Science of the Total Environment 951 (2024) 175655

Contents lists available at ScienceDirect

Science of the Total Environment

journal homepage: www.elsevier.com/locate/scitotenv

Circular fertilisers combining dehydrated human urine and organic wastes can fulfil the macronutrient demand of 15 major crops

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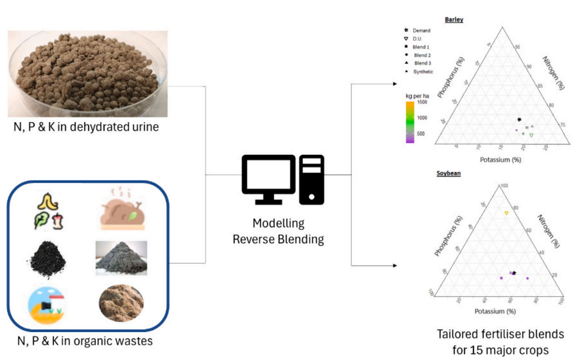
HIGHLIGHTS

- Fertiliser blends combining 359 organic wastes and dehydrated urine were simulated.
- 38 blends met the NPK demand of 15 major crops with variable risks of overfertilisation.
- Biochars and ashes were particularly suitable for blending with dehydrated urine.
- Dehydrated urine counterbalances the heavy metal content of organic wastes.

GRAPHICAL ABSTRACT



ARTICLE INFO

Editor: Huu Hao Ngo

Keywords:
Reverse blending
Nutrient recycling
Wastewater
Solid organic wastes
Crop yield
Heavy metals

ABSTRACT

This study evaluated the potential for combining dehydrated human urine with one other form of organic waste to create circular fertilisers tailored to meet the macronutrient demand of 15 major crops cultivated globally. Through a reverse blending modelling approach, data on 359 different organic wastes were used to identify 38 fertiliser blends. Materials found to be particularly suitable as blending materials were various biochars and ashes, due to their low nitrogen and high phosphorus and/or potassium content, and byproduct concentrates, due to their high phosphorus content, since the nitrogen content of human urine is disproportionately higher than its phosphorus content. Several organic wastes were suitable for fertilising more than one crop. The macronutrient content of the simulated fertiliser blends was comparable to that of blended inorganic fertilisers, but only a few blends precisely matched the macronutrient demand of crops. Fertilising crops with some simulated fertilisers would potentially result in excess application of one or more macronutrients, and thus overfertilisation. For organic wastes with data available on their content of six or more heavy metals, it was found that the simulated fertilisers generally met European Union regulations on use of fertilisers of organic origin in agriculture. Overall, these findings suggest that fertiliser blends combining dehydrated human urine and organic wastes, both of which are widely available globally, could replace inorganic blended fertilisers in

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https://doi.org/10.1016/j.scitotenv.2024.175655
Received 23 April 2024; Received in revised form 1 August 2024; Accepted 18 August 2024
Available online 20 August 2024

agriculture. Such recycling would help the global food system and water sector transition to circularity and promote better management of plant-essential nutrients in society.

1. Introduction

Safely recycling human excreta back to farmland has been proposed as a sustainable approach to better manage nutrients in society (Harder et al., 2019), feed the world without transgressing planetary environmental boundaries (Gerten et al., 2020), and increase circularity in the water and wastewater sector (Simha et al., 2020). Human excreta contain nearly all the plant-essential nutrients consumed as food (Jönsson et al., 2004). Most nutrients are excreted through human urine rather than faeces, including 70–90 % of nitrogen (N), 45–80 % of phosphorus (P) and 70–95 % of potassium (K) (Lentner, 1981; Vinnerås, 2002). Separately collecting urine at source, treating it and recycling it as fertiliser can simultaneously address multiple sustainable development goals. Over the past three decades, such innovative sanitation systems have made significant advancements, particularly in developing a full value chain and gaining broader acceptance and legitimacy in society (Aliahmad et al., 2022).

Nutrients in urine, such as urea, phosphate and potassium, are water-soluble and readily available to plants when urine is applied as a crop fertiliser (Kirchmann and Pettersson, 1994). Therefore, human urine, a biological/organic resource, acts just like inorganic fertiliser in soil. Numerous studies have demonstrated that human urine is comparable to inorganic mineral and synthetic fertiliser in promoting crop yields (Heinonen-Tanski et al., 2007; Martin et al., 2022; Viskari et al., 2018). However, the N-P-K ratio (relative to total mass of these three nutrients) in human urine is 74–7-19 (calculated based on Simha et al., 2023), i.e. the N content of urine is disproportionately high compared with the P content. Since different crops have different N-P-K requirements (Fig. 1), applying human urine alone as a fertiliser to fulfil a crop's demand for all three macronutrients would result in overfertilisation and excess nutrients. Previous research suggests that the nutrient composition of human urine or human-urine derived fertilisers must be adjusted by combining urine with other organic or inorganic fertilisers (Germer et al., 2011; Martin et al., 2021). Aligning the composition of human-urine derived fertiliser with crop macronutrient demand by blending it with other fertilisers of differing composition is important, as nutrient deficits can result in lower crop yields, while excessive application of nutrients can have negative environmental effects, including eutrophication and greenhouse gas emissions (Good and Beatty, 2011; Steffen et al., 2015).

