The Power of Poop: Human Excreta as a Bio-Based Fertiliser in the Netherlands

Achieving circular agriculture through the investigation of environmental and food safety

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Abstract

To achieve a circular economy, where ‘waste’ products are repurposed to mitigate the loss of nutrients, energy, and resources, human excreta (HE) must be handled differently. Humans are the largest consumers of agricultural products, and until they contribute as many nutrients as they take from the soil, a circular system will not be possible. There are hesitations about reusing HE due to concerns about pharmaceutical, chemical, and pathogenic contamination, and their potential to not only disturb the soil environment but also transfer into crops intended for human consumption, thus re-entering the food chain. This thesis investigates the risks associated with these types of contamination and explores the efficacy of treatment options to ensure food safety. The impact of involuntary exposure to chemical compounds and the risk of bioaccumulation in circular systems are also examined. For HE-derived BBF to become a well-accepted agricultural tool, it must meet or exceed the expectations and results farmers receive from chemical fertilisers. This research explores the extent to which HE can function as a sustainable yet effective fertiliser in the Netherlands, considering the country's nitrogen-saturated and soon-to-be phosphate-limited soils. Given nutrients are currently rarely recovered, they instead add to environmental pollution in the forms of gaseous emissions, leaching, or eutrophication, thus stressing the importance of development in this area. The third prong addressed in this thesis is the barriers that may impede the implementation of HE-based circular sanitation, including legislative, economic, and sociocultural factors. The conclusion emphasises the importance of policy change to include quality-controlled HE-derived fertiliser and the continued need to broadly address concerns regarding the presence of pharmaceuticals and other contaminants in HE in order to realise its full potential as an environmentally supportive and food-safe BBF.

Keywords

Human excreta, decentralised sanitation, bio-based fertilisers, Dutch nitrogen crisis, circular economy

Acronyms and Abbreviations

AD: Anaerobic Digestion
ADI: Acceptable Daily Intake
AGC: Amsterdam Green Campus
ARB: Antibiotic-resistant Bacteria
ARG: Antibiotic-resistant Genes
As: Arsenic
BBF: Bio-based Fertiliser
C: Carbon
Ca: Calcium
Cd: Cadmium
CF: Chemical Fertiliser
CFU: Colony-forming Units
CE: Circular Economy
CM: Cow Manure
CO_2: carbon dioxide
Cr: Chromium
Cu: Copper
DM: Dry Matter
EDI: Estimated Daily Intake
EPA: Environmental Protection Agency
EU: European Union
FAO: Food and Agricultural Organisation
Fe: Iron
HCO_3^-: bicarbonate
HE: Human Excreta
HFC: Human Fecal Compost
Hg: Mercury
HM: Human Manure
HMO: Human Manure from Organic eaters
Mg: Magnesium
N: Nitrogen
NEI: Net Economic Income
NEEI: Net Ecosystem Economic Income
NH_3: ammonia
NH_4^+: ammonium
Ni: Nickel
NO: nitrogen oxide
NO_x: nitrogen oxides
N_2O: nitrous oxide
NUE: Nitrogen Use Efficiency
OM: Organic Matter
P: Phosphorus
Pb: Lead
PM: Poultry Manure
STH: Soil-transmitted Helminth
TTC: Threshold of Toxicological Concern
TP: Transformation Product
UASB: Upflow Anaerobic Sludge Blanket
WHO: World Health Organisation
WWTP: Wastewater Treatment Plant
Zn: Zinc

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Introduction

Humans are the largest consumers of agricultural products (Foley, 2014), and until they start contributing as many nutrients as they take from the soil, a circular economy (CE) and agricultural systems will not be possible. Using human excreta (HE) as a bio-based fertiliser (BBF) is one way to repurpose and valorise a material previously thought by many to be ‘waste’ and best managed by removing it entirely from sight and mind. There are, however, valid concerns for the transmission of pharmaceuticals and their metabolites into plants intended for human consumption and accumulation in or disruption of the soil due to HE contamination. People today are highly medicated (Jacobson, 2021), chemicals are used liberally, and involuntary exposure to pharmaceuticals and pollutants is high (Piña et al., 2018). Evaluating the risks posed by compounds found in HE and the efficacy of treatment options to rid the BBF thereof will underscore the extent to which HE-fertilised crops can meet food safety requirements for consumers and farmers, whether urban or rural, commercial, or local.

