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ORIGINAL ARTICLE

Evaluating the performance of humanure as a potting mix for lettuce (*Lactuca sativa*) seedlings

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Abstract

Composting human feces ("humanure") is a simple, affordable method for recycling waste, producing a material similar to commercial potting mixes. This novel approach contrasts with more common practices like biosolids application and wastewater irrigation, offering new opportunities for fecal reuse in horticulture and home gardening. This study evaluated the suitability of humanure as a potting mix for lettuce (*Lactuca sativa*) seedlings in an emergence experiment. Four humanure blends from small-scale composting systems were compared to two garden soils and a commercial potting mix as a control. Emergence speed and total emergence were combined into an emergence index (EI), and seedling size was measured after 25 days. Three of the four humanure blends performed comparably to the control, with EIs over 77.4 and leaf growth above 2.36 cm. The fourth blend, with a lower pH, had good emergence (EI = 53.4) but stunted growth (<0.84 cm). These results highlight the variability in homemade compost quality and the importance of proper management. Garden soils performed poorly in terms of emergence (EI = 12.2 and 7.6), with insufficient seedlings for statistical analysis on growth. This study demonstrates that small-scale composting of human feces can produce high-quality compost suitable for use as a potting mix. It also underscores the need for improved guidelines and regulations for the production and use of humanure beyond traditional sewage applications.

Plain Language Summary

This study tested whether compost made from human feces ("humanure") can be used as a safe and effective potting mix for growing lettuce. While humanure is often used to improve soil, its potential as a direct growing medium is less understood. In this experiment, lettuce seeds were planted in four different humanure blends, two garden soils, and a commercial potting mix for comparison. Three of the humanure

Abbreviations: ANOVA, analysis of variance; DAP, days after planting; EI, emergence index; EU, European Union; GHG, greenhouse gas; LL, longest leaf; OSS, Onsite Sanitation System.

blends performed just as well as the commercial mix in terms of seed sprouting and plant growth. However, one blend with low pH had slower growth. The garden soils performed much worse in comparison. This research shows that humanure can be a viable, sustainable alternative to commercial potting mixes, with benefits for waste management and reducing reliance on environmentally harmful peat-based composts.

1 | INTRODUCTION

Safe sanitation requires that fecal material is not only captured and treated, but also disposed of in a safe and environmentally responsible manner. However, the conventional approach to disposal, prevalent in many modern sanitation systems, is based on two flawed premises; (i) that excreta is a waste and (ii) that the environment can indefinitely assimilate these wastes (Esrey, 2001). This way of thinking often leads to resource recovery being an add-on to infrastructure, rather than a core part of the system design (Harder et al., 2020). An alternative approach is therefore to deliberately consider the recycling of human excreta as an essential component of a high-quality sanitation system. This is a crucial step in realizing a circular economy, and offers opportunities for innovation in solid fuels, biogas, electricity, material recovery, building materials, irrigation, and crop nutrition, alongside partial cost recovery (Carrard et al., 2021).

While manures, both animal and human, can pose environmental and health risks, and also produce large quantities of greenhouse gas (GHG) emissions (Cheng et al., 2022; Gao & Cabrera Serrenho, 2023; Wang et al., 2022), human manures are an inevitable by-product of living; a valuable resource that has been an integral part of good soil management throughout human history (Sugihara, 2020), which we are now wasting on an enormous scale.

Human excreta is generated in quantities of approximately 8.10 × 1011 kg/year of feces (Berendes et al., 2018) and 7.3 × 109 m^3/year of urine (Martínez-Castrejón et al., 2022). This is approximately between one-fifth and one-quarter of the quantity produced by livestock (Berendes et al., 2018; Penakalapati et al., 2017). Human excreta contains organic matter, water, and essential plant nutrients, making it well suited for crop production (Menegat et al., 2022; Mihelcic et al., 2011; Rose et al., 2015). Human feces generally contain higher phosphorus (P) and nitrogen (N) than the feces of many livestock animals (Rose et al., 2015). Trimmer et al. (2017) estimate that human excreta could meet 11%, 9% and 12% of synthetic N, P and K use respectively, and yet currently less than 15% of N and 55% of P contained within human excreta is currently estimated to be returned to cropland.

However, questions remain about the efficacy of human excreta products, warranting further research. To date, most research has focused on large-scale reuse of sewage treatment by-products; namely, wastewater (liquid portion) and biosolids (semi-solid sludge portion). Wastewater irrigation and land spreading of biosolids offer undeniable benefits to crop production (Athamenh et al., 2014; Ladwani et al., 2012; Lu et al., 2012; Singh et al., 2012), but face pushback over environmental and safety concerns, particularly with a more recent focus on micro plastics, persistent chemical pollutants, and antibiotic resistance (Delibacak et al., 2020; Hashem & Qi, 2021; Ofori et al., 2021; Singh, 2021; Singh & Agrawal, 2008). In contrast, research on fecal material from onsite sanitation systems (OSSs), such as pit, vault, and container-based toilets, is much scarcer, despite OSS being more common globally than sewer-connected toilets (WHO & UNICEF, 2021). The material from OSS is drier than sewage, and often less contaminated with other waste streams, such as industrial and medical effluents and storm water (Strande et al., 2014). Collecting, processing and reusing the products of OSS requires different management strategies when compared to large-scale land-spreading typical of biosolids, but may also offer unique reuse opportunities and benefits.

