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Review

A Systematic Review of the Effects of Fecal Sludge Derived Amendments on Crop Growth and Soil Health

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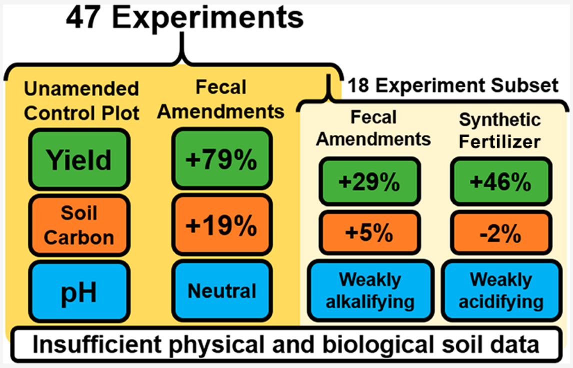
ABSTRACT: The use of human excreta in agricultural settings has the potential to meet crop nutrient requirements and improve soil health, while also providing a sustainable end use for fecal material. Previous reviews have focused on sewage sludge biosolids from wastewater treatment plants, but with on-site sanitation systems overtaking sewers as the leading sanitation system worldwide, greater attention to fecal sludge is warranted. This systematic Review is the first to compile the results of crop trials which utilized fecal amendments from on-site sanitation systems and includes 47 experiments. Overall, fecal amendments increased crop growth compared to unamended control plots and also produced comparable yields to synthetic fertilizers. Biological and physical soil parameters were underrepresented in the literature, which made a holistic assessment of soil health impossible. However, some improvements in chemical characteristics were observed, most notably for soil organic carbon. Inconsistent experimental design made aggregation of results and detailed statistical analysis difficult, highlighting the need for a more standardized approach for testing the efficacy of amendments and reporting results. Regardless, this Review compiles our collective existing knowledge to provide tentative results for the effect of fecal amendments on crop growth and soil health and offers recommendations for future work.



KEYWORDS: *ecological sanitation, circular economy, fecal sludge, crop trials, soil health*

■ INTRODUCTION

The beneficial use of human excreta for crop production and soil health is the missing link in establishing a circular flow of nutrients and is of great interest to both the sanitation and agricultural sectors. On-site sanitation systems have surpassed sewers as the most prevalent form of sanitation service worldwide[1] and offer enormous opportunity for nutrient recycling.[2]

Within the sanitation service chain, treatment and end use present huge challenges and poor management can cause systems to fail in their purpose of protecting people from exposure to enteric pathogens. Within on-site sanitation systems, such as pit latrines, septic tanks, and container-based sanitation systems, large quantities of fecal sludge may contaminate the local environment owing to flooding,[3] a lack of emptying services,[4−6] or the indiscriminate dumping of emptied fecal sludge due to unsuitable, inaccessible, or unaffordable disposal facilities.[7,8] Sewers, commonly perceived as preferable to on-site systems, offer no universal solution either and require proper design and management. Worldwide, many sewers are not connected to any form of treatment, thus simply conveying the contamination elsewhere.[9,10]

The sludge that is successfully collected is usually disposed to land or water, incinerated, utilized in agriculture, or incorporated into building materials.[11,12] While incineration does recover some energy, this, along with most other disposal options, squanders the other beneficial components of sludge, namely, its moisture content, organic matter, and nutrients. Ecological sanitation (sometimes called "resource-oriented sanitation" or "sustainable sanitation") recognizes that society can no longer afford to waste the almost 1 billion tons of feces generated each year.[2]

From an agricultural perspective, human excreta could meet between 9% and 22% of agricultural demand for the three essential plant macronutrients, nitrogen (N), phosphorus (P) and potassium (K).[13,14] This could substitute the use of synthetic fertilizers, offsetting the negative environmental impacts associated with their production, transport, and use, including pollution to water bodies and greenhouse gas emissions to the atmosphere.[15−18] Human excreta also influences "soil health", a useful concept for communicating

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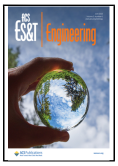

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an overall state of the soil and its ability to deliver soil functions, the groups of ecosystem services that soil provides as benefits to people.[19] Quantification of soil functions is underpinned by natural science theory and methods of observation that link physical, chemical, and biological parameters of soil (e.g., bulk density or organic matter content) to the rates of dynamic biophysical processes that deliver specific soil functions. Soil functions include nutrient supply for plant production, water storage and transmission, filtering pollution from infiltrating water, climate regulation by storing carbon (C) and nitrogen (N) as organic matter and preventing their release to the atmosphere as greenhouse gases, and providing habitat to sustain terrestrial genetic and function biodiversity.[20] Unlike synthetic fertilizers, feces contain organic matter which has been correlated with improved soil structure, water retention, nutrient retention and cycling, and microbial activity[19,21−28] in studies involving animal manures, sewage sludge biosolids, and other organic amendments. These soil improvements in turn help to support improved crop yields[29,30] while enhancing other ecosystem services[20,31−33] including capturing carbon.[34,35] Managing soil organic matter to reduce reliance on synthetic fertilizers is considered a critical component of sustainable intensification,[36] which will be necessary to feed the future human population.

The relative simplicity and affordability of agricultural use offers a mutually attractive solution for both the sanitation and agricultural sectors, although notable barriers to implementation do exist, particularly surrounding quality and safety regulation, financing, and scale up.[37,38] Demonstrating the agronomic value of excreta may help to drive wider uptake of ecological sanitation, resulting in a better level of service provision for the 3.6 billion people who lack access to safely managed sanitation.[1] At the same time, excreta can offer local nutrient security, liberating producers from their dependence on the volatile fertilizer market, in which price shocks and supply disruptions disproportionately affect the poorest and most vulnerable producers and consumers.[39]

GAP ANALYSIS

A search of academic literature databases reveals that most studies relating to agricultural use of human excreta have been focused on sewage sludge biosolids, including dozens of review papers focusing on (i) their effects on soil and crops,[23,40−43] (ii) their benefits and precautions,[44,45] (iii) their legislation,[46] and (iv) their pathogen risk.[47] One reason for this prevalence is the widespread use of centralized sewer networks and wastewater treatment plants in High Income Countries (HICs),[1] coupled with the finding of Plancikova et al.[48] that 84% of authors within public health research are based in HICs.

Much less attention in given to fecal sludge from on-site sanitation systems which serve more than half the global population.[1] On the topic of fecal sludge use, Trimmer et al.[14] noted a strong focus in the literature on energy recovery, despite estimating only negligible achievable impacts on global energy security. In contrast, they noted large potential impacts for nutrient security related to agricultural use, especially in the worlds least developed countries (LDCs). In addition to its global prevalence and the lack of published scientific research, fecal sludge is of interest due to its composition. Typically, fecal sludge is less contaminated with pollutants from industrial waste streams than sewage sludge biosolids[16,49] and, so, offers a more promising starting point for safe use on food crops.

Previous reviews on the topic of fecal sludge end-use have focused on (i) the general background theory,[50] (ii) FS collection and treatment,[51] (iii) product characterization,[52] (iv) human attitudes and perceptions,[53] (v) pathogen risk,[54] and (vi) economics.[55,56] At the time of publishing, no review had been conducted on the effects of fecal sludge on crop growth and soil health. This Review aims to determine the current state of research practice and knowledge on the effects of fecal sludge derived amendments on crop growth and soil health in agricultural settings, with a particular focus on recommendations for research priorities and improvement in research design.

METHODS

Preliminary searches were carried out on the four chosen databases, Web of Science, Scopus, PubMed, and Google Scholar, to familiarize the first author with the common wording found within the relevant literature in order to design effective search terms. Different search terms were tested out, and the first 100 results were title-screened for relevance. This preliminary search process identified two key findings: (i) the lack of studies focusing on on-site sanitation systems, which presented the research gap that guided the direction of the review, and (ii) the importance of constraining the "sanitation" term of the search to appear in the title of the paper in order to narrow down the total number of search hits while retaining high relevance.

Study selection involved the following steps:

- Step 1: Search of electronic databases.
- Step 2: Import results into reference management software (Endnote) for automatic deduplication.
- Step 3: Title screening by first author, with a 10% quality control check by second author.
- Step 4: Import results into the Rayyan QCRI web tool. Abstract screening conducted independently by first and second authors using PICO[57] framework. Discussion to resolve conflicts.
- Step 5: Full text screening by first author with a 10% quality control check by second author.
- Step 6: Data extraction.

Systematic Search. The systematic searches took place in February 2021 and again in January 2023. Four databases were used: Web of Science, Scopus, PubMed, and Google Scholar. Table 1 shows an example of the search terms used for Web of Science. Syntax was adjusted appropriately for compliance with each electronic database.