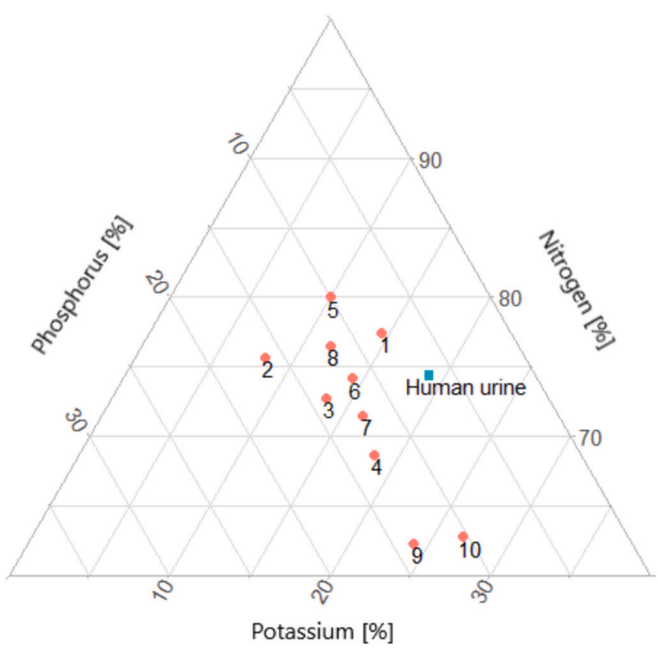

Fig. 1. Ratio of macronutrients (NPK) required by 10 crops and available in alkalised dehydrated human urine. The ratio for each nutrient was obtained by dividing its mass by the sum of the masses of all three macronutrients (see Table S2 in SI). The crops are (1) barley, (2) beans, (3) cotton, (4) maize grain, (5) millet, (6) rapeseed, (7) rice, (8) sorghum, (9) sugar beet and (10) sugar cane.

Solid organic wastes, as well as human urine, are rich in macronutrients, consistently produced in human settlements and widely available globally. Many treated and untreated organic wastes have been demonstrated to be effective crop fertilisers either alone (Marchuk et al., 2023; Melo et al., 2022; Roy et al., 2006; Schiemenz and Eichler-Löbermann, 2010) or combined with other organic wastes, provided that their properties (e.g. pH, dry matter) do not diminish each other's fertiliser efficacy (Brod et al., 2014). This suggests that organic wastes could be combined with human urine or urine-derived fertilisers to produce blended circular fertilisers with composition that aligns with the macronutrient demand of different crops. However, there are hundreds of organic wastes with different NPK content available in society (Roy et al., 2006; Vassilev et al., 2010) and recycling some of them could also add contaminants to agricultural systems (Sharma et al., 2019). The objectives of this study were therefore to (i) develop a comprehensive list of organic wastes with a nutrient content that complements that of human urine; (ii) simulate fertiliser blends comprising human urine and organic wastes that meet the macronutrient demands of the 15 major crops cultivated worldwide (see Table S1 in Supplementary Information (SI)); (iii) calculate the application rate (kg ha^{-1}) of these simulated fertiliser blends in agriculture; and (iv) estimate the amounts of six major heavy metals that would be added to soil through use of the selected fertiliser blends. The overall aim was to assess the feasibility of tailoring circular fertilisers with macronutrient composition that aligns with the macronutrient demands of various crops by blending solid and liquid waste resources available in society.

2. Methodology

A two-step modelling approach proposed by Benhamou et al. (2020), called reverse blending, was used. In the first step, fertiliser blends comprising of one organic waste and dehydrated human urine were selected. These blends were chosen based on their ability to meet the macronutrient (N, P, K) demand of 15 major crops and the required fertiliser application rate (kg ha^{-1}) of these blends in agriculture. In the second step, the amounts of heavy metals (Zn, Cu, Pb, Cd, Cr, Ni, Hg and As) in the selected blends were estimated for each crop and compared against threshold values stated in European Union (EU) regulation EU 2019/1009 on fertilisers of biological origin in agriculture (European Parliament and European Council, 2019). Despite evidence of contaminants of concern (microplastics and pharmaceuticals) in organic wastes and sludge (European Commission, 2023; Zhou et al., 2023), we considered only heavy metals, because the current EU regulation sets threshold values only for these. The EU Commission recently reviewed the regulation and concluded that it should be updated (European Commission, 2023), but to our knowledge there are no EU threshold values for contaminants of concern. This also applies to contaminants of concern from urine, although in this case there is ongoing research evaluating techniques to reduce and/or degrade contaminants before urine dehydration (Demissie et al., 2023). Data on the macronutrient and heavy metal content of different organic wastes and the macronutrient demand of the 15 major crops were sourced from peer-reviewed literature.

2.1. Selection of blends

2.1.1. Macronutrient content of organic wastes

A preliminary list of organic wastes was prepared by a systematic review in the Google Scholar database for literature published in the English language between 1980 and 2022. Different search strings were used for each type of organic waste (Table 1). In order to better focus the literature search, the organic wastes were classified as untreated and treated. For untreated wastes, we used the terms "organic waste" and "agricultural waste", and prioritised those already used for soil amendment in the search strings, because information about their macronutrient content was readily available. For treated organic wastes, we prioritised heat-treated forms by using the terms "dried", "pyrolysed" and "combusted", because they have lower moisture content and therefore higher macronutrient content. Several literature reviews on the composition and use of different wastes as soil amendments and soil conditioners have been published, and we also prioritised those.

The organic wastes from the preliminary list were categorised based on their content of N, P or K. In cases where multiple data points were available for the same waste material, the data were averaged. The aim was to obtain blends with as high a nutrient content as possible, because this is a convenient characteristic for any material to be used as fertiliser (Simha et al., 2020). Therefore, only organic wastes containing >10 % N, 5 % P or 12 % K were selected for further simulation. These were the values corresponding to the 90th, 90th and 80th percentile for the N, P and K content found in organic wastes, respectively.

2.1.2. Macronutrient demand of major crops

Two preliminary lists, comprising the 10 most cultivated crops in terms of arable area and the 10 most cultivated crops in terms of global production volume, were developed using data available from FAOSTAT (2022) for the year 2018. These lists were merged after discarding duplicates, resulting in a final list of 15 major crops (barley, beans, cassava, cotton, maize (grain), millet, oil palm, potato, rapeseed, rice, sorghum, soybean, sugar beet, sugar cane and wheat). The macronutrient demand of these 15 crops was estimated by averaging the amounts applied as fertiliser to these crops in 58 different countries in 2018 (data from Ludemann et al. (2022)). Data from 2018 were used because it was the last year before the COVID-19 pandemic for which data were available. To account for the variation in fertilization practices across different countries for a specific crop, we weighted the data for each country based on the area of the crop cultivated in that country and the area cultivated in all 58 countries:

$$R_{N\ crop} = \frac{\sum_{i=1}^{n}\left(Req_{N\ crop}i \times Sup_{crop}i\right)}{\sum_{i=1}^{n} Sup_{crop}i} \quad (1)$$

where $R_{N\ crop}$ is mean demand for a specific nutrient (N, P or K, kg ha^{-1}) by one of the target crops, $Req_{N\ crop}$ is the amount of the nutrient applied as fertiliser for the target crop in country *i* and Sup_{crop} is cultivated area for the target crop in country *i*. The full list of the 15 crops and estimated macronutrient demand of these crops can be found in Tables S1 and S2 in SI.

