Challenges in use of human urine in crop production

There are a number of challenges associated with use of human urine in agriculture. Some of them are as follows:

Human urine contains phytochemical and harmful bacteria

It has been reported that human urine contains pharmaceuticals such as ampicillin, ciprofloxacin, ibuprofen, and trimethoprim-sulfamethoxazole among others which are toxic to both plants and human beings. Some of the evidences are as follows: A laboratory experiment conducted by Sheneni *et al.* [8], reported that human urine contains the phytochemicals (flavonoid, tannins, saponins, cardiac glycoside and total phenol) which are a threat to both plant and human health when consumed in high concentration**.** At concentrations of 200 to 1,200ml, phytochemical constituents (flavonoid, tannins, saponins, cardiac glycoside and total phenol) become a threat to human health when consumed [25].

The application of urine as fertilizer is discouraged due to various hygienic pitfall. Urine contains bacteria causing infections, hence direct application can endanger human life [10]. Additionally, the genes from the urine bacteria may cause mutation to soil bacteria which can endanger the human life [10, 26]. The study by Cofie *et al.* [27], discovered the following constraints for using human urine in agriculture: causes itching of the body after use, foot rot and bad smell.

Social culture factors and ethics

Several studies have reported on the potential of using the human urine excreta in agricultural purposes. However, the use of human urine is associated with social culture challenges. To begin with, some people are not willing to use the human urine on their crops or to consume crops fertilized with human urine extract. For

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example, the study by Mariwash and Drangert [28] in Ghana, collected the data from 154 households and discovered that people had general negative attitude to fresh extract, they were not willing to handle it. The people could agree that the extract has potential to be used as fertilizer but were not willing to use it in their crops or consume the crops fertilised with the extract. A review by Lienert and Larsen [29], reported that 60% of people could not accept using the agriculture product fertilized by human urine. The study conducted in southern India, through which an interview was performed with 120 randomly sampled farmers observed that 59% of farmers were positive to re-use of human urine than re-use of human faeces. The other study reported that most farmers prefer their neighbours to use human urine in agriculture rather than their friends, family and colleagues [30]. This was complemented by Cofie *et al.* [27], who reported that farmers are not willing to use human urine in agriculture because it causes itching of the body after use, foot rot, bad smell, transportation cost due to bulkiness to be handled for use at large scale and storage problem. Not only that but it is also associated with public mockery.

Urine treatment, application rate and timing

Urine is treated in two ways. Firstly, its primary treatment, which is done to separate urine from faeces when they have collected simultaneously. This is very important because it reduces pathogens and smell from urine. The other treatment is secondary, where several techniques are used. Some of the methods are incineration and storage treatments. The incineration technique is very expensive since it requires a lot of heat. Additionally, it reduces the amount of N in the product. However, it is the most hygienic method of treating urine. The storage method is easy and cheap, as there is little decrease in N from urine using this method [31]. It was also reported that human urine storage treatment increases its pH while dilution with water decreases the pH [17].

Most of the nutrient sources have prescribed application rate and timing. For example, inorganic NPK in maize in Malawi is recommended to be applied soon after the emergence of maize seedling while chicken manure is recommended to be applied before planting and at a rate of 7000 to 10000kg/ha [21]. However, there is limited information on application methods, rate and timing for human urine. The following are some of the recommendations from other studies: to begin with, Parthy *et al.* [10], revealed that, the application of human urine before cultivation is less effective to the plant growth due to high nutrients leaching and high intensity in low saline soil. Additionally, application of human urine higher than plant requirement has no significant effect on plant growth and yield but the adequate urine volume results into no accumulation of N in the soil, no increased urine in plant tissues, and decreased plant K/Na ratio [17]. The adequate application of human urine based on N requirement and management of salt is required for sustainable reuse in

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agriculture. Pathy *et al.* [10], recommended the application range of 500ml to 1200ml diluted urine per maize planting hill which is equivalent to 3g to 8g per station.