Screening. All results were screened for inclusion using the "PICO" framework[57] shown in Table 2. The review was restricted to studies available in English and had no limits to the publishing date. The review was not limited to peer-reviewed journal articles in order to capture all relevant sources of knowledge.

Data Extraction. Data were extracted manually into Microsoft Excel from data tables, text, and graphs. WebPlotDigitizer Version 4.6 was used to extract numeric data from graphs where data tables were not included. An exemplar of the database is shown in Figure 1. Each paper was coded (Column A), and each treatment within each paper was numbered (Column B), which combined to give a unique code for every row of data (Column C). A "treatment" refers to one row of data, which related to one particular set of variables. For example, if a paper measured the effects of both (i) a compost and (ii) a dried sludge, each on both a (i) wheat crop and a (ii) potato crop, then this would result in four unique treatments. As such, most papers

Table 1. Search String Used for Web of Science Containing a “Sanitation” Term Constrained to the Paper Title and an “Agriculture/Soil” Term[a]

database	search term
Web of Science	TS = (“fecal sludge*” OR “faecal sludge*” OR “human excreta” OR “human excrement” OR “onsite sanitation” OR “pit latrine*” OR “container-based sanitation” OR “ecological sanitation” OR “ecosan” OR “human feces” OR “human faeces” OR “humanure” OR “terra preta” OR “arborloo” OR “fossa alterna” OR “compost* toilet*” OR “nonsewered sanitation” OR “bucket latrine” OR “fecal material” OR “faecal material” OR “septage” OR “septic tank*” OR “UDDT” OR “urine diverting dry toilet*”) AND TS = (“soil health” OR “soil propert*” OR “soil function*” OR “soil qualit*” OR “soil fertili*” OR “soil character*” OR “health of soil*” OR “propert* of soil*” OR “function* of soil*” OR “qualit* of soil*” OR “fertili* of soil*” OR “character* of soil*” OR “agronom* character*” OR “agronom* propert*” OR “soil chemi*” OR “soil biolo*” OR “soil physic*” OR “soil nutri*” OR “soil organ*” OR “soil carbon” OR “land application*” OR “agronom* application*” OR “agricultur* application*” OR “agronom* reuse” OR “agricultur* reuse” OR “soil amendment*”)

[a] Supplementary literature was found by hand-searching the reference lists of selected studies and recent reviews.

contained multiple treatments. Variables of interest related to the study design (Columns D−K), fecal amendment characteristics (Columns L−R), and experimental results pertaining to crop growth and soil health parameters (Columns S-AD).

Some fecal amendments (FAs) were enriched with or applied in combination with other commercial sources of nitrogen (N), phosphorus (P), and potassium (K), such as urea, potash, and phosphate rock. For simplicity, these have been collectively termed “Synthetic Fertilizers” (SFs), and these enriched treatments are considered a subset of the FA data. They are denoted with the additional nutrients in the subscript; e.g., FA_N was enriched with commercial N. FA therefore refers collectively to all treatment rows containing a fecal amendment, regardless of enrichment, and FA_o refers to those treatments which were not enriched with synthetic fertilizers.

All experiments were categorized as being either high or low methodological quality based on the criteria in Table 3. A paper which met all criteria in the table was considered to have high quality methods (HQMs). This subset of the total data set was reported separately alongside the full data set.

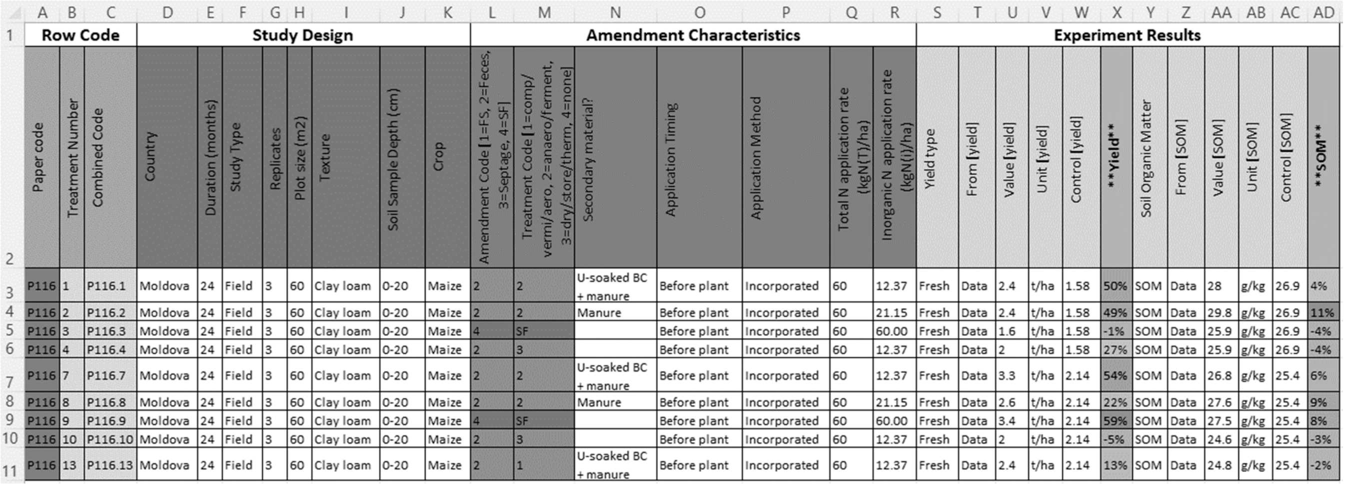
Synthesis of Results. The lack of consistency within the experimental design of each study made it impossible to directly compare the raw crop and soil data between the studies. Taking yield as an example, if two different studies using fecal amendments (FAs) reported (i) an average fresh yield of Swiss chard at 43 g/pot and (ii) an average dry yield of maize at 1.12 t/ha, these raw data cannot be combined.

Instead, these data were standardized by comparing the results of the FA to those of the unamended control plots/pots (UCPs), thereby controlling for site conditions and plot management differences between the studies. This gave the relative “effect size” of the amendment as a percentage change, which could then be easily aggregated across all the studies (Figure 1, Column X and Column AD). Percentage change relative to a control plot is a common method of results reporting in agricultural experiments, particularly for reporting yield.[58] Using the same example as before, it can be stated that adding the FA increased Swiss chard yields by 115% and maize yields by 61%, as compared to no amendment. These values can then be aggregated for statistical analysis. This method is useful for showing broad directional trends, while the variation in results between the studies gives an indication of certainty.

Comparison of Fecal Amendments and Synthetic Fertilizers. Papers which included fecal amendment (FA) treatments and synthetic fertilizer (SF) treatments within the same experiment were directly compared to assess their relative performance while controlling for all other experimental variables. This analysis was limited to FA treatments which were not enriched with synthetic fertilizer (FA_o) and which used a broadly comparable N application rate. Most experiments used similar total N (N_T) application rates, and so, this was used as the basis of comparison. Papers which used N_T application rates of SF and FA which were within 2× the value of each other were considered comparable and were included in this analysis. This resulted in the inclusion of 18 experiments. It should be noted that N loading is just one possible basis for comparison but was selected due to high reporting rate within the studies and because it is commonly used as a basis of equivalency for synthetic fertilizers. Additionally, within organic amendments, most of N_T is in the form of organic N, which must first be mineralized by soil microorganisms to become available for plants to utilize. Estimates of the readily available inorganic N (N_i) within organic amendments vary greatly, depending on the

Table 2. Inclusion and Exclusion Criteria for the Systematic Review Using the PICO Format

		includes	excludes
Population	Fecal sludge equivalent (FSE) (1) is used as the basis of the fecal amendment (FA) (2)	(1) Any human fecal excreta (a) sourced from on-site sanitation systems (b), including septic tanks. (a) By our definition, excreta must contain feces, but may or may not contain additional materials, including, but not limited to, urine, flushwater, toilet paper, menstrual blood, greywater, and cover material. (b) This includes any kind of pit, vault, or bucket where excreta is retained on the premises for any duration, rather than immediately conveyed via pipe, as with a sewer. (2) Includes raw excreta as well as any amount of further treatment. Examples include drying, storage, composting, anaerobic digestion and pyrolysis, but this list is not exhaustive.	(1) Nonhuman excreta. (1) Human excreta from sewer-based sanitation systems.(1) Urine-only experiments.
Intervention	Fecal amendment (FA) applied to soil (1) in a crop (2) growing study (3).	(1) Any soil type. Amendment may be applied in any way (e.g., surface, incorporated) at any time prior to crop harvest (e.g., before planting or at various plant growth stages).	(1) Other uses for the FAs.
		(2) Any arable crop for consumption by humans (e.g., vegetables) or animals (e.g., grass) or for commercial use (e.g., timber).	(2) Soil remediation experiments where a crop was not grown.
		(3) Any crop growing trial, including small plot, farm scale, or glasshouse, in which a FA was added to the soil.	(3) Other kinds of papers, e.g., review and discussion papers.
Comparison	Numeric results (1) reported with comparison to an unamended control plot (2)	(1) Numeric data may be presented in a table or text or on a graph so long as the numeric value can be interpreted.	(1) Papers with anecdotal or qualitative results (e.g., the crops were much taller under treatment 1).(1) Papers with indecipherable results or graphs.
		(2) A plot which was managed identically to the plots of interest, except for the addition of any kind of fertilization.	(2) Papers which only compared FAs to other organic amendments or synthetic fertilizers.
Outcome	Measures at least 1 crop or soil property of interest (1)	1. Included any measure of crop growth or nutrition or any physical, chemical, or biological measure of soil. Examples include, but are not limited to: −Crop: yield, biomass, size, nutrient content, nutrient uptake. −Soil: nitrogen (N), phosphorus (P), potassium (K), carbon (C), organic matter (OM), pH, electrical conductivity (EC), cation exchange capacity (CEC), microbial respiration, fungi:bacteria, earthworm counts, bulk density, porosity, water holding capacity.	(1) Papers which only measure other aspects, such as economics, pathogens, or farmer opinions.