One potential option is the direct use of fecal-based products as a growing substrate for plants, which contrasts the more common application to land as a soil improver (Allen et al., 2023). A potting mix refers to the substrate used to grow plants in containers, a method that is commonly used for the sowing and seedling stage of annual plants, but may be used throughout the plants lifecycle. Potting mixes comprise primarily of organic materials, often blended with other organic and mineral materials, and are used in hobby and professional horticulture (Hirschler et al., 2022).

Horticulture is the growing of garden crops, usually vegetables, fruits, herbs, and ornamental plants, and contrasts with arable agriculture, which comprises field crops like cereals, sugars, oils, and beans. While it is difficult to measure the total contribution of global horticulture, in 2022 vegetables comprised approximately 13% of crop production by mass, at 1.2 billion tonnes, behind cereals (3.1 billion tonnes) and sugar crops (2.2 billion tonnes) (FAO, 2023). Additionally, cultivation under glass or plastic ("greenhouse cultivation") covered an estimated 1.3 million ha globally in 2019 (Tong et al., 2024), around 1/1000th of the estimated 1.5 billion ha of global arable land (Altieri & Nicholls, 2020). Though these numbers may appear small by comparison, it is important to consider that for the global food system and human diets, vegetables typically represent higher value crops and offer enormous nutritional variety (Ricciardi et al., 2018). Comparatively, approximately 40% of cereal crops are grown for livestock feed (FAO, 2023), and just three plants (rice, wheat, and maize) supply more than half of all human calories (Awika, 2011). While not all vegetable or greenhouse production will utilize container-based growing, nor rely on the import of manufactured growing media, these numbers offer a good introduction to the importance of this component of the global food picture.

Peat is a fossil material extracted from peatlands used for both energy production and as a key constituent of growing media, and its extraction accounted for 8.5 Mega-tonne (Mt) of CO_2 emissions in the European Union (EU) in 2021 (UN Climate Change, 2021). In 2013, peat comprised 75% of the total 34,609 km^3 of growing media produced in 16 EU countries, contrasting just 7.9% derived from composted materials (wood and green waste) (Schmilewski, 2017). Reducing peat use and developing renewable alternatives for growing media are essential elements of a GHG mitigation strategy for horticulture (Hirschler et al., 2022), and an important part of the global effort to feed a growing population while reducing environmental impacts (FAO et al., 2024).

Using fecal material as a growing medium offers a unique way to recycle this material and could provide an alternative to commercial potting mixes. The material from OSS well suited for the production of fecal compost, termed "humanure" (Jenkins, 2019). Composting is a simple and affordable treatment process, making it applicable at a range of scales, from home-production to commercial production, and in a wide range of global contexts. OSSs are commonly situated in rural areas and other locations where demand for this reuse stream may be high, such as individual homes, farms, campsites, parks, and tourist areas. This proximity alleviates a common issue of urban ecological sanitation systems, that material must be transported long distances from the place of production to the place of use (Shirai et al., 2023; Trimmer et al., 2017).

This research aims to enhance our understanding of the potential of humanure as a viable potting mix by conducting an experiment to compare the emergence and early growth of lettuce plants in various growing media. The study comprised four different humanure batches, two garden soils and a commercial peat-free potting mix. The garden soils acted as a "negative" control, simulating what a gardener might grow seeds in without the purchase or creation of a specialized growing media, in order to determine whether the humanure offered benefits to emergence and growth. The potting mix acted as a "positive" control and a quality benchmark in order to determine whether the humanure could perform comparably to a commercially available product. Through this comparison, the study seeks to evaluate the effectiveness of humanure as a growing medium to promote the healthy germination and growth of lettuce plants.

Core Ideas

- Composting human feces (humanure) offers a simple and safe way to turn this waste stream into a valuable resource.
- Humanure performed comparably to commercial compost for lettuce seedling emergence and early growth.
- Humanure offers a novel, sustainable alternative to commercial potting mixes for home and commercial horticulture.
- Proper compost management is crucial for consistent quality and safe reuse for food production.

2 | MATERIALS AND METHODS

Lettuce (*Lactuca sativa*), variety "Posavka" plants were grown in seven different substrates, each replicated five times and arranged in a randomized block design in a polytunnel in Leeds, UK. The origin and description of these substrates can be seen in Table 1.

All soils and composts were collected in March 2024. A representative sample of each of the three wheelie bin composters (H2, H3, and H4) was taken by tipping the compost onto a ground sheet and mixing with a spade, before approximately 0.1 m^3 was collected and stored in a rubble sack. H1 was an outdoor pile that could be mixed in situ. Gloves were worn to protect from possible pathogen transmission, and hands were washed after handling the humanure. The soil samples were collected from two gardens, a rural garden in Powys, Wales, and an urban garden in Leeds, Yorkshire. Five holes were dug to a depth of approximately 15 cm and excavated, totaling approximately 0.1 m^3.