2.1.3. Macronutrient content in simulated fertiliser blends

Information on the content of the three macronutrients in the selected organic wastes and in dehydrated urine fertiliser was used to calculate their respective content in the simulated blends ($C_{N,blend;}$):

$$C_{N,blend} = \left(P_{dehydrated\ urine} \times C_{N,dehydrated\ urine}\right) + \left(\left(P_{dehydrated\ urine} - 1\right) \times C_{N,Waste\ material}\right) \quad (2)$$

where $C_{N,dehydrated\ urine}$ and $C_{N,waste\ material}$ is the content (%) of a specific nutrient (N, P or K) in the in dehydrated urine and in selected organic wastes, respectively, and $P_{dehydrated\ urine}$ is the proportion of dehydrated urine in the simulated blend. The N, P and K content in dehydrated urine was assumed to be 18 %, 1.6 % and 4.6 %, respectively, based on experimental results reported in Simha et al. (2023).

2.1.4. Comparing macronutrient balance of simulated blends vs. target crops

In this modelling step, the objective was to assess how the macronutrient demand of the target crops could be met by the simulated blends while preventing excessive fertiliser application. For each macronutrient, we apportioned the target crop's demand among the contents in the simulated blends. When the results of this operation were approximately equal for all three macronutrients (N ≈ P ≈ K), the blend was considered suitable for that crop and we proceeded to the next step, which involved calculating the fertiliser application rate.

2.1.5. Fertiliser application rate for the selected blends

The rate (mass per unit area) of the blend(s) ($M_{N,blend}$) to be applied as fertiliser for each target crop to meet its demand for nutrients (N, P or K) was estimated as:

$$M_{N,blend} = Req_{N,crop} \Big/ C_{N,blend} \quad (3)$$

where $Req_{N,crop}$ is the crop's demand for nutrients (N, P or K, mass per unit area) and $C_{N,Blend}$ is the nutrient content of the applied blend (N, P or K, mass of nutrient per unit mass of blend). We thus obtained three application rates (one each for N, P and K) for every blend, but we only considered the highest rate to ensure that crop demand for all three macronutrients was met by that particular blend.

Table 1
Search strings used in a systematic review of literature on different types of organic waste in the Google Scholar database.

Type of organic waste	Search string
Untreated	<"organic waste" OR "agricultural waste"> AND <"nitrogen"> AND <"phosphorus"> AND <"potassium">, <"review">, <"soil amendment">, <"sanitation urban waste">
Treated-Dried	<"thermal drying" OR "solar drying" OR "drying"> AND <"nitrogen"> AND <"phosphorus"> AND <"potassium">, <"amendment">, <"review">
Treated-Pyrolyzed	<"biochar OR char OR hydrochar">, AND <"nitrogen"> AND <"phosphorus"> AND <"potassium">, <"amendment">, <"review">
Treated-Combusted	<"ash">, AND <"nitrogen"> AND <"phosphorus"> AND <"potassium">, <"amendment">, <"review">

2.2. Addition of heavy metals to soils through application of fertiliser blends

2.2.1. Data collection

We sought information on the content of eight heavy metals (Zn, Cu, Pb, Cd, Cr, Ni, Hg and As) in the selected organic wastes that were used in the selected blends. These specific heavy metals were chosen because they are regulated by the EU when a fertiliser of biological origin is used as fertiliser on agricultural soil. Our primary source of information was the publications in which macronutrient content of the organic wastes was reported. When such data were not available, we conducted literature searches in the Google Scholar engine, specifying the organic waste and the six heavy metals. In cases where the publications did not contain data on these heavy metals, we used heavy metal content for similar wastes found in other published studies as input. Regarding the content of heavy metals in dehydrated urine, we used data previously reported in Simha (2021). A comprehensive list of heavy metal content of the organic wastes is provided in Table S3 in SI.

2.2.2. Heavy metal content in the simulated blends

The content of the six heavy metals in the selected blends was determined using Eq. (4), which is analogous to Eq. (2).

$$C_{M,blend} = \left(P_{dehydrated\ urine} \times C_{M,dehydrated\ urine}\right) + \left(\left(P_{dehydrated\ urine} - 1\right) \times C_{M,waste\ material}\right) \quad (4)$$

where $C_{M,blend}$, $C_{M,dehydrated\ urine}$ and $C_{M,waste\ material}$ is mass of the heavy metal (Zn, Cu, Pb, Cd, Cr or Ni) per mass of blend in the simulated blend, dehydrated urine, and selected organic wastes, respectively, and $P_{dehydrated\ urine}$ is the proportion of dehydrated urine in the simulated blend.

3. Results and discussion

3.1. Selection of fertiliser blends

We identified 38 fertiliser blends combining dehydrated human urine and organic wastes that met the macronutrient demands of the 15 crops (Table 2). Of these 38 blends, 20 were formed with ash, 10 with biochar, seven with animal byproducts and one with stored organic residues, in addition to dehydrated urine. Various blends that included ash or biochar met the demands of 13 crops. Ash contains no nitrogen and the N content of biochar is low; only one of the selected biochars had N content >3 % (Table S4). Most of the selected ashes had K content >10 %, while the four selected biochars had K content <2.8 %. The N content of dehydrated urine is much higher than its P and K content (around 11-fold and almost 4-fold higher respectively; Table S2). Therefore, mixing dehydrated urine with organic wastes with low N content and high P and/or K content, such as ash and biochar, resulted in blends that met the macronutrient demand of all crops considered except millet and sorghum. Byproduct concentrates have a higher N content than biochar and ash and they contain a higher proportion of P than K. Combining these with dehydrated urine resulted in blends with reduced N and increased P proportions compared with dehydrated urine alone. These blends were determined to be suitable for five of the 15 target crops (cotton, millet, rapeseed, rice and sorghum) that have similar demands for P and K, both of which are lower than their demand for N (Table 2, Table S2 in SI).