	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P	Q	R	S	T	U	V	W	X	Y	Z	AA	AB	AC	AD
1	Row Code			Study Design								Amendment Characteristics							Experiment Results											
2	Paper code	Treatment Number	Combined Code	Country	Duration (months)	Study Type	Replicates	Plot size (m2)	Texture	Soil Sample Depth (cm)	Crop	Amendment Code [1=FS, 2=Feces, 3=Septage, 4=SF]	Treatment Code [1=comp/vermi/aero, 2=anaero/ferment, 3=dry/store/therm, 4=none]	Secondary material?	Application Timing	Application Method	Total N application rate (kgN{T}/ha)	Inorganic N application rate (kgN{i}/ha)	Yield type	From [yield]	Value [yield]	Unit [yield]	Control [yield]	**Yield**	Soil Organic Matter	From [SOM]	Value [SOM]	Unit [SOM]	Control [SOM]	**SOM**
3	P116	1	P116.1	Moldova	24	Field	3	60	Clay loam	0-20	Maize	2	2	U-soaked BC + manure	Before plant	Incorporated	60	12.37	Fresh	Data	2.4	t/ha	1.58	50%	SOM	Data	28	g/kg	26.9	4%
4	P116	2	P116.2	Moldova	24	Field	3	60	Clay loam	0-20	Maize	2	2	Manure	Before plant	Incorporated	60	21.15	Fresh	Data	2.4	t/ha	1.58	49%	SOM	Data	29.8	g/kg	26.9	11%
5	P116	3	P116.3	Moldova	24	Field	3	60	Clay loam	0-20	Maize	4	SF		Before plant	Incorporated	60	60.00	Fresh	Data	1.6	t/ha	1.58	-1%	SOM	Data	25.9	g/kg	26.9	-4%
6	P116	4	P116.4	Moldova	24	Field	3	60	Clay loam	0-20	Maize	2	3		Before plant	Incorporated	60	12.37	Fresh	Data	2	t/ha	1.58	27%	SOM	Data	25.9	g/kg	26.9	-4%
7	P116	7	P116.7	Moldova	24	Field	3	60	Clay loam	0-20	Maize	2	2	U-soaked BC + manure	Before plant	Incorporated	60	12.37	Fresh	Data	3.3	t/ha	2.14	54%	SOM	Data	26.8	g/kg	25.4	6%
8	P116	8	P116.8	Moldova	24	Field	3	60	Clay loam	0-20	Maize	2	2	Manure	Before plant	Incorporated	60	21.15	Fresh	Data	2.6	t/ha	2.14	22%	SOM	Data	27.6	g/kg	25.4	9%
9	P116	9	P116.9	Moldova	24	Field	3	60	Clay loam	0-20	Maize	4	SF		Before plant	Incorporated	60	60.00	Fresh	Data	3.4	t/ha	2.14	59%	SOM	Data	27.5	g/kg	25.4	8%
10	P116	10	P116.10	Moldova	24	Field	3	60	Clay loam	0-20	Maize	2	3		Before plant	Incorporated	60	12.37	Fresh	Data	2	t/ha	2.14	-5%	SOM	Data	24.6	g/kg	25.4	-3%
11	P116	13	P116.13	Moldova	24	Field	3	60	Clay loam	0-20	Maize	2	1	U-soaked BC + manure	Before plant	Incorporated	60	12.37	Fresh	Data	2.4	t/ha	2.14	13%	SOM	Data	24.8	g/kg	25.4	-2%

Figure 1. An exemplar of the results database.

Table 3. Requirements for a High Quality Methodology (HQM)

study design feature	description
Replication	Each fecal amendment treatment was replicated at least 3 times (or in the case of single large fields, at least 3 samples were taken from around the field).
Randomization	Plots were arranged in a stated randomized format, such as Randomized Complete Block Design (or in the case of single large fields, multiple samples were taken from around the site in a representative way).
Fecal amendment purity	The fecal amendment was predominantly of fecal origin and was not enriched with inorganic sources of N, P, or K. In cases where blends were used (e.g., feces and food waste composts), the blend was >50% fecal material.
N application rate	The total N (N_T) application rate of the FA on the field was stated or calculable from the supplied data, in kgN_T/ha.
Field trial	Only field trials (small plot or large field) were considered high quality. More information about the limitation of pot trials is given in the discussion.
	Specific to Crop Parameters
Duration	The study lasted at least 1 whole crop cycle, from planting to plant maturation/harvest.
	Specific to Soil Parameters
Duration	The study lasted at least 1 full year to allow time for the amendment to be incorporated into the soil and to reduce seasonal variations in soil properties.
Soil sampling	The soil sampling depth is stated in the paper.

form of the amendment and its treatment conditions and duration,[59] but some studies assume a single value for N_i for simplicity (e.g., $N_i = 10\%$ of N_T in the case of Chirere et al.[60]). In addition to the N_i contained within organic amendments, it is also hard to predict how much of the organic N becomes mineralized into N_i during the course of the growing season, and different equations for this exist.[61,62] In summary, under comparable N_T loading rates, fecal amendments would supply significantly lower plant-available N as compared with synthetic fertilizers. This should be considered when interpreting the results.

Statistical Analysis. Only three papers were both (i) of high methodological quality (HQM) and (ii) reported the sample number (n) and standard deviation (SD). These two values are required to weight the effect size of a study which is necessary for formal meta-analysis. As such, true meta-analysis was not possible, and instead, the average of the treatments was found assuming equal weighting across all treatments. The data generally suffered from small sample sizes, high variance, and several significant positive outliers, which resulted in a positive skew in many of the parameters. A Shapiro−Wilk test was used for determining the normality of the data. The majority of the data was not normally distributed; thus, the median was selected as the most suitable measure of central tendency, and nonparametric statistical testing was employed. In cases where data was normally distributed, the mean and parametric testing were used, and this is clearly stated. A 95% confidence level ($\alpha = 0.05$) is also reported alongside the median and mean values.

95% confidence intervals for medians were determined using the binomial distribution to determine the jth (lower) and kth (upper) observation, using the following equations:

$$j = 0.5n - z\sqrt{0.5n(1 - 0.5)} \tag{1}$$

$$k = 0.5n - z\sqrt{0.5n(1 - 0.5)} \tag{2}$$

95% confidence intervals for means were calculated using the following equation:

$$\mathrm{CI} = z\left(\frac{\mathrm{SD}}{\sqrt{n}}\right) \tag{3}$$

where n = the sample size and $z = 1.96$ for a confidence interval of 95%.

Median results are reported as median [lower confidence interval, upper confidence interval] (n = value). Mean results are reported as mean [±confidence interval] (n = value). Where box plots are used to visualize the data spread, values outside 1.5× the interquartile range are shown as points.