Threats to the environment and long-term food security turn a scrutinous eye on the nutrient content of soils in the Netherlands. The Netherlands is the world’s second-largest exporter of agricultural goods (Ministerie van Buitenlandse Zaken, 2021) and has a dense livestock population (~116 million in 2021), leading to excess animal manure in the country (Centraal Bureau voor de Statistiek, 2023). Implementing circular sanitation (CS) can be justified from several angles. The heavy agricultural demand in the Netherlands has caused hyper-enrichment of soils through (chemical) fertilisation and diffusion of nitrous gases from the atmosphere, calling for the Dutch government to commit to reducing the livestock population by 30% by 2030 (Boztas, 2021). Although there is currently no demand for more nitrogen (N) in agriculture in the Netherlands, with the eventual reduction of livestock populations, this is a possible future scenario in which many countries already find themselves. Although the Netherlands is not an example of this, many soils around the world are indeed nitrogen deficient due to losses from crop harvest, gaseous emissions, runoff, erosion and leaching and would benefit from supplementation from an organic fertiliser like HE (FAO & ITPS, 2015). In the case of the Netherlands, phosphorus (P) will become the limiting variable in more (agricultural) systems and finding ways to recover enough P to meet demand will be essential. HE is richer in P than other fertilisers and should be explored as a feasible nutrient recovery pathway (Faridullah et al., 2015). However, it remains vital to ascertain that using HE as a BBF is a positive addition to the soil microbiome and effectively returns appropriate ratios of nutrients to the soil.

Investing in CS research and implementation is an opportunity to provide underserved people with hygienic and sustainable sanitation and create circular solutions to proactively oppose inevitable nutrient deficiencies with the purpose of safeguarding agricultural prosperity in the Netherlands and beyond.

This leads to the research question: To what extent can human fecal excretions be used as an environmentally supportive/sustainable and food-safe bio-based fertiliser in the Netherlands?

A complex challenge in this investigation is whether specific barriers, such as financial, sociocultural, and legislative, will prevent the implementation of circular sanitation. Unless HE can outcompete chemical fertiliser (CF) in terms of productivity and profitability, implementation will be near impossible, considering agricultural livelihoods depend on good crop yields (Tur-Cardona et al., 2018). Today, a ‘fecophobic’ mindset has varying origins: from a real threat of death and disease to negative cultural or moral symbology accompanying excreta (Buit & Jansen, 2016). Reckoning with fecophobic narratives, cultural ideologies, and psychological stiffness regarding the valorisation of ‘waste’ will be pivotal challenges to overcome to achieve social acceptance and normalisation of HE as a BBF.

In countries with less strict legislation or in rural areas with minimal monitoring, HE use may occur with less restriction. However, in the Netherlands, a lack of specific regulation and legislation governing its collection and use hinders implementation. In other European nations, legislation remains unclear, and the absence of definitive frameworks hampers the potential for innovation in this space (Joveniaux et al., 2022). Updating and harmonising existing fertilising regulations on a national and international level to include HE-derived products would be a crucial step in ensuring its safe and controlled use (Chojnacka et al., 2019).