Several wastes were suitable for more than one crop. In particular, blends of dehydrated urine with animal concentrate fishmeal, *E. coli* fermentation waste biochar, bone waste biochar and asai seed residue ash met the demand of five, four, three and three crops, respectively. Each of these wastes had either very high or very low content of two specific macronutrients. For instance, animal concentrate fishmeal had the highest N content (10 %) among all the wastes considered, resulting in blends with reduced N and increased P proportions compared with dehydrated urine alone, while *E. coli* fermentation waste biochar had the highest P content (8.5 %) among the wastes, N content exceeding 5 % and one of the lowest K contents. This nutrient profile led to blends with dehydrated urine that had slightly lower N content and higher P content compared with dehydrated urine alone. It was also identified as the only waste material that could meet the nutrient demand of beans. Similarly, bone waste biochar had the lowest K content (0.3 %) among wastes with high P content (>15 %), while ash from asai seed residues had the highest P content among wastes with high K content (>25 %).

Despite the large number of wastes initially identified (Table S5 in SI) and the optimisation approach used in simulations, only one simulated blend precisely matched the nutrient demand of the different crops. Applying most of the simulated blends to farmland resulted in a nutrient surplus. The surplus was negligible in some cases, such as for maize grain, where the excess K from the blend combining either meat bone meal ash, human manure biochar or sewage sludge ash and dehydrated urine was <5 % above total K demand of the maize crop (Fig. 2a, Table 2). For some crops, the surplus was much higher. For example, blending dehydrated urine with palm kernel ash resulted in a P content that was >50 % above the total P demand of soybean, while blends combining dehydrated urine with either asai seed residue ash or chicken litter ash resulted in a K content that was >65 % above the total K demand of soybean.

The field application rate of the simulated blends was influenced by both the crop macronutrient demand and the macronutrient content of the blends. Based on our simulation results, it is feasible to produce blends with up to 17.5 % N for barley, and 10.3 % P and 20.2 % K for soybean. Several synthetic and mineral fertilisers have much higher nutrient content, e.g. urea (46 % N), diammonium phosphate (20 % P or 46 % P_2O_5) and potash (50 % K or 60 % K_2O). Thus, blends made with such fertilisers will always result in lower application rates than blends of dehydrated urine and organic wastes (Fig. 2d). However, the contents simulated in our blends (dehydrated urine and an organic waste) were similar or lower than those in blended mineral and synthetic fertilisers like calcium nitrate (15.5 % N) and ammonium phosphate sulphate (18 % N and 9 % P). Furthermore, most application rates of the blends would be <1 t ha^{-1} (Fig. 2, Table 1), enabling the use of conventional implements in field application, which is an important aspect influencing introduction of new products to the fertiliser market. Based on both their nutrient content and their application rate, blends combining organic wastes and dehydrated urine can replace blended chemical fertilisers currently used in agriculture. Our results were constrained by the limited availability of data on the macronutrient content in organic wastes. Since these contents can vary due to various contextual factors (Vassilev et al., 2010), it is important to determine specific nutrient content before using these materials for blending. Another relevant aspect that was not included in our study is that a glue/binder is generally added to fertilisers during granulation or pelleting and could potentially dilute the macronutrient content of fertiliser, by as much as 10–30 %.

In selecting blend materials, we did not consider the availability, accessibility or acceptability of these materials in a local or global context. For example, *E. coli* fermentation waste, which was found to be the only suitable waste when blended with dehydrated urine for beans, is mostly available in Asia (Ault, 2004; Thuy et al., 2020). However, beans are also widely cultivated in the Americas and Africa. In the case of maize grain, the appropriate materials to blend with dehydrated urine were meat-bone meal ash, sewage sludge ash and human manure biochar, which might not be accepted for food production in some places. If the selected materials were available and their use was acceptable, the infrastructure needed to collect, transport and blend it with dehydrated urine would have to be put in place or adapted from existing systems (Simha et al., 2020). This means that to produce competitive bio-based

Table 2
Materials selected to be blended with dehydrated urine, proportions of the materials and nutrients in each resulting blend, amount of blend and excess amount of nutrients added via blend compared with macronutrient demand of each target crop and their corresponding expected yield, according to performed simulations. The crop requirements were calculated from Ludemann et al. (2022), as indicated in Section 2.1.2. The three materials that, blended with dehydrated urine, would fulfil the crop demand with the lowest amount of blend required are shown for each crop. Ash (HT) stands for high-temperature ash (>500 °C), "–" indicates that the amount of nutrient added with that blend would match the crop demand.