Biochar description, production and properties

Biochar is the solid residue that is recovered through thermal cracking of biomass in an oxygen free atmosphere in a process referred to as pyrolysis [32]. It has potential in relation to agronomy and carbon sequestration ability [33]. The following are desirable properties of biochar. It is characterised by large surface areas, and porous structure with variable sizes, it is also described as an efficient carbon-rich material for amending soil quality and promoting crop N uptake [34]. This is in line with the study by Pathy *et al*. [10] which revealed that biochar is characterised by high surface area, porosity and surface charges. According to studies by Mousavi *et al*. [35], biochar had a surface area of 8.92 m^2 g^{-1}, electrical conductivity of 139.75 µs cm^{-1}, total P of 1.61gkg $^{-1}$, organic carbon of 0.5g kg^{-1} and total ash of 20.8%. The study by Mingxin [13], revealed that biochar is in general associated with low in plant macronutrients and cannot be used as a major nutrient source especially nitrogen to plants. The biochar, specially produced from manure and waste at temperature less than 400 °C contains the essential nutrients such as phosphorus and potassium which are correlated with its pH [35]. The properties of biochar depend mainly on the source of feedstock and pyrolysis conditions [36].

Factors that affect quality of biochar

The quality of biochar is affected by a number of factors including temperature during pyrolysis, type of biomass used, and production techniques. An increase in pyrolysis temperature increases carbon content, nitrogen content and surface area of biochar but decreases amount of hydrogen, oxygen and biochar content [37]. The other factors that affect the quality of biochar are: biomass type, biochar production technique, and operating parameters among others. Cellulose, hemicellulose and lignin are the main ingredients of biomass which influence the product yield of pyrolysis [38]. The char from lignin is relatively with weak bonds which results into formation of more condensed solid [38]. Additionally, it is reported that biochar stability depends on the oxygen to carbon (O: C) molar ratio. More carbon is desirable [33].

The response of plant to applied biochar depends on 4 R principles. These are right source, right application rate, right time of application and right placement. The followings are some of the best sources of biochar: feedstock with high stable organic carbon (OC), high water content and nutrients holding capacity. Optimal amendment rate of 2-5 mass % of soil results to best output [13].

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Maize Response to Biochar

The study conducted on two groups of pot experiments on the new biochar experiment and one-timer biochar applied in the last seven years at Ck: 0t ha^{-1}, C1: 15.75t ha^{-1}, C2: 31.5 t ha^{-1}, C3: 63 t ha^{-1}, and C4: 126 t ha^{-1} and planted with maize. This experiment revealed that maize plant biomass, and yield of maize increased at the rate of 31.5 t ha with 22.2% increased biomass and 8.46% increase in grain yield compared to control (no application) [38]. Additionally, the biomass and plant height increased gradually with increase of biochar application rate under one-time biochar application seven years ago treatments. The change in plant leaf greenness (SPAD value) was also affected by increase in biochar application rate [38]. Biochar produced from corn, biosolids, eucalyptus, fresh pine or willow pyrolyzed applied from 0 to 10 t ha $^{-1}$ did not significantly affect the germination or early growth of maize [39]. The corn cob biochar (CCB) was mixed with soil at different rates (0.5%, 1%, 2%,2.5% and 3% w/w) before seed sowing and it was discovered that increasing application rate have neutral to positive effects on seed germination and seedling growth of maize. Additionally, biochar addition at the rate of 1.5% (w/w) significantly increasing shoot dry biomass (40%), root dry biomass (32%), total chlorophyll content (55%), germination percentage (13%), seedling vigour (85%), and relative water content (RWC) (68%), in comparison to un-amended [40].