Each substrate was used to fill five 22-cm diameter plastic pots, gently crumbled by hand into the pots to the fill line. A sample of each substrate was taken at the start of the experiment to determine the physical and chemical properties displayed in Table 2.

Substrate pH was measured using an Oakton pH 700 m. Moisture content was assessed by weighing the sample before and after oven drying at 105°C for 24 h. Organic matter was determined by loss-on-ignition; weighing the sample before and after heating to 550°C for 12 h. Bulk density was assessed by weighing the pots that were filled to known volume, and adjusting the value based on the moisture content. Inorganic nitrogen was assessed via extraction with KCl and assessment

TABLE 1 Source and description of each substrate used in the experiment.

Substrate code	Substrate type	Details
H1	Humanure	Humanure created onsite by residents of a housing co-op using a bucket system for containment and outdoor compost piles for maturation. Very fine sawdust bulking agent. 18 months old.
H2	Humanure	Humanure created onsite by a resident using a bucket system for containment and a wheelie bin system for maturation. Some food waste and other solid waste debris also added into composters. Sawdust bulking agent: >2 years old.
H3	Humanure	Created by volunteers and workers at an urban farm, using a bucket system for containment and a wheelie bin system for maturation. Coarse woodchip bulking agent: >2 years old.
H4	Humanure	Same production as H3, different batch.
S1	Garden soil	Rural garden lawn soil, uncultivated. Powys, Wales.
S2	Garden soil	Urban garden soil dug over for use as a vegetable patch. Leeds, West Yorkshire.
Com	Commercial potting mix	A bag of all-purpose potting compost purchased from a local garden center used as a control comparison.

TABLE 2 Physical and chemical properties of the substrates.

Substrate code	Textural class	pH	Dry bulk density (g/cm^3) ± SEM	Inorganic nitrogen concentration (mg/kg dry substrate) ± SEM	Inorganic nitrogen supplied (mg/pot) ± SEM	Organic matter (% dry substrate) ± SEM	Moisture (% fresh substrate) ± SEM
H1	Compost	5.33	0.10 ± 0.007	38.77 ± 2.24	19.28 ± 2.36	87.76 ± 1.75	74.14 ± 1.41
H2	Compost	8.42	0.22 ± 0.005	325.60 ± 74.15	338.49 ± 77.21	69.36 ± 1.30	77.12 ± 1.21
H3	Compost	7.33	0.16 ± 0.005	107.60 ± 10.40	81.89 ± 9.62	69.39 ± 1.04	74.40 ± 1.20
H4	Compost	7.43	0.17 ± 0.003	97.76 ± 14.07	75.79 ± 10.23	71.91 ± 0.59	78.21 ± 0.38
S1	Sandy loam	5.02	0.73 ± 0.016	24.67 ± 2.41	85.22 ± 9.75	11.49 ± 0.34	26.73 ± 1.07
S2	Sandy loam	6.85	0.62 ± 0.005	31.43 ± 4.99	93.07 ± 15.25	20.97 ± 1.19	31.42 ± 0.68
Com	Compost	7.22	0.10 ± 0.003	1368.32 ± 96.35	623.68 ± 30.95	84.18 ± 0.92	66.29 ± 0.52

on a Skalar SAN++ continuous flow auto analyzer. A more detailed breakdown of the forms of inorganic N present in each substrate is given in Figure S1.

Most of the substrates fell within a neutral pH range, from 6.5 to 7.5. H1 and S1 were moderately acidic (pH < 6) and humanure H2 was moderately alkaline (pH > 8). The compost substrates all had lower bulk densities, higher organic matter content and higher moisture content than the soils. The inorganic nitrogen concentration (mg/kg) total available within each pot (mg/pot) was highly variable across the substrates.

Six seeds were surface sown into each pot on April 12, 2024, totaling 30 seeds per substrate. The seeds were then covered with a layer of corresponding substrate to the next line (0.5 cm) before being watered in with a watering can. The four different humanure blends can be seen in Figure 1.

Emergence was monitored every day for the first 6 days, and then approximately every other day for a total of 24 days. At 25 days the longest leaf (LL) of each plant was measured. Watering and weeding were done manually throughout the experiment, and total weed count was recorded and is presented in Figure S2.

The number of days after planting (DAP) for the emergence of each shoot was used to calculate the emergence index (EI). The EI assigns weighted scores to emergence; the earlier a seedling emerges, the higher the weighting, which is more informative than focusing solely on final emergence percentage, since there is evidence that faster germination is correlated with healthier seedlings (Burris et al., 1969; Pinthus & Kimel, 1979).

The EI (Equation 2) was calculated across 24 days and was modified from the germination index equation (Equation 1), as recommended by Kader (2005). Germination refers to the protrusion of a radicle (root) from the seed coat, while emergence refers to a visible shoot above the soil surface.

$$GI = (10 \times n1) + (9 \times n2) + (8 \times n3) \ldots + (1 \times n10) \quad (1)$$

$$EI = (24 \times n1) + (23 \times n2) + (22 \times n3) \ldots + (1 \times n24) \quad (2)$$

where n is the number of seedlings which emerged on each particular day.