Crop & selected blending material	Proportion in blend (%)					*Expected yield*[a] & blend to be added to plot (kg ha^{-1})	Crop demand & excess added with blend (kg ha^{-1})			References
	Material	Dry urine	N	P	K		N	P	K	
1. Barley						*4545*[a]	96	10	18	
- Human manure biochar	3	97	17.5	1.8	4.5	549	–	–	6.9	Liu et al. (2014)
- Swine manure biochar	4	96	17.4	1.8	4.5	551	–	–	7.0	Tsai et al. (2012)
- Sewage sludge ash (HT)	4	96	17.3	1.8	4.5	554	–	–	6.8	Vassilev et al. (2010)
2. Beans						*473*[a]	28	6	3	
- *E. coli* fermentation waste biochar	50	50	13.3	5.0	2.5	210	–	4.5	2.2	Kim et al. (2018)
3. Cassava						*11573*[a]	16	2	9	
- Sunflower husk ash (HT)	19	81	14.6	1.9	8.2	110	–	0.1	–	Vassilev et al. (2010)
- Oat straw ash (HT)	20	80	14.4	1.8	8.1	110	–	–	–	Vassilev et al. (2010)
- Pepper plant ash (HT)	21	79	14.2	1.7	8.0	115	–	–	0.1	Vassilev et al. (2010)
4. Cotton						*2462*[a]	147	28	27	
- Fishmeal	30	70	15.6	2.3	3.7	1215	42.4	–	17.5	Roy et al. (2006)
- *E. coli* fermentation waste biochar	30	70	15.2	3.7	3.3	968	–	7.4	5.3	Kim et al. (2018)
5. Maize grain						*6442*[a]	127	24	34	
- Meat-bone meal ash	9	91	16.4	3.1	4.4	776	–	–	0.3	Vassilev et al. (2010)
- Human manure biochar	19	81	15.1	2.9	4.2	842	–	–	1.6	Liu et al. (2014)
- Sewage sludge ash (HT)	21	79	14.3	2.7	3.9	889	–	–	0.9	Vassilev et al. (2010)
6. Millet						*959*[a]	8	1	1	
- Fishmeal	20	80	16.4	2.1	4.0	49	–	–	0.9	Roy et al. (2006)
- Bonemeal	5	95	17.3	2.2	4.4	46	–	–	1.0	Roy et al. (2006)
7. Oil palm						*17614*[a]	93	20	135	
- Grape marc ash (HT)	41	59	10.6	2.5	15.3	880	–	2.2	–	Vassilev et al. (2010)
- Arundo grass ash (HT)	45	55	10.0	2.2	14.4	933	–	0.3	–	Vassilev et al. (2010)
- Oat straw ash (HT)	49	51	9.2	2.1	13.3	1016	–	1.6	–	Vassilev et al. (2010)
8. Potato						*28256*[a]	124	28	79	
- Asai seed residue ash (HT)	22	78	14.1	3.2	9.4	882	–	–	3.6	Albuquerque et al. (2021)
- Pistachio shell ash (HT)	32	68	12.3	2.8	8.1	1010	–	–	2.5	Vassilev et al. (2010)
- Marine macroalgae ash (HT)	37	63	11.4	2.6	7.6	1087	–	–	3.4	Vassilev et al. (2010)
9. Rapeseed						*2180*[a]	109	17	21	
- Fishmeal	44	56	14.5	2.6	3.2	752	–	2.7	3.4	Roy et al. (2006)
- Bone waste biochar	7	93	16.8	2.6	4.3	650	–	–	6.8	Zwetsloot et al. (2016)
- *E. coli* fermentation waste biochar	21	79	16.1	3.0	3.7	679	–	3.5	4.3	Kim et al. (2018)
10. Rice						*4887*[a]	123	21	28	
- Fishmeal	40	60	14.8	2.5	3.4	832	0.3	–	–	Roy et al. (2006)
- Bone waste biochar	13	87	16.1	3.0	4.0	764	–	2.1	2.9	Zwetsloot et al. (2016)
- *E. coli* fermentation waste biochar	18	82	16.3	2.9	3.8	756	–	0.7	0.9	Kim et al. (2018)
11. Sorghum						*1335*[a]	13	2	2	
- Fishmeal	55	45	13.6	2.9	2.9	96	–	0.8	0.8	Roy et al. (2006)
- Bonemeal	9	91	16.8	2.6	4.2	77	–	–	1.2	Roy et al. (2006)
12. Soybean						*2763*[a]	15	20	35	
- Palm kernel ash	73	27	4.8	10.3	11.3	310	–	12.1	–	Vassilev et al. (2010)
- Asai seed residue ash (HT)	72	28	5.1	6.8	20.2	296	–	–	24.8	Albuquerque et al. (2021)
- Chicken litter ash (HT)	77	23	4.1	5.5	8.8	396	–	–	23.6	Vassilev et al. (2010)
13. Sugar beet						*55715*[a]	137	30	53	
- Palm kernel ash	15	85	15.3	3.4	5.9	893	–	–	0.1	Vassilev et al. (2010)
- Chicken litter ash (HT)	26	74	13.3	2.9	6.0	1026	–	–	8.8	Vassilev et al. (2010)
14. Sugar cane						*73802*[a]	133	22	57	
- Asai seed residue ash (HT)	14	86	15.6	2.6	7.6	854	–	–	7.5	Albuquerque et al. (2021)
- Olive pits ash (HT)	25	75	13.6	2.2	6.8	979	–	–	9.8	Vassilev et al. (2010)
- Marine macroalgae ash (HT)	24	76	13.6	2.2	6.6	977	–	–	7.4	Vassilev et al. (2010)
15. Wheat						*3619*[a]	103	17	14	
- Bone waste biochar	8	92	16.6	2.7	4.2	620	–	–	12.3	Zwetsloot et al. (2016)
- Dog manure (stored)	25	75	13.9	2.3	3.5	739	–	–	11.8	Rose et al. (1995)

[a] *Expected yield* was calculated on weighted yield data for each country based on the area cultivated in that country and the area of that crop cultivated in all 58 countries.