Methods

This thesis will take the form of a literature review, using academic papers related to the field published in or translated into English or Dutch. Articles and papers will be sourced from Google Scholar and BASE, using a varying combination of the following keywords: *human excreta* OR *human manure* OR *human feces,* AND *(bio-based) fertiliser OR xenobiotics OR food safety OR circular economy OR ecological sanitation OR nutrient cycling.* These keywords have been selected due to their presence in the research question and relevance to the literature scope sought. A 'snowballing' technique will also be employed to consider relevant papers cited in the aforementioned texts. No publication date exclusion criteria will be used, given the limited research into areas explored in this thesis. Relevant news articles, media, and press releases will also be considered due to the pertinence of this topic as a rapidly developing topic of interest. A criteria-based framework will be created to visually represent critical factors affecting HE's feasibility as a BBF in the Netherlands.

This literature review investigates the intersection of several blossoming fields of research, namely eco-toxicology, innovative agriculture, and circular economy. The diversity of forms that research in these fields takes allows this investigation to serve as a comprehensive compilation of existing findings that address the research question and set the scene for future research. For example, researchers at Amsterdam Green Campus (AGC) are being funded by the Municipality of Amsterdam to undertake practical laboratory and greenhouse experiments to ensure the safety of human feces as a BBF for food intended for human consumption. Before this, the AGC team is curious about what information is already published on this topic to side-step avoidable pitfalls and design their experiments effectively by already having a comprehensive knowledge base. Contributing to this foundation will be an added purpose of this literature review.

1. Ensuring Food Safety and Minimising Xenobiotic Contamination in Circular Agriculture

Transfer of contaminants from human excreta (HE) to soil and plant tissue intended for human consumption is a significant concern for its functionality as a food- and farmer-safe fertiliser. This section will explore the occurrence and risk that antibiotics, other pharmaceuticals, their metabolites, and environmental pollutants pose to human consumers and people exposed to the agricultural environment. Additionally, the threat of pathogens from HE will be explored and evaluated, alongside a discussion of potential mitigation and treatment strategies to make HE-based BBF suitable for agricultural use.

Some studies in this section employ the threshold of toxicological concern (TTC) methodology to classify compounds based on their genotoxic potential, meaning their potential to affect DNA. It is a conservative estimate based on “5% of the level at which there are no observed adverse effects with an additional 10^{-6} uncertainty factor” (Malchi et al., 2014). Class I compounds have simple structures and are easily metabolised, whereas Class II are likely more harmful than Class I but do not contain structural features indicative of toxicity, such as reactive functional groups, as those in Class III do (Malchi et al., (2014). A benefit of this approach is that it takes the possibility of chronic exposure to a mixture or cocktail of pharmaceuticals into account and is adapted for people at higher levels of risk (children and pregnant or elderly people) (Malchi et al. (2014).

1.1. Antibiotics

Antibiotics have been a revolutionising and often life-saving therapeutic intervention that inhibit the growth of bacteria that cause infectious diseases (Patangia et al., 2022). However, their excessive or inappropriate prescription, in combination with administration in the veterinary and agricultural industry, means that they are often present in excretions, thus enter sewage systems and, eventually, biological environments (Miguez-Suarez et al., 2022; Zhou et al., 2022). Understanding the potential risks associated with antibiotic contamination of HE will be essential in ensuring safe implementation. Due to a lack of studies investigating the presence of antibiotics specifically in raw HE, evaluating the threat they pose will be conducted through papers exploring their presence in sewage sludge, animal manure, and wastewater and, subsequently, the effect of their application on agriculture. Similarities in antibiotic classes prescribed to animals and humans and the congruence in the composition of sewage sludge and raw HE largely allows for conclusions to be transferred between waste types and management systems. Table 1 illuminates that antibiotics of animal- or sewage sludge-origin measured in upcoming studies are also used in human medicine and thus may conceivably be found in HE as well.