METADATA RESULTS

Systematic Search. The systematic search process identified 45 papers written between 1939 and 2023 which

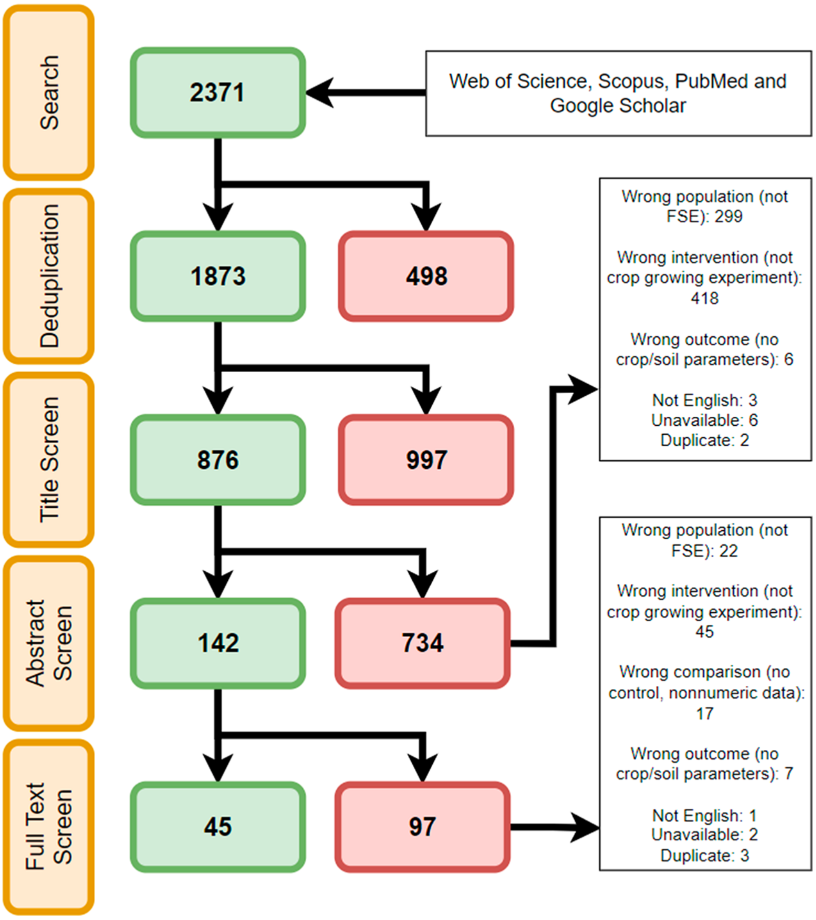


Figure 2. Flow diagram of the systematic search and screening process, including the major reasons for paper exclusion at each step. The exclusion reasons are detailed in Table 2. FSE = fecal sludge equivalent.

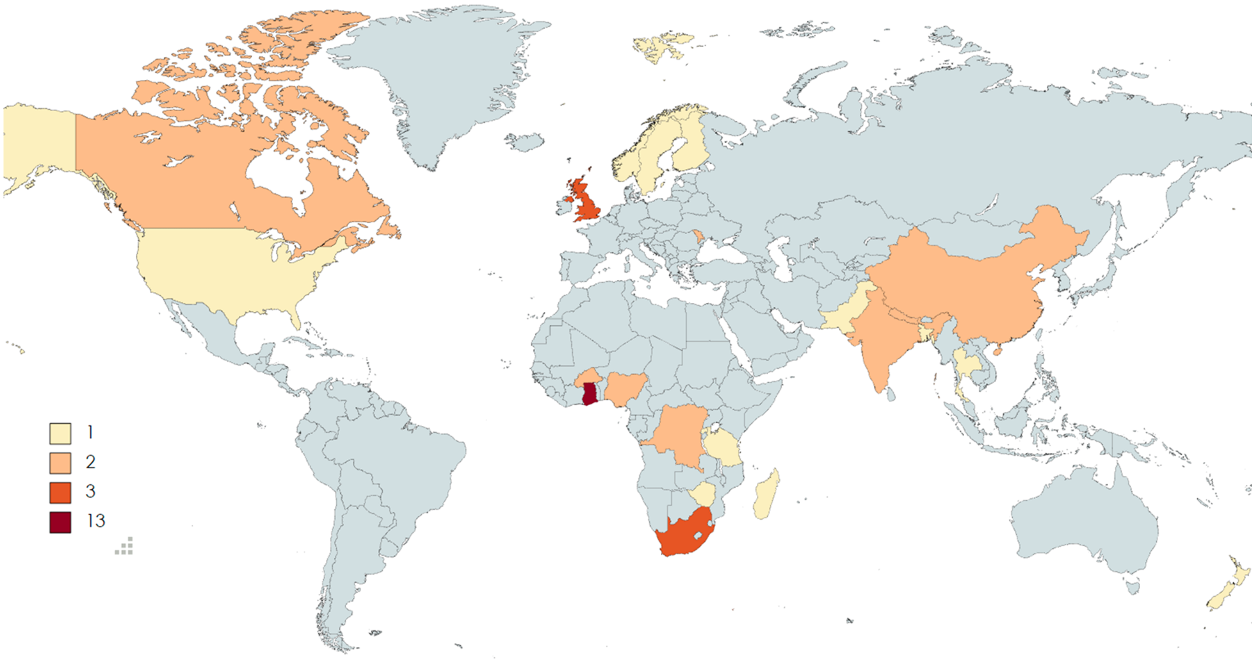


Figure 3. Map of the distribution of included studies worldwide. Made with MapChart.

met the inclusion criteria (Figure 2). All reasonable steps were taken to locate the papers, and only two papers could not be found after using interlibrary loan. A summary of the included papers, their key design features, and summary results is included in the Supporting Information. In two instances, two distinct papers described the same experiment (N013 and

Table 4. Number of Data Rows for Each Type of Fecal Amendment[a]

amendment source[b]	total	anaerobic	composting	drying	storage	vermi/insect compost	fermentation	none/unknown
Fecal sludge	**116**	5	64	33	5	33	6	
Feces	**110**		25	24	32	4	16	7
Septage	**63**	6	27	12	16	6	2	
Synthetic fertilizer	**85**							

[a] Fecal amendments are disaggregated into three “sources” and seven “treatment” categories. [b] “Fecal sludge” included those which had been collected from pits or buckets without urine separation. “Feces” generally referred to the solids from a urine diverting system (typically a drier material with lower N content). “Septage” was the sludge removed specifically from septic tanks. Rows do not sum to the total due to instances where more than one treatment approach was used.

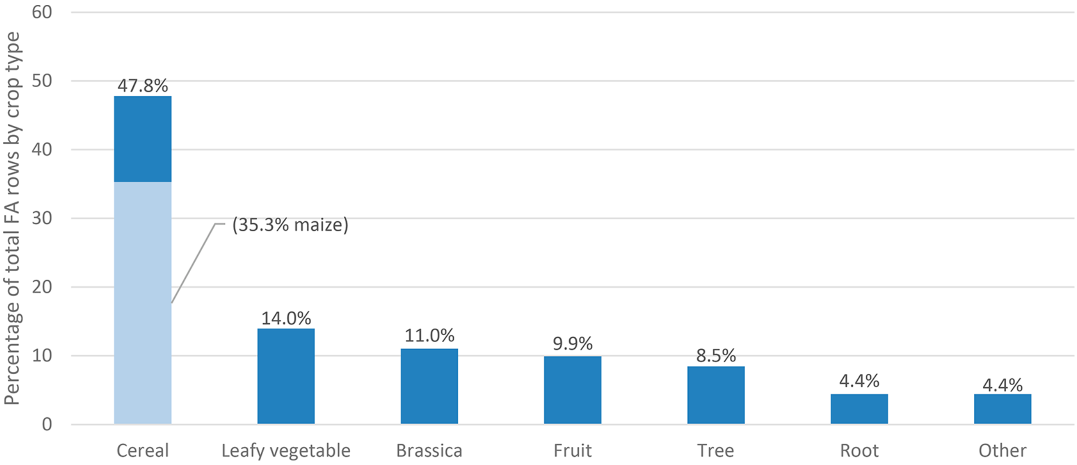


Figure 4. Graph showing the proportion of included data which related to each crop type.

Table 5. Frequency of Reporting on Different Crop Parameters within the Included Studies

crop parameter	description	no. of experiments	no. of fecal amendment treatment rows
Yield	Mass per area or per pot, e.g., kg/ha, g/pot. May be fresh or dried.	35	188
Produce Average Mass (PAM)	Mass per plant or fruit/vegetable, e.g., 1000 grain mass, average cabbage head weight. May be fresh or dried.	11	64
Height	Height of plant, e.g., centimeters	22	98
Biomass	Mass of plant material, including nonsaleable parts of plant, e.g., total biomass (g), above ground biomass (g). May be fresh or dried.	15	84
Tissue nutrients (N, P, and/or K)	Concentrations of at least one of the three macronutrients (NPK) in any part of the plant (usually leaves). Reported as mass/mass or percentage. May be fresh or dried.	13	68

N035; P049 and P087), and so, their results were combined. Three papers (P011, P053, and P089) described multiple unique experiments, which are denoted with a letter after the main paper code. This gave 47 unique experiments, which yielded 289 rows of FA data, each relating to a unique treatment.