Biochar, nutrients uptake and soil health

The study by Hossain *et al.* [34], reported that biochar increases soil nitrogen retention by reducing the leaching and gaseous loss and increases the soil availability of phosphorus. It also improves soil porosity, soil pH, soil aggregates stability, soil water holding and decreases bulk density of the soil. Biochar also influences biological soil properties such as microbial population, enzyme activity, soil respiration and microbial biomass. According to Akhil *et al.* [41], biochar has a positive effect on soil properties, nutritional qualities and microorganisms. It is also reported that application of biochar with and without additional compost manure can enhance both soil water retention and nutrients retention [42]. Application of biochar helps to improve nutrient use efficiency and nutrient uptake [34]. The on-field study by Lu *et al*. [43] conducted in China, amended the soils at 0, 10, 20 and 40 t ha^{-1} of biochar in rice farm. It was reported that biochar amendment from 10t ha^{-1} upwards, increased soil organic carbon storage by 45%, total and available nitrogen pool by 30%, and decreased the bulky density while the soil pH was not affected by the amendment. Additionally, it helped to increase the mean weight diameter of waters stable aggregates, enzyme activities by 30%, 32 % and total bacteria abundance compared to non-biochar study units. According to Das *et al*. [44], biochar has capacity to reduce leaching of soil nutrients, increases soil structure and pH, enhances nutrients availability for plants, increases water quality of runoff, reduces

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aluminium toxicity to plant roots and micro biota, reduces bio availability of heavy metals, decreases N_2O and CH_4 emissions from the soils. The study by Burrow *et al.* [45], in Nkhata-bay and Lilongwe districts of Malawi reported that Maize + Biochar + manure in Nkhata-bay showed higher level of organic carbon (1.67%), aligning with recommended range of 1% to 5 %. Additionally, it resulted to elevated cation exchange capacity (CEC) levels. In Lilongwe CEC levels reached 0.72 Meq/100g, which shows enhanced nutrient retention capacity. Table 2 shows additional information on effects of biochar on soil health.

Biochar and urine integration for maize crop production and soil health

According to Pathy *et al*. [10], there is a possibility of engineering biochar to enhance the recovery of P and N from human urine and to reduce the concentration of phytochemicals. Positively charged ions present in human urine, such as ammonium (NH_4^+), potassium (K^+), calcium (Ca^{2+}), and magnesium (Mg^{2+}), can be adsorbed onto biochar because most biochar types have a net negative surface charge, which attracts cations [10]. The study where cattle urine-enriched biochar plus manure was amongst the treatments reported that urine-enriched biochar significantly improved soil pH compared to non-treated control and sole biochar treatment with mean values of 5.63, 5.19 and 5.35, respectively [46]. In this study the organic carbon, was also increased from 1.12% for no application to 1.23% and 1.64% for sole biochar and biochar plus urine plus manure treatments, respectively. Additionally, the soil nutrient levels (NPK) ($p<0.05$) were significantly increased by biochar enriched with human urine and manure treatment. The non-treated soils had 0.1% N while biochar plus urine treatment had 0.14% (above critical value) N. The trend was similar with available phosphorus where control had soil available P of 17.4 mg kg^{-1} and biochar plus urine plus manure had soils available phosphorus of 26.9 mg kg^{-1}. The soil potassium (K) after harvest was 76.6 mg kg^{-1} and 140 mg kg^{-1} for untreated soils and biochar plus urine plus manure treatments, respectively [46]. The other study reported that, the urine-enriched biochar resulted in significantly increased maize plant NPK uptake and a 62% increase in maize yield compared to control (no application) [46]. The study by Dernier [47], reported that urine-charged biochar had the potential to increase sweet corn yield and improve soil health while Golakiya *et al.* [48] reported that cattle urine-biochar treatment improved chemical indicators of soil health such as organic carbon by 0.58%, and available nitrogen by 0.31% compared to control (no application). The study conducted at the research station of Indonesia Soil Institute in East Lampung discovered that application of biochar plus urine had higher dry maize grain (12%) compared to sole urine. Additionally, biochar +urine treatment produced 7.15 t ha^{-1} compared to inorganic urea and sole urine which produced 5.11 t ha^{-1} and 6.05 t ha^{-1}, respectively. The biochar plus urine treatment apart was increasing maize yield, it also positively affected the soil

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chemical properties such as pH, organic carbon and cation exchange capacity (CEC). The urine plus biochar treatment was reported with pH (6.43), organic carbon (123%) and CEC (8.66) compared to sole urine which had pH (4.98), organic carbon (1.14%) and CEC (7.54). In this study the sole urine treatment performed statistically the same with inorganic fertilizer on soil pH, soil organic carbon and soil CEC [49].