Table 1

Antibiotic Classes, Examples, and Their Applications in Human Medicine

Antibiotic Class	**Example**	**Example Use in Medicine**
Sulfonamides	Sulfamethazine (Zhou et al., 2020; Pan & Chu, 2017)	Sepsis, gonorrhoea (Vardanyan & Hruby, 2006)
Fluoroquinolones	Norfloxacin (Pan & Chu, 2017, Boehme et al., 2004)	Urinary tract infections, pyelonephritis (Joost, 1986; EMA, 2018)
Tetracyclines	Tetracycline (Pan & Chu, 2017; Liu et al., 2009)	Chlamydia, acne (Shutter & Akhondi, 2020)
Broad-spectrum antimicrobial	Chloramphenicol (Chen et al., 2018)	Typhoid fever, superficial eye infections (Oong & Tadi, 2022)
Macrolides	Erythromycin (Pan & Chu, 2017, Piña et al., 2018)	Pneumonia, syphilis (Farzam & Quick, 2019)
Aminoglycosides	Gentamicin (Boehme et al., 2004)	Septicaemia, meningitis (Chaves & Tadi, 2020)

Note. This table takes examples of antibiotics found in waste (human, livestock, or sewage) and aligns them with their treatment use in human medicine. The intention is to emphasize that although some of these studies in this section investigated animal manure, the same antibiotics treat humans and thus can possibly be found in human excreta as well.

Animals do not absorb and metabolise antibiotics well, and as such high concentrations are found in animal manure globally, with one study finding 36.3% of manure-based fertiliser samples to contain one or more types of antibiotics (Zhou et al., 2020). Most (veterinary) antibiotics are water soluble and are therefore incompletely absorbed by the body, with one study finding that 17-75% of chlortetracycline was excreted in manure in its unchanged form (Chen et al. 2018) and another finding significant antibiotic residues of 75-90% being excreted from the body (Pan & Chu, 2017). A study investigated the potential of five different (classes of) antibiotics to transfer from wastewater and animal manure into soil and plants (Pan & Chu, 2017). Tetracycline, sulfamethazine, norfloxacin, erythromycin, and chloramphenicol-contaminated wastewater and animal manure were used to irrigate and fertilise different crops. The pharmaceuticals investigated in this study are select agents of overarching classes of antibiotics, which in most cases are also used to treat infections in humans as well (See Table 1).

Pan & Chu (2017) found that for tetracycline, norfloxacin, and chloramphenicol, the order of contamination from greatest to least was fruit > leaf/shoot > root, whereas the opposite applied for sulfamethazine and erythromycin (root > leaf/shoot > fruit). Tetracycline and norfloxacin were present in high concentrations in the edible parts of the plant due to their high tendency to adsorb to surface soil, allowing for increased uptake (Pan & Chu, 2017). Erythromycin remained in the plant's root due to its large molecular weight, and sulfamethazine had overall minimal uptake in that it was poorly retained in the surface soil and not taken up in the plant (Pan & Chu, 2017). Daily exposure to the five tested antibiotics through vegetable consumption ranged from 0.64 to 150 ng. The concentrations of antibiotics that reached the edible parts of the plant were much lower than the acceptable daily intakes (ADIs) set by the Food and Agricultural Organization (FAO) of the United Nations set as 5.7, 11.4, and 10.0 mg/kg body weight for tetracycline, norfloxacin, and sulfamethazine respectively (Pan & Chu, 2017). For reference, 150 ng is equivalent to 0.00015 mg, and with a hypothetical body weight of 75 kg, approximated daily intake would be 0.01125 mg. As such, they conclude that the risk of antibiotic exposure through plant matter treated with wastewater or manure-amended fertilisers is minimal (Pan & Chu, 2017). However, Piña et al. (2018) stress that sulfonamides (of which sulfamethazine is a constituent), and macrolides (of which erythromycin is representative), deserve special attention and caution during the reuse of wastewater due to their respective potential to conjugate with other human metabolites and recalcitrancy in soil. They further warn that current parameters measuring antibiotic risk, such as the TTC method, may have to be adjusted to incorporate new knowledge of potential genotoxicity and carcinogenicity (Piña et al., 2018).