The studies took place in 23 countries, with 13 of the 47 experiments conducted in Ghana and sharing a similar pool of authors affiliated with the International Water Management Institute (IWMI). The remaining studies were distributed around North Europe, North America, East Asia, and Sub-Saharan Africa (Figure 3). There were no studies conducted in Central Asia, Middle East and North Africa (MENA), Central and South America, or the Asian Pacific islands The majority of experiments ($n = 28$) were less than 6 months in duration. Nine lasted 7−12 months, 5 lasted for 2 years, and just 1 lasted more than 2 years. Four studies did not report their duration. Only 10 experiments monitored changes over at least 1 crop growth cycle, most of which were short cycles of fast growing crops. As such, only 8% of the fecal amendment rows report data collected from at least a second calendar year of a crop trial, which highlights a distinct lack of studies measuring long-term impacts.

Nineteen experiments were determined to have high quality experimental design and methodological reporting for crop results, based on the criteria in Table 3, meaning they were conducted in the ground rather than in pots, were grown until the point of plant maturity or harvest, reported a randomized layout, and had at least 3 replicates. Only two of these experiments were determined to also have high quality reporting for soil results, meaning they lasted for at least 12 months and reported the soil sampling depth.

Amendment Characteristics. Table 4 shows the breakdown of the papers by amendment source and main treatment method. Composting was the most common sanitation treatment method, used in 40% of the fecal amendment treatment rows. When considered alongside vermicomposting, these aerobic treatment processes made up half of the data.

Although septage, fecal sludge, and source separated feces can have very different compositions and rheological properties,[63] the range of different source and treatment combinations made it impractical to disaggregate results in this way. Since this Review represents the first attempt to quantify the effects of fecal amendments from on-site sanitation systems on crop and soil systems, it is appropriate to keep the assumptions and findings broad. Subsequent studies could investigate whether amendment source or treatment process are good predictors of agronomic outcomes.

Crops. The studies covered 32 different crops, grouped into types in Figure 4. Cereal crops dominated the data, with maize alone comprising 35% of the fecal amendment data.

Every paper measured at least 1 crop parameter; see the summary in Table 5.

Soil Characteristics. Twenty-eight experiments conducted field trials in which the soil remained in situ, and 19 conducted pot trials using excavated topsoil. Soil preparation differed and was inconsistently reported. Soil classification was rarely reported, and those which did used different national classification systems, making analysis by soil type impossible. Of the field trials which reported soil results ($n = 16$), 13 of them reported the soil sampling depth. All sampling depths were within the 0−40 cm range, with 6 experiments only sampling to a depth of 15 cm. Only 3 experiments stratified the soil sample into two distinct depths. The lack of reported soils depths and the inconsistent parameters measured across each study provided insufficient data points for analysis to differentiate results by depth.

Only 25 experiments (53.2%) measured changes in any soil parameter; the predominant focus was on chemical parameters (Table 6). Some experiments reported physical parameters of the baseline soil at the start of an experiment, but only one paper measured a change between the start and end of the experiment. Measures of biological activity, such as microbial respiration or fungal:bacterial mass ratios, were also lacking, being reported in just three experiments, and each reported different biological parameters, which was insufficient for statistical analysis.

Table 6. Frequency of Reporting on Different Aspects of Soil Health within the Included Studies

soil parameter	no. of experiments	no. of fecal amendment treatment rows
Soil N (Total, NO_3, or NH_4)	14	71
Soil P	18	80
Soil K	19	102
Soil C	12	65
SOM	8	39
pH	18	93
EC	11	49
CEC	5	24
Biological (any)	3	12
Physical (any)	1	3

■ CROP AND SOIL RESULTS

Effect of Fecal Amendments on Crop Parameters. Measures of crop yield were the most commonly reported of any parameter. The addition of fecal amendments (FAs) increased crop yields by a median of 79% [60%, 97%] ($n = 188$). A Wilcoxon Signed-Rank test found this to be a significant difference from the unamended control plots ($p < 0.001$). The High Quality Method (HQM) subset of the FA data increased median crop yields by 49% [33%, 77%] ($n = 45$, $p < 0.001$) (Figure 5).

FAs increased produce average mass (PAM) by a median value of 19% [11%, 39%] ($n = 64$, $p < 0.001$); however, the HQM subset found the median difference to be 5% [−5%, 16%] ($n = 18$), which was not a statistically significant difference from the control ($p = 0.208$).

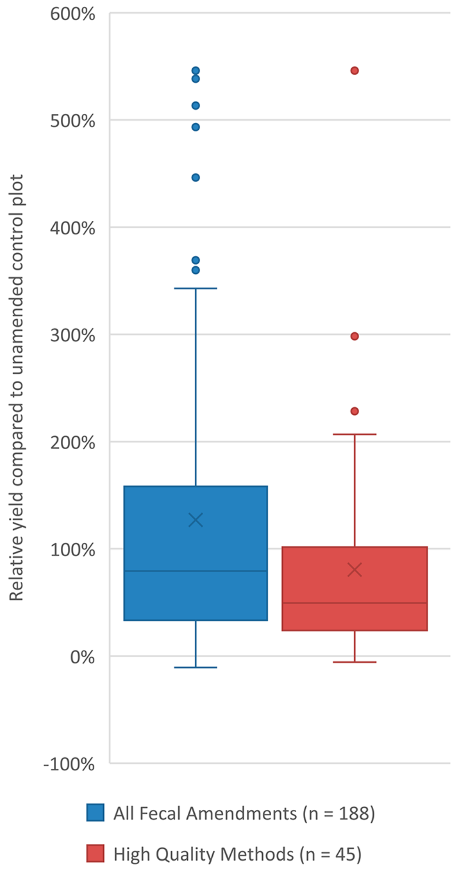


Figure 5. Box plot showing the relative yield performance achieved by the application of fecal amendments as compared with their unamended control plots, shown as percentage change from zero. Three outliers (+1677%, +1235%, and +675%) are not shown for visual clarity. A subset of just those experiments with high quality methodological reporting is also shown.

FAs significantly increased plant height by a median value of 24% [15%, 31%] ($n = 98$, $p < 0.001$) over the control and plant biomass by a median value of 82% [64%, 113%] ($n = 84$, $p < 0.001$). Considering just HQM results in less pronounced findings. FAs in HQM experiments increased plant height by a median value of 9% [2%, 31%] ($n = 18$, $p < 0.001$), but changes in plant biomass showed conflicting trends, such that the overall change was not found to be statistically significant, with a median = 16% [−65%, 70%] ($n = 30$, $p = 0.342$).

FAs significantly increased the three plant tissue macronutrients. The median increase in tissue N was 7% [0%, 13%] ($n = 68$, $p < 0.001$). The median increase in tissue P was 28% [2%, 62%] ($n = 68$, $p < 0.001$). The median increase in tissue K was 17% [2%, 33%] ($n = 67$, $p < 0.001$). For HQMs, the median increase in tissue N was 11% [5%, 29%] ($n = 10$, sample insufficient for significance testing). The median increase in tissue P was 29% [8%, 54%] ($n = 10$, $p = 0.007$). The median increase in tissue K was not statistically significant, median = 14% [−11%, 34%] ($n = 10$, $p = 0.103$).

Since N is commonly a limiting plant nutrient[64] and is the focus of much work on fertilization optimization, a positive correlation was expected between the N application rate and the resulting crop yield. However, this analysis found no correlation

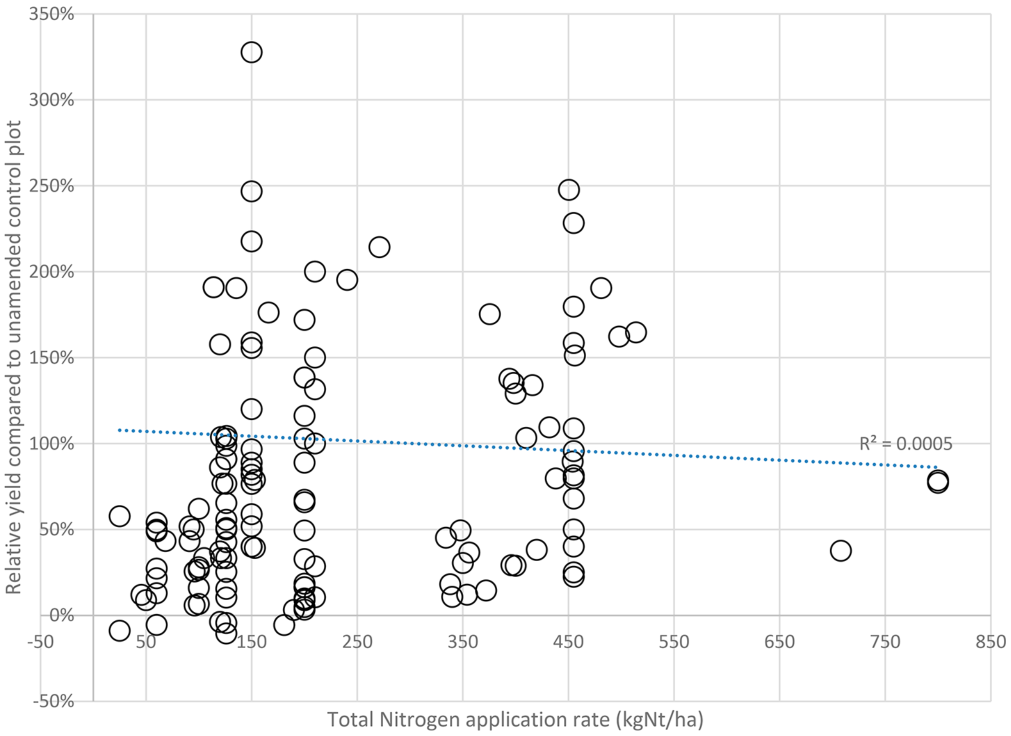


Figure 6. Relationship between the total N (N_T) application rate and crop yield performance for all fecal amendment across 26 experiments. Three outliers are not shown for visual clarity (90 kgNt/ha, +1677%; 90 kgNt/ha, +1235%; 210 kgNt/ha, +675%). No linear relationship was observed.