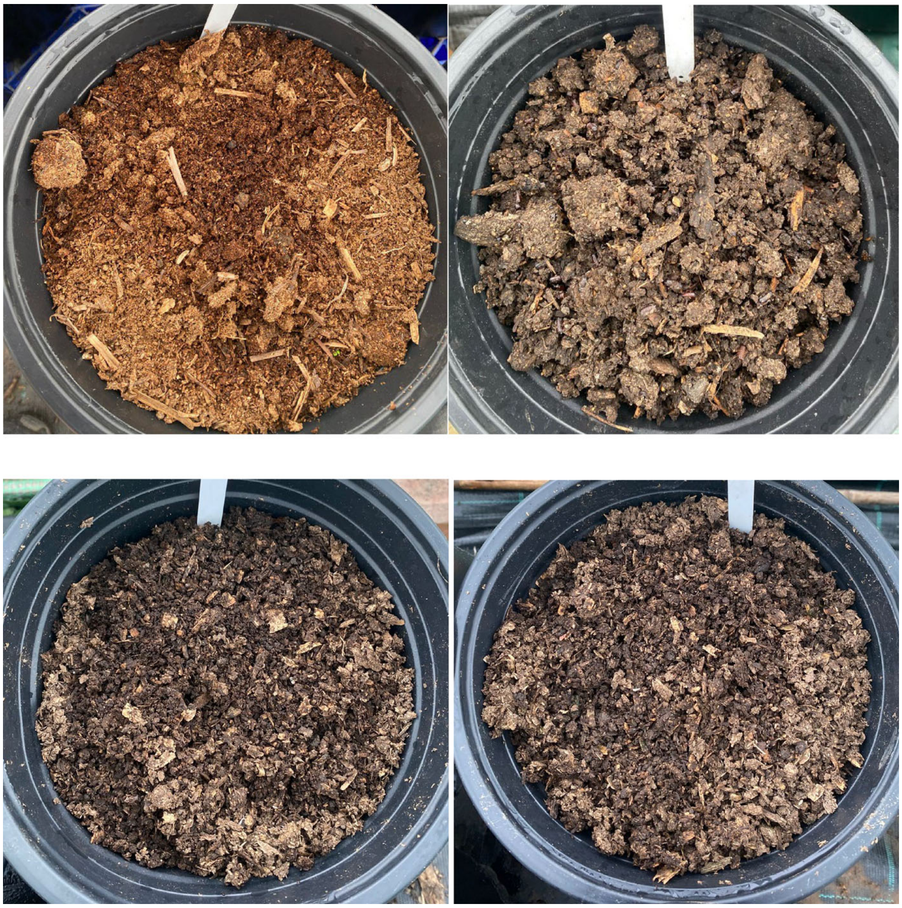

FIGURE 1 The four humanure substrates after sowing and first watering. H1 (top left), H2 (top right), H3 (bottom left), and H4 (bottom right).

Measurement of the LL on day 25 gave an indication of early seedling vigor. EI and LL both underwent *Z*-score normalization, which were averaged to give a combined *Z*-score that encompassed comparative emergence and growth aspects of the seedlings. The equation used to calculate *Z*-scores is given in Equation (3):

$$Z = \frac{x - \mu}{\sigma} \quad (3)$$

where Z is the normalized value, x is the raw score value to be normalized, μ is the population mean, σ is the population standard deviation.

Differences in results between the substrates were assessed using a one-way analysis of variance (ANOVA), followed by post hoc pairwise comparisons with a Holm correction in order to determine significance between individual groups.

3 | RESULTS

3.1 | Emergence index

When considered together, the four Humanure substrates (H1, H2, H3, and H4) achieved a final emergence of 76.7%. This was significantly higher than that achieved by the garden soils (S1 and S2) (15.0%, $p < 0.0001$). The commercial potting mix (Com) achieved 73.3% emergence, which was statistically similar to the humanure substrate ($p = 0.688$) and significantly higher than the soils ($p < 0.0001$; Figure 2).

We can observe that humanure H1 performed the worst of the four humanure substrates and was the only one to achieve a lower final emergence percentage than the commercial potting mix. This humanure was the least aged (18 months) and most acidic (pH 5.33) of the humanure substrates, which could be contributing factors.

When considering emergence speed, H2, H3, H4, and Com all had first emergence 5 DAP. H1 had first emergence at 6 DAP. The garden soils took twice as long to emerge, with S1 first emerging 10 DAP and S2 12 DAP.

Combining both speed of emergence and final emergence percentage gives the EI (Figure 3).