It was also found that soil and crops treated with contaminated wastewater had higher uptake of antibiotics in the crops, which they attribute to the constant antibiotic exposure that occurs via irrigation, compared to a limited number of exposures via fertiliser application (Pan & Chu, 2017). This supports the argument that applying a solid fertiliser, such as a HE-based BBF, would yield greater food safety despite the risks of antibiotic contamination. The findings of Pan & Chu alone cannot guarantee the food safety of crops treated with manure-based fertiliser as the concern for the transfer of antibiotic-resistant genes (ARGs) is still present, yet the very low levels, relative to established ADIs sustain the position that the threat at hand may be very small, in particular when compared to the level of insecurity posed by the inability to feed the world's inevitably growing population.

1.1.1. Antibiotic Resistance

The spread of antibiotic resistance is a threat of paramount importance to human health. The mobile nature of antibiotic-resistance genes (ARGs) elevates this threat in the soil and human ecosystem (Zhou et al. 2020) because it allows for the vertical and horizontal spread of genetic information that encodes for bacterial resistance (Boehme et al., 2004). Resistant genes can be spread vertically via clonal dissemination, whereby a specific clone, strain, or variant is spread via bacterial replication, or horizontally between different isolates, species, genera, or kingdoms due to contamination (Boehme et al., 2004).

Boehme et al. (2004) investigated the spread of antibiotic-resistant bacteria (ARB) from animals to humans via the food chain by screening ‘common vegetables’ typically eaten raw for different kinds of bacteria found in human and animal excreta, such as coliform bacteria and enterococci and the extent to which they possess antibiotic resistance (Boehme et al., 2004). Sprouts (freshly sprouted/germinated vegetable seeds usually from legumes, radishes, or broccoli), compared to other vegetables, like lettuce and tomatoes, had significantly higher bacterial contamination levels (Boehme et al., 2004). Of the bacteria found on the vegetables, 43% were resistant to tetracycline, 29% to chloramphenicol, 26% to kanamycin, 37% to streptomycin, and 4% to gentamicin. Interestingly, washing the vegetables did not significantly reduce the overall bacterial count, measured in colony-forming units (CFU)/g of coliforms (Boehme et al., 2004). Given this potential for ARB (like coliforms, for example) to carry ARG and contaminate vegetables, it is crucial to consider their pharmaceutical translocation potential to ascertain their threat to food safety.

The location of pharmaceutical translocation in plants is relevant when assessing the food safety of a fertilisation technique. Piña et al. (2018) showed that plants grown in soil contaminated with sulfonamides have the potential to internalise ARB and ARGs, given these were both found in the leaves of the plants (Piña et al., 2018). This points to the need for special consideration of what plants or crops are grown using a HE-BBF. The interesting element that these studies bring to light is the potential for ARB (i.e., coliforms) originating in HE that carry ARG on transferable elements to contaminate crops (especially their edible portions) fertilised with the excreta. Subsequent human consumption of contaminated vegetables could lead to increased antibiotic resistance through (potential) colonisation of the gut microbiome and further contribute to the public health crisis involving ARB (Piña et al., 2018).

Further to the effects that antibiotics have in terms of ARB and the transmission of ARGs, their presence has been found to depress seed germination and crop growth, along with evidence found for their assimilation into crops (Zhou et al., 2020). For example, Liu et al. (2009) found sulfonamides to strongly affect rice growth and tetracyclines and sulfonamides to inhibit seed germination (Liu et al., 2009). In isolation or a “cocktail” (combination) situation, antibiotics and other pharmaceuticals show lower rates of germination, growth, photosynthetic rate, and chlorophyll content (Piña et al., 2018). They also are more likely to have tissue deformities and exhibit phytotoxic effects, with a high possibility of the combination of concerning compounds amplifying their detrimental effects (Piña et al., 2018). Besides this, pharmaceutical compounds are disruptive in the soil environment regarding microbiome content and function. The treatment of HE to remove harmful pharmaceuticals will be essential in reducing deficits in crop growth and reducing the risk they pose to human and soil ecosystems.