Table 7. Summary of the Effects of Fecal Amendments (with No Synthetic Fertilizer Mixing, FA_o) and Synthetic Fertilizer (SF) Application in Paired Experiments Which Used Comparable Total N (N_T) Loading Rates[a]

parameter	FA_o median change compared to UCP	SF median change compared to UCP	significance
Yield	Median 29% [16%, 50%] ($n = 31$)	Median 46% [26%, 71%] ($n = 24$)	$p = 0.208$
Produce average mass	Median 14% [3%, 26%] ($n = 26$)	Median 19% [−3%, 81%] ($n = 11$)	$p = 0.936$
Plant height	Mean 29% ± 9% ($n = 23$)	Mean 27% ± 14% ($n = 12$)	$p = 0.820$, d.f. = 33
Biomass	Median −32% [−70%, 62%] ($n = 24$)	Median 40% [−71%, 89%] ($n = 13$)	$p = 0.308$
Tissue N	Mean 12% ± 8% ($n = 7$)	Mean 40% ± 22% ($n = 7$)	$p = 0.038$, d.f. = 12 SFs resulted in significantly higher tissue N than FAs, but the small sample size should be noted
Tissue P	Mean 18% ± 13% ($n = 7$)	Mean 28% ± 22% ($n = 7$)	$p = 0.435$, d.f. = 12
Tissue K	Mean 26% ± 18% ($n = 7$)	Mean 26% ± 22% ($n = 7$)	$p = 0.991$, d.f. = 12
Soil N	Median 7% [−26%, 51%] ($n = 13$)	Median 47% [−9%, 97%] ($n = 13$)	$p = 0.682$
Soil P	Mean 18% ± 8% ($n = 24$)	Mean 25% ± 14% ($n = 14$)	$p = 0.323$, d.f. = 36
Soil K	Median 11% [3%, 38%] ($n = 34$)	Median 6% [−3%, 143%] ($n = 19$)	$p = 0.379$
Soil organic carbon	Median 5% [−1%, 23%] ($n = 40$)	Median −2% [−6%, 11%] ($n = 24$)	$p = 0.054$
Electrical conductivity	Median 9% [−5%, 27%] ($n = 16$)	Median 26% [0%, 55%] ($n = 16$)	$p = 0.479$
Cation exchange capacity	$n = 2$, statistical testing not possible	$n = 2$, statistical testing not possible	
pH	Mean 0.22 ± 0.24 ($n = 19$)	Mean −0.26 ± 0.13 ($n = 18$)	$p = 0.002$, d.f. = 35 Significant difference in pH results indicates a weakly acidifying effect of SFs

[a] The significance for median values was determined using a Mann Whitney-U test, and for mean values, a 2 samples *t*-test was used.

between the total N (N_T) application rate of the fecal amendments and the yield across the 26 experiments which reported N_T and yield (Figure 6).

Effect of Fecal Amendments on Soil Parameters. Only two experiments met the criteria for High Quality soil methods (predominantly due to the short length of most studies), and so, the HQM subset could not be reported for soil parameters. Adding fecal amendments (FAs) significantly increased soil nutrients. Soil N was increased by a median of 33% [22%, 51%] ($n = 71$, $p < 0.001$), soil P by 26% [19%, 38%] ($n = 80$, $p <$

0.001), and soil K by 26% [15%, 47%] ($n = 102$, $p < 0.001$). These results are of limited use without also understanding the baseline soil nutrient status, the nutrient quantity applied, and the time between application and measurement in order to determine whether nutrients would build up or deplete over time. Insufficient papers reported on these parameters to establish a quantitative mass balance to determine the relative mass contribution of added nutrients and the partitioning of added nutrients between soil, plant, and environmental emissions.

Measures of soil organic matter and soil organic carbon were combined to create a larger data set, with the assumption that the two values are directly proportional,[65] which allowed for simple aggregation of the percentage-change data. FAs significantly increased soil organic C (SOC) by a median value of 19% [6%, 50%] ($n = 104$, $p < 0.001$) over the UCP, which was expected due to the direct addition of C from the fecal biomass. As with the soil nutrients, this finding is of limited use without the context of the C loading rates, baseline soil C, and time between application and sampling which were not possible with the data provided.

FAs significantly increased soil cation exchange capacity by a median value of 10% [5%, 33%] ($n = 24$, $p < 0.001$). FAs also significantly increased soil electrical conductivity by a median value of 15% [7%, 25%] ($n = 49$, $p < 0.001$); however, all soils began and remained below 4 dS/m, which is considered the threshold for a "saline" soil,[66] and so, salinization effects were not concerning.

FAs did not significantly alter soil pH, median change = 0 [0, 0.08] ($n = 93$, $p = 0.064$). Plants have an optimal soil pH for growth which generally falls between 6 and 7 due to nutrient availability,[67] and so, it is important to consider the proportion of results which took the soil pH toward or away from this optimal range. Of 93 data rows, 19 (20.4%) made alkaline soils more alkaline, with a median change of +0.3. Seventeen (18.3%) made acidic soil more acidic, with a median change of −0.2. Twenty-seven (29.0%) altered soil pH toward the optimum range with a median change of ±0.12, and in 30 (32.3%) cases, both the control and treatment plots remained within the optimum range, with a median change of ±0.05. This indicates that FAs exhibit a weak neutralizing effect on soil pH.

DIRECT COMPARISON OF FECAL AMENDMENTS AND SYNTHETIC FERTILIZERS

Twenty-nine experiments directly compared the effects of fecal amendments (FAs) to synthetic fertilizers (SFs) while controlling for all other experimental variables. Excluding FA treatments, which were enriched with synthetic fertilizers (FA_{NPK}), and limiting only to studies which used comparable N_T application rates between the FA_o and SF treatments reduced this number to 18 papers, which comprised 72 FA data rows and 45 SF data rows.

Table 7 offers a summary of the overall effect of FA_o treatments as compared to their paired SF treatments.

Figure 7 shows the relative yield performance of FA_o and SF treatments. Although SFs exhibited a higher median yield, the difference between the two data sets was not found to be statistically significant ($p = 0.208$).

Only 9 experiments reported pH changes for paired FA and SF plots. Overall, the FA_o increased pH by a mean change of 0.22 ± 0.24 ($n = 19$), and SF decreased pH by −0.26 ± 0.13 ($n = 18$), showing a significantly more acidifying effect of SFs as compared to FAs ($p = 0.002$).

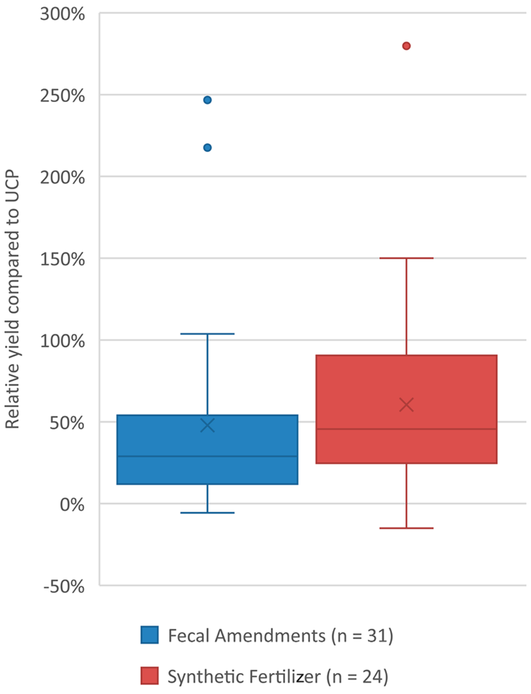


Figure 7. Box plot showing the relative yield performance achieved by the application of fecal amendments (FA_o) and the application of synthetic fertilizer (SF) against the unamended control plots across 14 paired experiments.