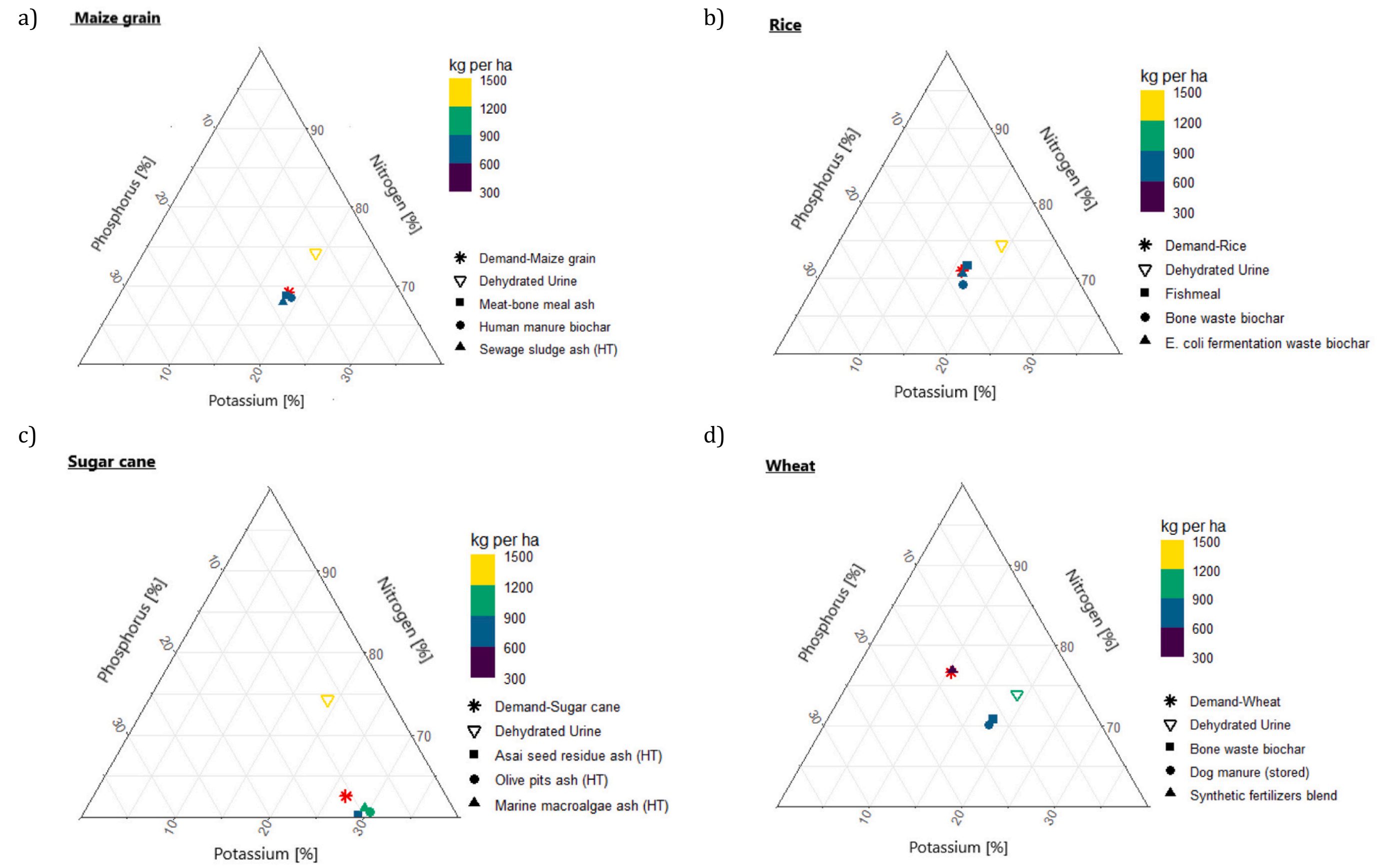

Fig. 2. Distribution (%) of macronutrient demand of four major crops (asterisks) and macronutrient content of simulated blended fertilisers and dehydrated urine (filled symbols and empty triangles, respectively). Application rates (kg per hectare) of the fertilisers are also shown.

fertilisers, either ingredients to produce suitable fertiliser blends must be transported or local alternatives must be accepted, and infrastructure must be set up to produce a blend that is almost as good as the optimal blend. There is also a substantial opportunity to identify more organic wastes that could be blended with dehydrated urine in different geographies, as the nutrient profile of some wastes have not yet been reported, e.g., quinoa residues, orange peel ash and yerba mate (*Ilex paraguariensis*) grounds. The advantage of bio-based fertilisers is that their raw materials (organic waste) are widely distributed and thereby often available locally.

Besides identifying other organic wastes with a macronutrient content that is better suited to that of crops, another strategy to decrease nutrient excesses can be to develop blends of dehydrated urine with more than one organic waste. We conducted such simulations with some of the organic wastes in our database and found that the resulting blends aligned well with crop demand, with lower nutrient surplus and fertiliser application rate. For instance, applying 981 kg ha^{-1} of a blend comprising 79 % dehydrated urine, 5 % fishmeal and 16 % bone waste biochar would meet the macronutrient demand of cotton. This is about 230 kg ha^{-1} less than the rate needed for the blend we found suitable on blending dehydrated urine with fishmeal (70 % dehydrated urine and 30 % fishmeal). For blends with more than one organic waste, the challenges encountered when selecting a single waste to blend with dehydrated urine, such as waste availability, would be more pronounced. However, further investigation on this is warranted, considering the potential benefits of avoiding excess nutrients in the environment.

In soil-based cultivation systems, the nutrient needs of plants, based on their yield potential, must always be considered alongside the potential nutrient supply from the soil. Any fertilization strategy that ignores the soil's nutrient supply risks leading to overfertilization. This paper aimed at developing a theoretical framework for using human urine in circular fertiliser formulations for various crops. Consequently, urine-based fertiliser application strategies that optimize nutrient supply to crops were not addressed here and will need to be explored in future work focused on fertiliser product development

3.2. Addition of heavy metals to agricultural soils

We could not find data on the content of all eight heavy metals for 20 of the organic wastes used to simulate the 38 selected blends (Table 3). For 32 of the selected blends, we could not find data on the content of two or more of the heavy metals. In a similar way, we could not find data on hexavalent Cr (i.e. the chemical form is of concern in the Regulation EU 2019/1009) for any of the selected organic wastes. These are knowledge gaps that must be addressed, as the presence of heavy metals can potentially be detrimental to agricultural systems and human health (Wuana and Okieimen, 2011). Of particular concern are six organic wastes and the corresponding 11 blends that include these wastes, for which there are no data on any of the six heavy metals. One such waste is *E. coli* fermentation waste biochar, which was part of simulated blends for four different target crops (Tables 2 & 3).