1.2. Non-Antibiotic Pharmaceuticals

Häfner et al. (2023) compared two nitrified urine fertilisers and one human fecal compost (HFC) while cultivating white cabbage plants. Initial screenings of the HFC found an extremely wide range of pharmaceuticals, with diphenhydramine (antihistamine), salicylic acid (anti-inflammatory), gemfibrozil (for high cholesterol), and allopurinol (to treat gout), in the highest concentrations. A secondary test was conducted with a more adapted set of target compounds, which showed lower results of the aforementioned compounds, and gemfibrozil and naproxen (an anti-inflammatory) were below the level of detection. Conversely, carbamazepine (an anticonvulsant) was higher, with many metabolites present. Ibuprofen was also not detected in the initial screening but was present at low levels in the second, making these the only two pharmaceuticals found in the cabbage plant. Localisation of pharmaceuticals in the plant varied, and carbamazepine was predominantly found in the outer leaves of the plant (2.80 µg kg^{-1} dry matter (DM)), which are typically not consumed, compared to the head of the cabbage (1.16 µg kg^{-1} DM), thus may pose less risk to food safety. An interesting addition is that the concentrations of carbamazepine found in the HFC (1.4-7.767 µg kg^{-1} DM) were several magnitudes lower than that found in sewage sludge (680 µg kg^{-1}) or chemical fertiliser (67.3 µg kg^{-1}), indicating that HFC may be a safer alternative fertiliser, than the aforementioned (Häfner et al., 2023; Krause et al., 2021).

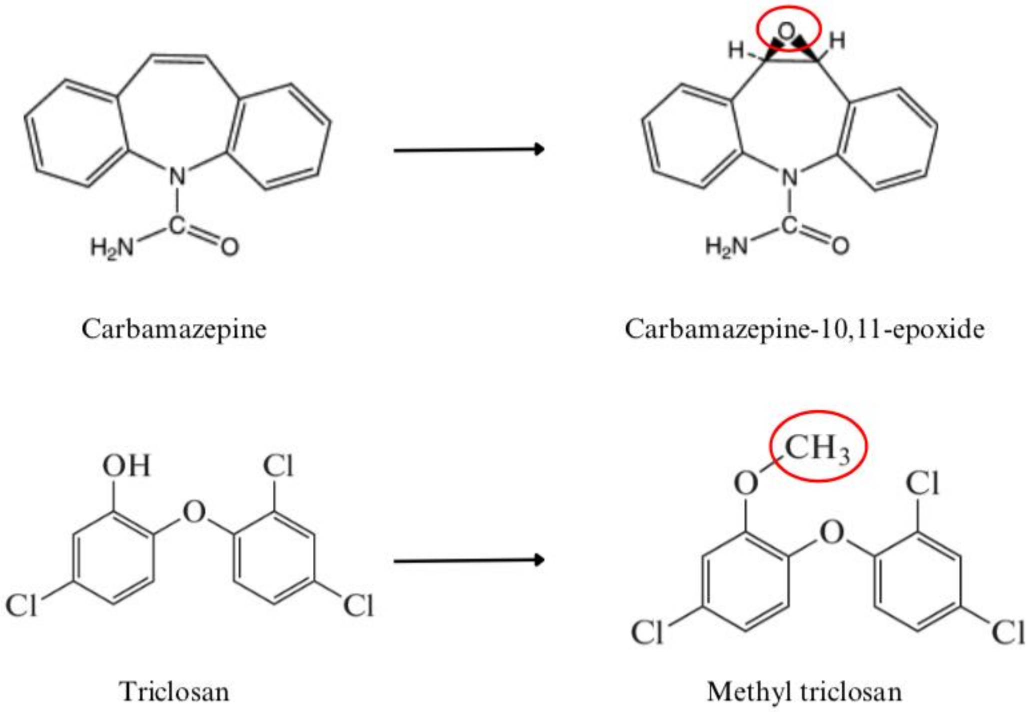
Malchi et al. (2014) found that when plants were grown in treated wastewater, nonionic pharmaceuticals (those without electric charge) were present at significantly higher concentrations than ionic compounds (Malchi et al., 2014), likely attributable to ionised compounds permeating cells with ease (Piña et al., 2018). Malchi et al. (2014) employed the TTC framework to evaluate toxicological threat and found that lamotrigine's (an anticonvulsant just like carbamazepine) TTC level could be exceeded through a child consuming half a carrot. This is an alarming result compared to Häfner et al., who found carbamazepine to pose a much lower threat. However, the difference in source from wastewater (Malchi et al., 2014) compared to fecal compost (Häfner et al., 2023) should be considered, further supporting the notion that HFC is a safe BBF option.