DISCUSSION

The major finding from this analysis was that fecal amendments (FAs) derived from on-site sanitation systems not only have a positive impact on crop yields when compared to unamended control plots (median increase of 79% [60%, 97%], $n = 188$) but also produce crop yields that are not significantly different to synthetic N-based fertilizers ($p = 0.208$). This finding was confirmed by the high quality method (HQM) subset of the data, which found FAs to improve crop yield by a median value of 49% [33%, 70%] ($n = 45$) over the control.

This finding opposes the view that feces-derived, or indeed any other organic, amendment could never produce yields that rival synthetic fertilizers,[68,69] a narrative commonly cited in defense of the continued use of synthetic fertilizers.

These comparable yields were observed within relatively short time scales, predominantly single cropping cycles, which challenges previous findings showing that organic amendments are slower-acting than inorganic ones[70] and that transitioning away from synthetic fertilizers would take multiple years, causing yields to decline temporarily before the soil and wider ecosystem is restored sufficiently to support plant growth.[71−74] One reason for comparable yields could relate to antecedent soil nutrient status (depleted soils that respond well to either fertilization treatment), residual soil fertility, either from inherent properties of the soil type or from over application of nutrients from previous land uses.[75−77] Reporting baseline soil fertility measures and conducting longer studies would therefore be necessary to determine the relative contribution of antecedent nutrient status and residual soil nutrition versus the amendments.

No positive relationship was observed between fecal amendment N_T application rate and crop yield, which indicates that crop yield is determined by a complex range of factors and that crop nutrition requires greater attention than simply using conventional practices which emphasize N loading rates.

Another key finding was that fecal amendments increased soil organic carbon by a median of 19% [6%, 50%] ($n = 104$) over the unamended control. The difference in soil organic carbon between fecal amendment and synthetic fertilizer treatments became significant at a 90% confidence interval ($p = 0.054$), with FAs exhibiting a null to large increase in soil carbon (median = 4.8% [−1%, 23%] ($n = 40$)) and SFs exhibiting conflicting trends, with results ranging from a slight decrease to a moderate increase (median = −1.7% [−6%, 11%] ($n = 24$)).

This positive effect is expected due to the direct addition of the organic matter within the FAs, but organic amendments have also been shown to stimulate above- and below-ground productivity, further contributing to soil carbon sequestration.[78] Increasing soil organic matter has been extensively linked to higher crop yields[29,30] due to beneficial impacts on soil structure, microbiology, and nutrient cycling.[25,27,28] These benefits could help to explain the comparable yields observed between fecal amendments and synthetic fertilizers, although these effects were unexpected within such short time scales.[73]

Overall fecal amendments exhibited a slight neutralizing effect on soil pH, which contrasted with the acidification effect of synthetic fertilizers. This is beneficial because the low pH of acidic soils can reduce the availability of macronutrients and may also affect microbial activity.[79] This tentative finding is consistent with other studies[80] and suggests another benefit of fecal amendments over synthetic fertilizers, particularly for already acidic soils.

Fecal amendments also significantly increased soil N, soil P, soil K, electrical conductivity, and cation exchange capacity (all $p < 0.001$). These findings are less useful in isolation without an understanding of baseline soil conditions, the soil type, and the intended agronomic function of the land; however, none of the results indicated any alarming negative effects of fecal amendment application.

Consistency with Wider Literature. These key findings are consistent with studies which compared other forms of organic amendments with synthetic fertilizers. Edmeades[58] reviewed 14 field trials ranging from 20 to 120 years and concluded no significant difference in crop productivity between (animal) manured and synthetically fertilized soils. Additionally, manured soils had higher measures of soil organic matter, microfauna, porosity, hydraulic conductivity, and aggregate stability than synthetically fertilized soils. The topsoil was also more enriched with P, K, Ca, and Mg, and the subsoil was more enriched with nitrate N, Ca, and Mg. Te Pas and Rees[81] conducted a meta-analysis of 88 papers comparing different farming practices, which were grouped as either organic or conventional, and found that overall organic practices saw higher yields (+26%), profits (+51%), and soil carbon (+53%). In contrast, de Ponti et al.[82] conducted a meta-analysis of 362 organic/conventional comparisons and found on average that organic practices yielded lower (−20%) than conventional practices, although the range was large (−80% to +77%). Both papers observed differences in yield across other factors, including location, climate, soil, income level, crop type, and study duration, but no strong causal relationships were suggested.

Regarding sewage sludge biosolids, Ippolito et al.[83] conducted a 22-year field study which found that biosolids improved soil chemical and biological health indices compared to inorganic fertilizers. Cioca et al.[84] reviewed biosolids applications in Romania and found that they increased crop yields and reduced costs compared with SFs. A review by Lu et al.[45] concurred that biosolids use in the USA produced "similar or higher yields than inorganic fertilizers, especially when applied for multiple years". These findings lend support to a wider adoption of organic amendments, including fecal amendments, with a particular focus in contexts where they offer superior performance to synthetic fertilizers.

Limitations and Data Gaps. *Language.* The authors acknowledge that limiting the Review to papers written in English will omit some studies from the analysis; however, this is not anticipated to have a directional effect on the findings since the included studies cover a large geographical and climatic distribution.

Study Length. The lack of studies lasting for more than a single cropping cycle is a crucial gap in our knowledge of the effects of fecal amendments and weakens the conclusions that can be drawn from this analysis. The value of agricultural experiments increases with time[85] as longer studies better simulate the reality of adopted farm practices and are less susceptible to annual fluctuations in farming operations. They are of critical importance in helping to understand how the soil system responds to management interventions over realistic time scales, especially for those soil characteristics which change very slowly. Longer studies also give greater insight into residual effects, such as accumulation of phosphorus[58] or heavy metals.[86] Unfortunately, long agricultural trials can be prohibitively expensive[70] and time-consuming, resulting in a lack of such studies particularly in low income settings.

Sample Size. Sample sizes for each soil and crop parameter were generally small even after synthesizing results across differing methodologies, which lowered the confidence of the findings; thus, all reported results should be interpreted with caution.

Soil Functions and Soil Health. Analysis of soil is difficult due to complex interactions between the lithosphere, biosphere, hydrosphere, and atmosphere. Analysis is also complicated by the fact that soil is geospatially variable in its properties and supports a wide variety of soil functions, which affects value judgments of which characteristics are desirable. Soil health attempts to simplify assessment of this complex interplay between soil properties and soil functions into a manageable set of measurements, but no universally agreed standard approach exists.[87,88] In this study, we adopt the FAO definition of soil health to mean the soil's ability to function as a living system and to sustain plant and animal productivity,[89] due to the focus of this work on assessing agronomic benefits of fecal amendments in a crop production system. Soil health is an analogy taken from medicine, which is widely used in public and policy discourse, as it is a useful concept for considering the overall state of soil to perform desired soil functions. The concept assumes that this state may be worsened or improved as a result of actions taken and can be assessed by the measurement of selected parameters. Attempts have been made to determine a standard set of measurable parameters to indicate overall soil health, ranging from highly complex to overly simple,[90−92] and there is general consensus for the need to include physical, chemical, and biological indicators.

In this Review, only 25 experiments (53.2%) measured any soil parameters and the studies were almost exclusively focused on chemical characteristics (Table 6). This lack of biological and physical parameters makes it impossible to comprehensively monitor soil health, and chemical measures are fairly meaningless in isolation, requiring interpretation regarding dynamic soil processes such as nutrient cycling. Organic matter is sometimes considered a proxy biological indicator as it indicates past or present biological activity and may positively correlate with true biological measures, like microbial biomass. As such, organic matter is often measured in place of other biological measures for simplicity, but common methods like loss-on-ignition lack a standardized protocol.[93] Physical measures, like density and porosity, help to quantify whether the soil is in a satisfactory condition to support life, and the presence of plants, soil microorganisms, and larger macro-invertebrates indicate a functioning ecosystem which is necessary for the cycling of nutrients and the conversion of organically bound nutrients into a plant-available form. Studies on other organic amendments indicate positive effects on soil physical[94] and biological properties[95] and therefore offer a baseline for comparison with future studies of fecal amendments.

Pot Trials. The inclusion of pot experiments may have affected results, as the most extreme outliers for crop growth and the highest variation across most parameters came from pot trials. Pot trials have been criticized for their inability to simulate reality[96] but are often cheaper than field experiments, easier to replicate, and easier to control environmental conditions.[97] Their contribution to scientific research is valid, but it is likely that their results translate less directly to in situ soil conditions at farm scale, and so, the results are less certain when guiding changes to farming practices and the expected impacts at field scale. This is likely a major reason the HQM subset of the data, which omitted pot trials, tended to show less extreme positive effects of fecal amendments on crop performance, since there are many more variables in the field such as weather and pest damage.