For wastes with almost complete data on heavy metal content (six or seven out of eight), it was determined that blending them with dehydrated urine and applying them to soil as fertiliser would not exceed the annual limit values stipulated in the EU regulation on sewage sludge use in agriculture (European Council, 1986). However, there were three exceptions, two of them involving excessive Cr, and another one involving excessive Cu. The annual addition of Cr to soil by adding the blend consisting of marine macroalgae ash and dehydrated urine for

Table 3
Simulated amounts of heavy metals added annually to agricultural land from using selected materials blend with dehydrated urine as fertiliser, compared with limit values in European Union regulations. The symbol "–" indicates that we found no data on the content of that element. Bold font indicates the values higher than the limit in European Union regulations.

Limit values, crops and their respective selected blending materials	Proportion material: dry urine in blend	Blend to be added to plot (kg ha^{-1})	Amount of heavy metals in the blend (mg kg^{-1})								References
			Zn	Cu	Pb	Cd	Cr	Ni	Hg	As	
Limit values[b]			800	300	120	1.5	0.04	50	1.0	40	
1. Barley											
- Human manure biochar	3:97	549	–	–	–	–	–	–	–	–	
- Swine manure biochar	4:96	551	253	58	6	0.06	0.03	4	–	–	Shen et al. (2020); Zeng et al. (2018); Zhi et al. (2020)
- Sewage sludge ash (HT)	4:96	554	79	27	15	0.16	<0.01	3	–	2	Mattenberger et al. (2008)
2. Beans											
- *E. coli* fermentation waste biochar	50:50	210	–	–	–	–	–	–	–	–	
3. Cassava											
- Sunflower husk ash (HT)	19:81	110	30	23	5	0.03	<0.01	4	–	1	Jagustyn et al. (2017); Zając et al. (2018)
- Oat straw ash (HT)	20:80	110	28	10	5	–	<0.01	3	–	1	Zając et al. (2018)
- Pepper plant ash (HT)	21:79	115	–	–	–	–	–	–	–	–	
4. Cotton											
- Fishmeal	30:70	1215	–	–	4	0.13	–	–	0.04	2	López-Alonso (2012)
- *E. coli* fermentation waste biochar	30:70	968	–	–	–	–	–	–	–	–	
5. Maize grain											
- Meat-bone meal ash	9:91	776	–	–	4	–	–	–	–	–	López-Alonso (2012)
- Human manure biochar	19:81	842	–	–	–	–	–	–	–	–	
- Sewage sludge ash (HT)	21:79	889	404	117	56	0.78	**0.06**[a]	13	–	5	Mattenberger et al. (2008)
6. Millet											
- Fishmeal	20:80	49	–	–	4	0.09	–	–	0.03	2	López-Alonso (2012)
- Bonemeal	5:95	46	–	–	–	–	–	–	–	–	
7. Oil palm											
- Grape marc ash (HT)	41:59	880	2	**509**	13	0.98	<0.01	6	–	–	Toscano et al. (2013); Vamvuka et al. (2017)
- Arundo grass ash (HT)	45:55	933	–	–	–	–	–	–	–	–	
- Oat straw ash (HT)	49:51	1016	64	14	6	–	<0.01	6	–	1	Zając et al. (2018)
8. Potato											
- Asai seed residue ash (HT)	22:78	882	–	5	–	–	–	–	–	–	Aires et al. (2020)
- Pistachio shell ash (HT)	32:68	1010	15	52	–	–	–	**286**	–	–	Çelik et al. (2021)
- Marine macroalgae ash (HT)	37:63	1087	21	17	4	**1.84**	**0.11**[a]	15	–	3	Vassilev et al. (2014)
9. Rapeseed											
- Fishmeal	44:56	752	–	–	3	0.18	–	–	0.05	3	López-Alonso (2012)
- Bone waste biochar	7:93	650	31	9	6	0.19	<0.01[a]	6	–	–	Möller (2015)
- *E. coli* fermentation waste biochar	21:79	679	–	–	–	–	–	–	–	–	
10. Rice											
- Fishmeal	40:60	832	–	–	3	0.17	–	–	0.05	3	López-Alonso (2012)
- Bone waste biochar	13:87	764	51	12	7	0.19	<0.01[a]	10	–	–	Möller (2015)
- *E. coli* fermentation waste biochar	18:82	756	–	–	–	–	–	–	–	–	
11. Sorghum											
- Fishmeal	55:45	96	–	–	2	0.23	–	–	0.06	3	López-Alonso (2012)
- Bonemeal	9:91	77	–	–	–	–	–	–	–	–	
12. Soybean											
- Palm kernel ash	73:27	310	352	–	–	–	–	<1	–	–	Masiá et al. (2007)
- Asai seed residue ash (HT)	72:28	296	–	3	–	–	–	–	–	–	Aires et al. (2020)
- Chicken litter ash (HT)	77:23	396	**831**	259	49	–	–	**57**	–	–	Faridullah et al. (2009); Masiá et al. (2007)
13. Sugar beet											
- Palm kernel ash	15:85	893	73	–	–	–	–	<1	–	–	Masiá et al. (2007)
- Chicken litter ash (HT)	26:74	1026	281	91	20	–	–	19	–	–	Faridullah et al. (2009); Masiá et al. (2007)
14. Sugar cane											
- Asai seed residue ash (HT)	14:86	854	–	6	–	–	–	–	–	–	Aires et al. (2020)
- Olive pits ash (HT)	25:75	979	13	82	5	–	<0.01	4	–	–	Romero et al. (2017)
- Marine macroalgae ash (HT)	24:76	977	15	13	4	1.23	0.01	10	–	2	Vassilev et al. (2014)
15. Wheat											
- Bone waste biochar	8:92	620	34	10	6	0.08	0.03[a]	2	–	–	Möller (2015)
- Dog manure (stored)	25:75	739	–	–	–	–	–	–	–	–	

[a] Assuming the extreme case in which the crop is cultivated repeatedly in the same plot for one year.
[b] According to Regulation EU 2019/1009. Since no data was found for Cr (VI) in the selected materials, the Swedish limit value for total Cr in sludge annually added to agricultural soils was used.