A one-way ANOVA found significant differences between the EI of the seven substrates ($p < 0.001$). Pairwise comparisons found that all four humanure substrates were statistically similar to the commercial potting mix and to one another at the standard significance level ($p > 0.05$). However, substrate H1 approached significance when compared to Com ($p = 0.0896$)

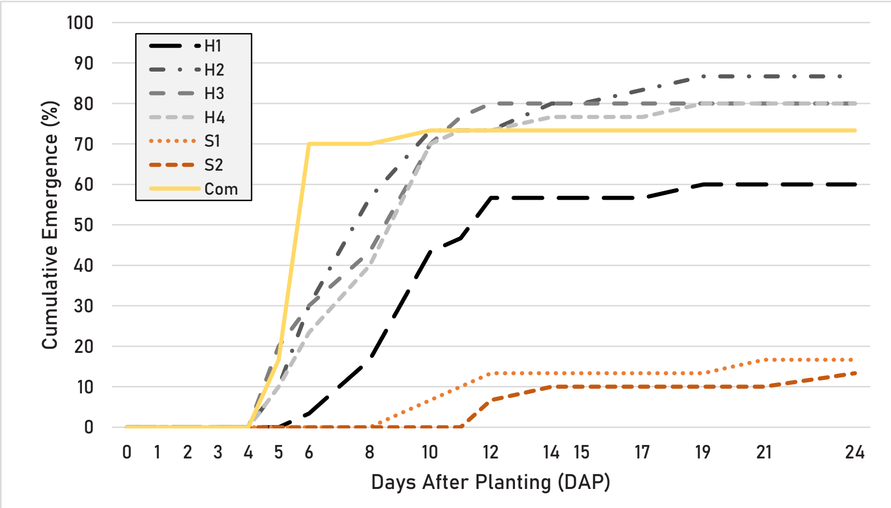

FIGURE 2 Cumulative emergence of lettuce seedlings over 24 days.

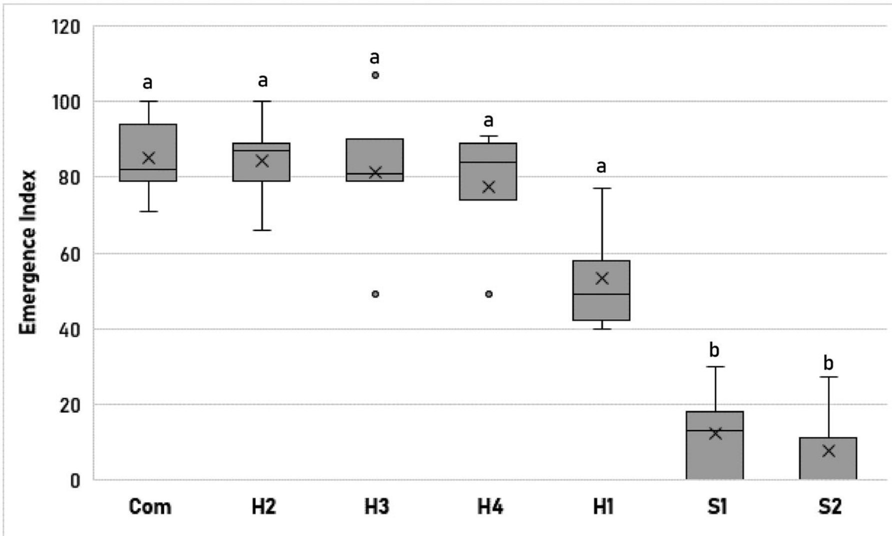

FIGURE 3 Emergence index score for each substrate. Statistically similar groups at a significance level of $\alpha = 0.05$ are shown with the same letter.

and to H2 ($p = 0.0856$), suggesting a trend toward a difference. While this does not reach the conventional threshold of significance ($\alpha = 0.05$), it is noteworthy that at a more lenient significance level ($\alpha = 0.1$), this substrate may be considered statistically different. All four humanure substrates at the commercial potting mix performed significantly better than the two soil substrates in all cases ($p < 0.05$).

3.2 | Longest leaf

The LL of each seedling was measured on day 25 (Figure 4). Slug destruction of lettuces meant that sample sizes were reduced by day 25, making statistical analysis of the garden soils impossible ($n = 2$).

A one-way ANOVA of the four humanure substrates and the commercial potting mix revealed significant differences between the groups ($p < 0.05$). A pairwise analysis found that humanure substrates H2, H3, H4, and the commercial potting mix were all statistically similar ($p > 0.21$), while humanure H1 was significantly lower than all of them ($p < 0.05$).

3.3 | Seedling *Z*-scores

The average EI and LL were normalized to produce *Z*-scores (Table 3). These Z-scores were then averaged together to give an overall combined performance of the seedlings within each substrate.

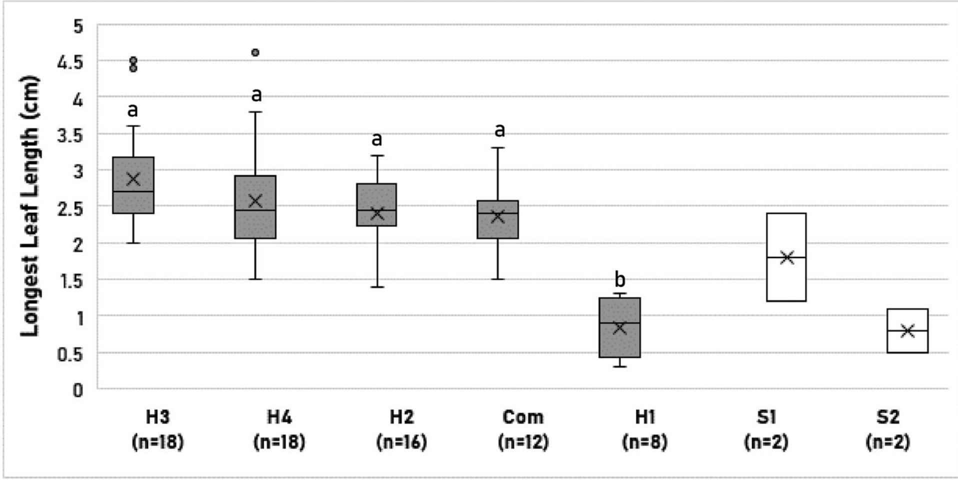

FIGURE 4 Longest leaf length of each seedling on day 25 of the experiment. Statistically similar groups at a significance level of $\alpha = 0.05$ are shown with the same letter. Due to slug damage, sample sizes for S1 and S2 were too small for statistical analysis ($n = 3$).