Sample Depth. Many studies failed to report the sampling depth which further limited the validity of the findings. Those which did often sampled to shallow depths and so may not have captured the entire active region. Fixed depth measures can also be problematic, particularly if the soil bulk density changes,[98] potentially leading to false conclusions; for example, if nutrients have moved below the sampling depth but remain accessible to plant roots, they may be incorrectly believed to be lost from the soil.

Data Standardization. The variation in experimental design, chosen parameters, and methods of measure made it impossible to aggregate the results across different studies without standardization. Calculation of percent-change relative to the unamended control plot was considered the best option, as it best controlled for all variables and is commonly used in agricultural studies due to its tangibility in practice;[58] however, it does have its own limitations. Using percent-change can magnify effect sizes when values for the control conditions are small; for example, a 3 cm difference in plant height is a much larger relative change for a seedling than for a tree. Interpretation of percent changes in values is also vulnerable to the control performing unexpectedly, which could make the treatment of interest appear very good or very bad, when in actuality the control and treatment values may fall within the expected range of random error or may result from systematic error that is not identified. To exemplify this point, the two most extreme yield outliers for FAs (+1677% and +1235%) in this Review were both from the same paper,[99] which studied tomato plants grown in pots over a 3 month period. It appears that the control plants performed incredibly poorly, producing just 3.1 g of tomatoes per plant, compared with 41.4 and 55.1 g for the two fecal amendment treatments. These high positive outliers and right skew were present in many studies across several parameters, invalidating the use of parametric statistical testing. Instead, the median was used as the main measure of central tendency as it is less vulnerable to these large outlier values, and reporting the 95% confidence intervals helps to give an indication of the spread of the data.

All agricultural systems are unique due to differences in soil, climate, crops, management practices, and other factors, and so, the studies included in this analysis can never be truly representative of every unique situation. Despite these limitations, the findings of this Review still provide guideline values for the expected effects of fecal amendments on some crop and soil parameters which can be used as a basis of comparison for subsequent studies.

WIDER IMPACT

Social Impacts. The findings of this Review indicate the realistic possibility of using feces as an alternative to synthetic fertilizers. Food security is defined as meaning that "all people, at all times, have physical, social, and economic access to sufficient, safe, and nutritious food that meets their food preferences and dietary needs for an active and healthy life".[100] Ensuring sufficient, nutritious food at all times is dependent on crop nutrient security, of which the stability of the source is of critical importance. While synthetic fertilizers do facilitate high yields of nutritious food, the dwindling availability of raw material,[16] the emissions associated with production and transportation,[101] the geopolitical risks to supplies,[102] international trade disruptions, and financial volatility[103] make them an insecure source of crop nutrition, as exemplified by the impacts of the Russian invasion of Ukraine in 2022.[39] In contrast, feces offer a sustained source of local crop nutrition, although challenges remain for processing, transportation, financing, and quality monitoring.[104] Trimmer et al.[14] identified that many of the world's least developed countries (LDCs) had high colocation of supply and demand, meaning that fecal amendments could form "meaningful connections between sanitation and agriculture with minimal transport requirements".

Additionally, reimagining excreta not as a waste but as a valuable product may help to promote better sanitation service provision. On-site sanitation systems and low-cost treatment methods like composting are appropriate for a wide range of contexts due to their simplicity, affordability, and low water requirements. An additional benefit from scaling up on-site sanitation is the reduced water demand as compared to sewers, which may reduce competition for agriculture and drinking water demand in arid regions.[105]

Environmental Impacts. Along with benefits for crop productivity, increasing soil carbon is a critical tool for tackling climate change,[106] as soil represents the world's largest carbon sink.[107] Addition of organic soil amendments represents just one method for sequestering carbon from the atmosphere,[35,108] and its net effect is dependent on the alternate fate of the amendment.[109] Ryals et al.[110] found that adding organic compost amendments to soil generated a net greenhouse gas sink with effects persisting for several decades. Additionally, organic amendments have been shown to stimulate above and below ground productivity, further contributing to carbon sequestration.[78] Replacing synthetic fertilizers with fecal amendments has the potential to offset the negative environmental impacts associated with their production, transport, and leaching.[15−18]

Economic Impacts. On-site sanitation systems are usually cheaper to implement than sewer systems[111] and the use of FA in agriculture offers an opportunity to establish a value chain. A review by Mallory et al.[55] found the scale of this potential revenue generation from excreta use to be inconsistent, and Diener et al.[112] determined agricultural use as a "low-value" reuse option. Despite this, there exist examples of self-funding financially viable models,[113,114] and even partial cost recovery could act as a driver for improved sanitation, especially when considered alongside all the other related social and environmental benefits. For farmers, fecal amendments could signify a cheap or even free source of crop nutrition, lowering their input costs and thus increasing profits. Improving soil health could also lower agrichemical input requirements like pesticides and fertilizers by improving nutrient cycling, disease resistance, and weed suppression,[115] which could further reduce input costs.

■ CONCLUSIONS AND RECOMMENDATIONS

This Review demonstrates that fecal amendments from on-site sanitation systems generally exhibit neutral to positive effects across a range of crop and soil parameters and, on average, produce similar yields to synthetic fertilizers when applied at a similar N loading rate. Adoption of ecological sanitation has the potential to address multiple Sustainable Development Goal targets beyond simply improving sanitation service provision and local crop nutrient security. It can help to realize a sustainable, circular economy for nutrition, whereby raw material input for the synthesis of chemical fertilizers is minimized, and the loss of nutrients from the system via excreta disposal is eliminated.

On-site sanitation systems coupled with simple treatment methods, like composting, can lower the energy and water demands associated with excreta management, and valorization of the end product may promote wider uptake, thus contributing to improved public health. Fecal amendments may offer an affordable, local alternative to synthetic fertilizers, thereby reducing farmers input costs and reliance on imported fertilizer prices and supply, thus improving profits without compromising on yield performance. Additionally, sequestering carbon into soil may help contribute to mitigating climate change. That said, notable barriers still exist to scale-up, particularly surrounding regulation of quality and safety, transportation, and financing.

This Review highlights the need for more long-term field experiments across a range of climatic, soil, and agricultural contexts. Future studies would also benefit from a more standardized approach to parameter selection and reporting. Yield remains the simplest and most tangible indicator of crop growth performance but should include reporting the duration of plant growth, sample preparation, and whether the yield was on a per-plant or per-area basis. Additionally, reporting crop nutrient content should be considered as an indication of crop quality, rather than focusing solely on quantity. Measures of "soil health" vary widely but should include measures of physical, biological, and chemical properties which are measured before and after the experiment, while considering the balance between thoroughness and simplicity when selecting parameters. Physical measures could include measures of soil structure including bulk density, porosity, soil water retention, water infiltration, and aggregate stability. Biological measures could include microbial biomass, microbial respiration rate, enzyme activity, fungal:bacterial ratios, and macroinvertebrate assessments. Chemical measures could include organic matter content and composition, pH, salinity, and a range of key plant macro- and micronutrients.

In addition to parameter selection, key experimental design features should also be reported. The characteristics of the amendment should also be reported, including major macronutrient and carbon content as well as its application rate, application method (e.g., surface applied or incorporated into the soil), and application timing (e.g., before or after planting, repeat or single applications). Any previous land uses should be reported as this may have residual effects on the study, and an assessment of the baseline soil characteristics should be conducted before beginning the experiment. The study duration should be reported as well as the timeline of key management events, including any extreme weather. It is recommended that all studies include an unamended control as part of their experimental design to facilitate easier comparison across different studies. Finally, the methods of sample collection should be reported, in particular the timing of the sample collection relative to the study start as well as the depth for soil samples. It is recommended that the selected depth exceeds the crop rooting depth and ideally is stratified at least into topsoil and subsoil layers, and care should be taken to avoid errors associated with fixed-depth sampling. A suggested checklist for future crop trials using fecal amendments is included in the Supporting Information.

■ ASSOCIATED CONTENT

Supporting Information

The Supporting Information is available free of charge at https://pubs.acs.org/doi/10.1021/acsestengg.2c00438.

Full list of the 45 papers included in the systematic review and their key experimental design features; summary of the results from the 47 experiments; a table of recommended study design and reporting considerations (PDF)

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CRediT: **Katie Allen** conceptualization, data curation, formal analysis, investigation, methodology, project administration, visualization, writing-original draft, writing-review & editing; **Erika L Rodríguez López** data curation; **Steven A. Banwart** supervision, writing-review & editing; **Barbara Evans** conceptualization, methodology, supervision.

Notes

The authors declare no competing financial interest.

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