1.2.1. Metabolites of Pharmaceuticals

Wu et al. (2010) reports that carbamazepine was detected in the leaves of soybeans and tomato plant but not in the bean or tomato itself. This appears at first to be good news, yet further research elucidated that although the parent compound carbamazepine was not found, its metabolites did accumulate in the fruit/bean part of the plant (Wu et al., 2010). This exemplifies that although a substance is undetectable, one cannot necessarily conclude that it was eliminated or destroyed but must contend with the possibility that it exists in another (transformed) state (Díaz-Cruz et al. (2003). Many metabolites, also called transformation productions (TPs) (Piña et al., 2018), accumulate and induce (adverse) effects in soils and sediments (Díaz-Cruz et al. (2003). In most cases, TPs are less toxic than their ‘parent’ compound. However, there are situations where TPs can be equally or more toxic than the original compound (Boxall et al., 2006). Malchi et al. (2015) critiqued the work of Prosser & Sibley (2015) for failing to consider this very point. In particular, they stressed the elevated genotoxic potential of carbamazepine-10,11-epoxide (TP of carbamazepine) and methyl triclosan, TP of triclosan, a widely used antimicrobial agent in household products (See Section 1.3.1) (Malchi et al., 2015; Nie et al., 2020). As shown in Figure 1, it only takes a small modification during metabolisation to alter the toxicity of the compound. Both compounds have been found in significantly higher concentrations than their parent compounds in plant tissue. A previous study by Malchi et al. focused explicitly on the metabolites of carbamazepine as an environmentally persistent pharmaceutical compound, confirming carbamazepine-10,11-epoxide to be present in all roots, leaves, aqueous soil extracts, and soils (Malchi et al., 2014). This is an important finding because it asserts that only measuring parent compounds in plants, soils, or fertilisers may underestimate the bioconcentration factor of metabolites and, thus, the risk that these pose for human consumption and food safety.

Figure 1

Transformations of Carbamazepine and Triclosan to their Metabolites



Note. These transformations demonstrate small changes (circled in red) in chemical structure having large toxicological differences. Adapted from Trager (2007) and Tenkov et al. (2021).

The interactions between pharmaceuticals, their metabolites, and other (synthetic) organic compounds during co-occurrence is a pertinent avenue to consider in assessing food safety, yet it has been frequently overlooked in favour of studying compounds individually (Malchi et al., 2015). Boxall et al. (2006) refer to a study where lincomycin (a powerful antibiotic) co-occurred in water bodies with 27 other synthetic compounds. Given the assumption that water transfers to soil and a percentage is translocated into plant tissue, the mixture of contaminants is a reason for concern. For example, many antibiotics, like those mentioned in Table 1, interact with other pollutants they come into contact with, for example, metals and their cations, to form complexes and chelates, which modify and complicate their environmental fate and implications for the food safety (Boxall et al., 2006). Studies like that by Prosser & Sibley (2015), which conduct risk assessments for compounds in isolation, have been heavily criticised for being poorly representative of real-life application or contamination scenarios (Malchi et al., 2015). Despite Boxall et al. using the same methodology, they, alongside Malchi et al. (2015), both argue that the cocktail effect of pharmaceutical compounds should be investigated and additional uncertainty factors should be applied to ADIs. This practice will avoid underestimating the threat to human health that consuming contaminated products has by accounting for the potential genotoxicity, metabolic, or compounding effects of a mixture of pharmaceutical compounds. Further, the TTC approach may be more suitable given its consideration of exposure to a mixture of compounds (Malchi et al., 2014). This may also be most applicable in testing HFC, HE-BBF, or the crops grown with them, as pharmaceutical contamination in isolation is unlikely.