TABLE 3 Summary table of emergence index and leaf length results, and their *Z*-scores. These Z scores were then averaged to give a combined *Z*-score to indicate performance across both measures of growth. The low *n* values of S1 and S2 should be considered and are highlighted.

Substrate code	EI ± SEM	EI *Z*-score	LL (cm) ± SEM [*n*]	LL *Z*-score	Combined *Z*-score
H3	81.20 ± 9.45	0.70	2.87 ± 0.17 [18]	1.08	0.89
H4	77.40 ± 7.69	0.59	2.64 ± 0.19 [18]	0.81	0.70
H2	84.20 ± 5.65	0.79	2.41 ± 0.12 [16]	0.54	0.66
Com	85.20 ± 5.23	0.82	2.35 ± 0.15 [12]	0.46	0.64
H1	53.20 ± 6.73	−0.12	0.84 ± 0.15 [8]	−1.33	−0.72
S1	12.20 ± 5.70	−1.32	1.80 ± 0.60 [2]	−0.19	−0.75
S2	7.60 ± 5.30	−1.45	0.80 ± 0.30 [2]	−1.37	−1.41

As discussed previously, H2, H3, and H4 all performed well for both emergence and leaf growth, giving a combined *Z*-score, which was higher than the commercial potting mix. H1 performed poorly due to highly stunted leaf growth, and both garden soils performed poorly across both metrics.

4 | DISCUSSION

4.1 | Humanure effects on emergence and growth

This experiment found humanure compost to have a positive effect on seedling emergence speed and total emergence when used as a potting medium, as compared with garden soils. Humanure also performed comparably to commercial potting mix. Faster emergence is favorable as it is believed to correlate with healthier seedlings (Burris et al., 1969; Pinthus & Kimel, 1979). A final emergence value of 80% is a widely adopted benchmark within the seed industry to assess the quality of seed batches and the effectiveness of germination conditions, and above which is generally considered good quality. Humanure substrates H2, H3, and H4 all achieved or exceed this threshold, while H1 achieved 60%.

The superior performance of the humanure compost for emergence may be attributed to its favorable physical properties: high organic matter, low bulk density, and good moisture retention. Organic material has a loose, light texture, promoting good water drainage to prevent waterlogging, air circulation to support healthy root growth and limit fungal disease, and allows for easy root penetration, and as such is a critical component of commercial potting mixes. These physical properties appear to be more critical than the nutrient status of the soil for germination and emergence, with some studies even indicating that high nitrogen loading may actually inhibit seed germination (Zhang et al., 2020) but this is contradicted in other cases (Agenbag & de Villiers, 1989; Monaco et al., 2003; Pérez-Fernández et al., 2006). Considering lettuce specifically, Page and Cleaver (1983) found that increasing nitrogen fertilizer addition inhibited lettuce emergence, although the experimental N doses used were far in excess of the N quantities present in this experiment.

Humanure also showed promising results for early lettuce growth over 25 days, with H2, H3, and H4 all growing similar in size to the commercial potting mix. However, by contrast, humanure H1 showed severely reduced seedling growth, which indicates that the variation in characteristics between the different humanure composts may have affected their suitability as seedling composts. Early seedling growth is an important determinant of overall plant yield, particularly in plants harvested in the vegetative (leaf-producing) growth stage, including lettuce (TeKrony & Egli, 1991). The positive effect of humanure on growth was less pronounced than the positive effect on emergence, which is consistent with findings from Bekier et al. (2022) when growing lettuce seedlings in willow biomass compost.

After initial germination and emergence, seedlings transition from using energy stored within the seed to autotrophic photosynthesis (Deleens et al., 1984; Ha et al., 2017) as the plumule (first "true leaves") emerges. Around this time seedlings also begin to require nutrition from the soil environment. As such, the N content of the substrates may have had a larger influence on seedling growth than on emergence, which could explain the stunted growth of humanure H1, which contained the lowest inorganic N.

4.2 | Variation in compost characteristics

The four humanure substrates were produced in slightly different ways and had differing physical and chemical characteristics as a result. Humanure H1 showed the worst EI and growth of the four. It was the only outdoor compost pile and was the least aged, at 18 months old. By contrast, H2, H3, and H4 were all matured in wheelie bins and were at least 2 years old, which is a compliant with the World Health Organization's guidelines for ambient-temperature storage to ensure sufficient pathogen reduction for reuse (WHO, 2006). H1 was acidic (pH 5.33), while humanure H3 and H4 had a pH close to 7, and H2 was alkaline with a pH of 8.42.