CONCLUSION AND RECOMMENDATIONS FOR DEVELOPMENT

Human urine and biochar have the potential to be used as fertilizers with no negative effect on yield, provided they are managed properly. Additionally, urine has a low concentration of both P and K, which need to be supplemented with either inorganic fertilizers or manure, which are rich in P and K for better crop productivity. On the other hand, biochar possesses very low N but is characterised by desirable properties such as higher CEC, electro- conductivity, organic carbon, pH and large surface area. Biochar is a very good soil conditioner that contributes to carbon stocks. Therefore, integration of urine and biochar is expected to have better implications on soil health and balanced plant nutrition for maize growth and productivity.

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1. Lameck Vwalika: Initial draft, writing-revisions
2. Associate Professor Wezi Mhango: Revision and student supervision
3. Associate Professor Keston Njira: Writing-revision and student supervision

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Table 1: The elemental components of human urine

Serial number	Element	Reference
1	Nitrogen (N)	Pathy *et al.* [10], Sridevi *et al.* [16], Araujo *et al.* [17], Shrestha and Amatya [18] Alemayehu *et al.* [19], and Kumar *et al.* [20]
2	Phosphorus (P)	Pathy *et al.* [10], Sridevi *et al.* [16], Araujo *et al.* [17], Shrestha and Amatya [18] Alemayehu *et al.* [19], and Kumar *et al.* [20]
3	Potassium (K)	Pathy *et al.* [10], Sridevi *et al.* [16], Araujo *et al.* [17], Shrestha and Amatya [18] Alemayehu *et al.* [19], and Kumar *et al.* [20]
4	Calcium (Ca)	Pathy *et al.* [10], Sridevi *et al.* [16], Araujo *et al.* [17]
5	Magnesium (Mg)	Pathy *et al.* [10], Sridevi *et al.* [16], Araujo *et al.* [17],
6	Sulphur (S)	Pathy *et al.* [10], Sridevi *et al.* [16], Araujo *et al.* [17],
7	Sodium	Pathy *et al.* [10]
8	pH (8.9)	Araujo *et al.* [17]
12	Zinc	Pathy [10]

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Table 2: Effects of biochar on soil health

Soil health indicator	Biochar effect	Reference
Chemical	Increases soil nitrogen retention. Increases availability of phosphorus, and soil pH. Improves nutrients use efficiency and nutrients uptake.	Hossain *et al.* [26], Karam *et al.* [28], Krishnakumar *et al.* [25] Manolikaki & Diamadopoulos [32], Akhil *et al.* [33], Seyedsadr *et al.* [34] Lu *et al.* [35], Das *et al.* [36],
	Helps to remove toxic metals	Das *et al.* [36]
	Increases stable soil carbon with potential of mitigating carbon emission. Capable of exchanging soil cations. Saves as a sink for atmospheric carbon Enhances the sorption of inorganic and organic compounds.	Krishnakumar *et al.* [25] Karam *et al.* [28], Lu *et al.* [35], Burrow [37]
Physical	Improves soil porosity, aggregate stability, soil water holding, decreases soil bulky density	Hossain *et al.* [26], Krishnakumar *et al.* [25] Seyedsadr *et al.* [34], Lu *et al.* [35]
	Improves soil structure Increase root penetration, reduces soil erosion	Das *et al.* [36]
Biological	Increases microbial population, enzyme activities, soil respiration, microbial biomass. Bacteria abundance	Hossain *et al.* [26], Akhil *et al.* [33], Lu *et al.* [35]

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