cultivating potato and the blend consisting of sewage sludge ash and dehydrated urine for cultivating maize grain would exceed the limit value of 0.04 kg ha^{-1}. The content of Cd in the blend including marine macroalgae was also found to surpass limit value of 1.5 mg kg^{-1}. Sewage sludge contains heavy metals (Nunes et al., 2021; Yang et al., 2020), especially when produced in cities where industrial wastewater is collected and treated together with domestic wastewater. The heavy metal content in raw sewage depends on the type of industrial activities, with production of steel, textiles and leather being the main sources of chromium (Buta et al., 2021). This implies that the content of Cr and other heavy metals in sewage sludge ash varies between cities. Similarly, in the case of marine macroalgae, the content of Cr, Cd and other heavy metals can vary depending on human activities and geological factors near/in water bodies (Sawidis et al., 2001; Rakib et al., 2021). Thus, for both sewage sludge ash and marine macroalgae ash, it is important to determine their heavy metal content before considering them for fertiliser blending. However, it should be noted that the annual amounts of blends resulting in excess Cr were calculated based on a relatively rare scenario where each crop is cultivated in the same plot twice or more in a year without crop rotation (Table 3). Thus, the simulated annual addition of Cr is unlikely to occur in typical agricultural settings. The content of Cu in the blend consisting of grape marc ash and dehydrated urine for cultivating oil palm would exceed the limit value of 300 mg kg^{-1}. Excessive foliar application of Cu-based fungicides in vineyards has been shown to increase Cu content in stems (Miotto et al., 2014), which become further concentrated when grape marc is converted into ash. To mitigate this, it is essential to determine the Cu content in ash before blending it. Additionally, implementing alternative methods to control fungal infections with lower amounts of Cu-based products in vineyards may be beneficial (Romanazzi et al., 2016). In the case of chicken litter ash blended with dehydrated urine for soybean fertilization, high levels of Zn and Ni can be problematic. These elevated levels likely originate from formulations used in chicken feed, as only 5–15 % of such elements are absorbed by the birds (Kyakuwaire et al., 2019). It is important to evaluate the source of the metals, since the net addition to soil would be zero if metals originate from agriculture, but higher if metals originate from industries, forestry or other agricultural systems where heavy metals in soil are high. Consequently, the addition of metals to the soil via imported crop residues would be higher than with local crop residues. In such cases, there is an increased risk of heavy metal accumulation in both soil and crop.

Overall, dehydrated urine itself has a heavy metal content much lower than that of the different organic wastes we chose for blending (Table S3). Given that the majority of our blends (27 out of 38) consisted of ≥70 % dehydrated urine, blending resulted in dilution of the heavy metals present in the organic wastes. As a result, blending dehydrated urine with organic wastes could increase recycling of nutrients in those organic wastes that would otherwise be discarded.

4. Conclusions

Ashes and biochars produced from different organic wastes were identified as the most suitable materials to combine with dehydrated human urine, producing blended fertilisers that fulfilled the macronutrient demand of 15 major crops. This was attributed to low N content and high P and/or K content in these two types of wastes, and the high N content and low P and K content in dehydrated human urine. Combining dehydrated urine with byproduct concentrates resulted in fertiliser blends with lower N and higher P content compared with dehydrated urine alone, making them suitable for crops with proportionally higher P demand such as cotton, millet, rapeseed, rice and sorghum. Several of the organic wastes selected for blending with dehydrated urine were found to be suitable for more than one crop.

The macronutrient content in most simulated fertiliser blends was similar to that found in blended mineral and synthetic fertilisers. This suggests that blends of dehydrated urine and organic wastes could replace inorganic fertilisers in agriculture with little to no changes in farming practices. However, most of the blends did not exactly match the nutrient demand of the crops, so applying them on farmland would result in potential overfertilisation with one or more macronutrients. To address this issue, we recommend that future research evaluates i) the nutrient content of other organic wastes that could be blended with dehydrated urine and ii) the feasibility of blending dehydrated urine with two or more waste materials to develop combined fertilisers that exactly match crop macronutrient requirements.

The content of heavy metals in the simulated fertiliser blends could not be fully determined for the selected organic wastes, due to lack of published data. This research gap should be addressed in future studies, to overcome barriers to recycling such organic wastes in agriculture. For organic wastes with available data about heavy metals, applying most in combination with dehydrated urine would not exceed the limit values stipulated in the European Union regulation on use of fertilisers of organic origin in agriculture.

There is an urgent need to produce bio-based solid fertilisers of industrial quality, increase the circularity of plant-essential macronutrients and reduce the environmental impact of the global food system. This study demonstrated a viable approach for producing tailored circular fertilisers with macronutrient composition that aligns with the macronutrient demands of various crops by blending solid and liquid waste resources available in society.

Supplementary data to this article can be found online at https://doi.org/10.1016/j.scitotenv.2024.175655.

CRediT authorship contribution statement

Luis Fernando Perez-Mercado: Writing – original draft, Visualization, Software, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Prithvi Simha:** Writing – original draft, Methodology, Funding acquisition, Conceptualization. **Aline Paiva Moreira:** Writing – original draft, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Paula Loureiro Paulo:** Writing – review & editing, Supervision, Project administration, Funding acquisition, Conceptualization. **Björn Vinnerås:** Writing – review & editing, Supervision, Resources, Project administration, Methodology, Funding acquisition, Conceptualization.

Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: Prithvi Simha and Björn Vinnerås are co-owners of Sanitation360 AB, a university spin-off commercialising various technologies for recycling human urine. They declare that the work reported in this study was not influenced by their involvement in this company. Prithvi Simha reports financial support was provided by Research Council of Norway. Bjorn Vinneras reports financial support was provided by Swedish Research Council. Paula Loureiro Paulo reports financial support was provided by Coordination of Higher Education Personnel Improvement. If there are other authors, they declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

Acknowledgements

This study received funding from the Swedish Research Council Vetenskapsrådet (Grant # 2022-04188) for the project NECESSITY (Nästa generations källsorterande avloppssystem), the Research Council of Norway (Grant # 335008) for the project “Food security through better sanitation: the case of urine recycling", and Coordenação de Aperfeiçoamento de Pessoal de Nível Superior - Brasil – CAPES (Finance Code 001 and Capes PrInt program).

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