Hemphill and Jackson (1982) found lettuce yield response to decline at pH below 5.6, or below 6.4 under higher N loading rates. Low pH limits the availability of key plant nutrients of N, P, and K, as well as sulfur, calcium, and magnesium (Roques et al., 2013). Acidic compost is indicative of immaturity, as pH drops in the early stages of composting due to the synthesis of intermediary organic acids by mesophilic microorganisms (Anda et al., 2008; Hubbe et al., 2010), before rising again as these acids are further broken down in the thermophilic phase. This pH drop is important for encouraging fungal growth to break down lignin and cellulose, but if systems are also insufficiently aerated, the pH may drop too low (<4.5), which severely limits microbial activity. However, this dip in pH usually occurs within the first few weeks of composting (Tchobanoglous et al., 1993), and so the low pH of compost H1 is surprising when considering the 18-month age of the compost. Another reason could be due to too much sawdust addition, indicated by the lower bulk density and higher organic matter content as compared with the other humanure composts, since most wood has a pH of 4.0–5.5 (Geffert et al., 2019). Sawdust addition was not standardized; instead, toilet users are encouraged to cover their defecation with sawdust after use. Another problem with high sawdust addition is creating a too high initial C:N ratio. This, along with drying out, which is common in open piles, can prevent thermophilic temperatures from being reached, and thus inhibit the succession of the composting process (Hubbe et al., 2010). High temperatures are essential for compost maturation, the destruction of weed seeds and pathogens, and to allow the conversion of organic material into stable humus (Hubbe et al., 2010).

The high pH of compost H2 may relate to the higher prevalence of ammonium (NH4) in the substrate, eight times more concentrated than in humanure H1. Humanure H2, H3, and H4 were managed the most similarly (2-year-old in-vessel wheelie bin composters with a more coarse bulking agent), and so the differences in pH and total inorganic N quantity are assumed to be caused by differences in the initial ratios of fecal material and bulking agent, while the higher relative proportion of nitrate in H2 is indicative of a more mature compost.

4.3 | Compost maturity

Maturity is a general term referring to a point at which a compost becomes stable and free from pathogens and phytotoxic compounds, and is predominantly a factor of time, temperature, and moisture content (Hill et al., 2013).

During aerobic decomposition, organic materials are broken down and transformed into simple compounds (e.g., CO_2, NH_4^+, and H_2O) and recalcitrant humic substances, including humin, humic acids, and fulvic acids (Andreux, 1996; Hayes & Swift, 2020). These stable compounds make up the vast majority of organic matter found in soils. Proteins are broken down first into ammonium (NH_4^+), before conversion into nitrite (NO_2^-) and then into nitrate (NO_3^-). Higher proportions of nitrate are therefore indicative of compost maturity, and are slowly released during the curing process, providing abundant, readily available plant nutrition (Hadar et al., 1985). We can therefore infer from Figure S2 that humanure H2 was the most mature, with an NH_4^+/NO_3^- ratio of 0.19. H3, H4, and H1 had a ratio of 0.83, 0.93, and 1.00, respectively. By comparison, a well-managed fecal sludge aerobic composting system can achieve NH_4^+/NO_3^- ratios of 0.20 (Rihani et al., 2010). The difference in maturity between the composts is notable, since they are all of a similar age, which indicates that differences in starting materials or in temperatures reached influenced the final compost characteristics.

It is commonly believed that immature compost may inhibit germination and growth due to the presence of phytotoxic compounds (Castro-Herrera et al., 2022), namely, ammonium ($NH4^+$). However, other studies have also found no influence of compost maturity on germination and growth (Bekier et al., 2022), with Warman (2013) finding immature composts to outperform control soils. Growers are also typically advised to avoid the use of compost alone as a direct potting mix, for fear of the high nutrient content burning seedlings, as well as fears of phytotoxicity. Instead it is usually recommended that compost is mixed with soil, sand, vermiculite, peat moss, or other material streams to create a potting mix, and that it should not exceed around 30% of the total mix (e.g., Gianfrancesco, 2020; Hashemimajd et al., 2004). For example, Öztekin et al. (2017) compared ratios of a compost comprised of cattle and poultry manure with straw, and found that the 100% compost performed worst for both germination and growth, and recommended a 25% compost to 75% peat ratio as optimal.

However, by contrast, Alexander (2009) studied the performance of amateur-produced green waste compost in different types of composting vessel, and found that the undiluted (100% compost) compost did not inhibit germination, and produced the highest tomato plant biomass, on par with the commercial peat-based and peat-free mixes. Additionally, Hadar et al. (1985) compared 100% cow manure compost of different maturities to 100% peat and found no difference in germination across all substrates. They even found that the mature and immature cow manure compost far outperformed peat in producing tomato plant biomass. Yet despite these results, they still concluded that "for practical application, it is usually recommended that composts are mixed with peat," which further drives this common narrative.

We can therefore state that mature compost, indicated principally by a reduction in ammonium-N and pathogens, and influenced by feedstock ratio, age, temperature, and moisture (Hill et al., 2013), is likely to confer the most benefits to plant germination and growth while minimizing possible harmful effects (Hadar et al., 1985). The findings of this study support the assertion than human fecal material and sawdust can create a well-performing potting medium if properly composted. However, practical challenges remain for small-scale or home-made composting systems to reach the required temperatures (~55˚C for days/weeks) to produce a good quality compost product, which Hill et al. (2013) report are rarely seen in practice.

4.4 | Research and policy implications: Humanure as a compost product

Although the practice of using human feces for food production is an ancient one (Rockefeller, 1998; Shirai et al., 2023; Sugihara, 2020), the direct use of fecal material as a growing medium is not well studied nor is research relating to products from OSSs. Instead, most research focuses on nutrient extraction from waste streams to substitute synthetic fertilizers (Sengupta et al., 2015), instead of utilizing the entirety of the resource (Harder et al., 2019), which wastes the huge intrinsic value of the organic matter. When considering whole-material reuse, most attention is focused on use as a soil amendment, as opposed to as a direct growing medium (Allen et al., 2023; Budiyanto & Prabasari, 2023; Nyakeoga, 2015; Trimmer et al., 2019).

The primary aim of this study was to evaluate the effectiveness of humanure compost as a potting medium for emergence and establishment of lettuce seedlings. The results showed that humanure performed comparably to commercial potting mix, which indicates a promising reuse pathway and may offer an abundant and low-cost growing medium for pot-based growing and seedling establishment in home or commercial settings. However, the poorer performance of one of the humanure blends, along with conflicting evidence in literature about the effects of compost on plant growth, indicate that compost products are highly variable depending on feedstock (Ali et al., 2019; Huang et al., 2017; Song et al., 2014) and processing method (Alexander, 2009), and thus warrants further research into quality compost production (Salomon et al., 2021).

The use of fecal material in food production does not come without risk, but steps can be taken to reasonably minimize these risks. Ensuring appropriate temperatures and/or storage times are reached during composting is the first step to creating a pathogenically safe material. Effective composting requires temperatures of around 50˚C–60˚C to be reached for successful transformations by thermophilic bacteria (Azim et al., 2018; Hubbe et al., 2010; Nakasaki et al., 1985). Higher temperatures also serve to inactivate pathogenic organisms more quickly (Espinosa et al., 2020); however, since high temperatures are rarely or inconsistently achieved in home-compost systems (Hill et al., 2013), the WHO guidelines suggest that sufficient pathogen die-off for agricultural reuse will be achieved after 2 years of storage at ambient temperatures (WHO, 2006).

Other concerns relate to the possible presence of toxic or other harmful substances within the material. These substances could pose risk to human or environmental health, such as water pollution or soil contamination. While sewage sludges can contain high levels of contaminants from sources beyond household toilet material (Fijalkowski et al., 2017), source-separated toilet material is expected to contain much lower concentrations of certain contaminants. Typically, the inputs to these systems are more localized and so can be better controlled. However, due to the importance of this topic and the large number of possible contaminants more research is needed to identify the major substances of concern, which persist in this resource stream (Carter et al., 2024).

If intended for commercial sale and for application in commercial food growing, then further research and policy development are required. The monitoring and regulation of treatment and reuse practices vary globally; however, in the United Kingdom, the reuse of biosolids is legislated under The Sludge (use in agriculture) Regulation 1989. Presently there are no established guidelines for the reuse of humanure, which creates a barrier to adopting this practice. For sale as a compost product, appropriate standards must be created and adopted, which already exist in several countries. In the United Kingdom all compost must be certified under the PAS100 standards, however, these standards currently do not accept toilet material as an input material, making the commercial production and distribution of humanure compost impossible (Environment Agency, 2012). This differs from other regulations (e.g., the Canadian Fertilizer Act), which permit more input materials, including toilet material, and instead evaluate the quality of the final compost product for certification. Adapting the UK regulations to follow this approach would allow for the commercial composting of more organic waste streams while still ensuring a safe and high-quality end-product.

Composting is a simple and affordable technology applicable across a range of contexts, which utilizes the entirety of the toilet material, aligning with zero waste and circular economy principles. Two notable enterprises stand as excellent examples of commercial humanure production: SOIL, Haiti, and Sanergy, Kenya. Both offer sanitation services and collect the fecal material for central production of humanure for resale. The findings of this study and the commercial examples above, are promising and especially relevant for low- and middle-income countries and rural areas where OSSs are prevalent. The resulting compost from this process is well suited for local-scale reuse, but legislation and monitoring must be strengthened to help facilitate this reuse and ensure it is done safely.

AUTHOR CONTRIBUTIONS

Katie Allen: Conceptualization; data curation; formal analysis; investigation; methodology; project administration; visualization; writing—original draft; writing—review and editing. **Effie Papargyropoulou**: Supervision; writing—review and editing. **Ruth Wade**: Conceptualization; supervision; writing—review and editing. **Barbara Evans**: Conceptualization; supervision; writing—review and editing.

CONFLICT OF INTEREST STATEMENT

The authors declare no conflicts of interest.

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SUPPORTING INFORMATION

Additional supporting information can be found online in the Supporting Information section at the end of this article.

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