1.2.2. Endocrine Disrupting Pharmaceuticals

Endocrine-disrupting agents, like pharmaceuticals containing sex hormones like oestrogen, progesterone, and testosterone, are excreted by humans largely via urine in conjugated and unconjugated forms. Much like commonly taken pharmaceuticals such as Ibuprofen, concerns are raised about the effect of the contraceptive pill, composed of 17α-ethinylestradiol, if HE is to be used as a fertilising agent. The origins of these concerns are illuminated by Díaz-Cruz et al. (2003) through the example of the emission of ethinylestradiol into aquatic ecosystems, which led to macroscopically identifiable alterations to male and female reproductive organs in carp species (Díaz-Cruz et al., 2003). Furthermore, recent links between oestrogen pollution and breast and prostate cancer (Adeel et al., 2017), and the fact 720 kg of synthetic oestrogens are excreted by 60 million people every year, cements the undoubted reason for concern and further research in this area (Combalbert & Hernandez-Raquet, 2010).

Oestrogens and progesterone in wastewater are adsorbed to sludge particles and tend not undergo biotransformation, thus not extending their environmental fate (Huang & Sedlak, 2001). These findings support the notion that human excreta is a relatively low-risk source of hormone transfer to soil and plants. Especially compared to ruminants, that mainly excrete oestrogen via feces, human feces pose a low risk considering 95% of (synthetic) oestrogen is excreted in urine (Combalbert & Hernandez-Raquet, 2010). Although hormonal contamination could occur if human urine and feces are not collected separately, the finding of hormones tending not to undergo biotransformation due to adsorption lessens this risk. Furthermore, in the instance of contamination, Combalbert & Hernandez-Raquet (2010) report that ethinylestradiol can be eliminated by abiotic nitration, whereby nitrogen oxides (NO_x) are produced at high concentrations of ammonium (NH_4^+) (See Figure 2). Eliminating hormones from fecal matter still requires more investigation, with some conflicting conclusions being drawn in relation to the effect of temperature in composting. Gomes et al. (2009) found a correlation between a decrease in temperature and the inhibition of conjugated hormone hydrolysis, meaning hormones remain bound to (organic) matter at low temperatures. This finding potentially complicates the treatment process of fecal compost, which usually involves elevated instead of decreased temperature. However, Bartelt-Hunt et al. (2013) found that in cow manure, 79-87% of steroidal hormones were able to be removed through composting and argue for composting as a “viable manure management strategy” (Bartelt-Hunt et al., 2013).

1.2.3. Involuntary Exposure to Pharmaceuticals

Involuntary exposure to pharmaceuticals has also been shown to occur via drinking water (World Health Organization, 2012). Involuntary exposure to pharmaceuticals is a health hazard because of the potential for unknown combinations of exposure and conjugation with other drugs or pollutants to occur with unknown effects (Piña et al., 2018). When individuals are prescribed medication (for example, an antihypertensive for high blood pressure), they are told what other medications they should not take (Ibuprofen, for risk of kidney damage) (University of Waterloo, 2022). In the case of involuntary exposure, people are not granted this disclaimer. Piña et al. (2018) refer to a study demonstrating that carbamazepine and its metabolites can be found in the urine of people consuming vegetables irrigated with reused wastewater who were otherwise completely unmedicated.

Using liquid chromatography-tandem mass spectrometry, Miguez-Suárez et al. (2022) found 21 different drugs in water intended for human consumption, including anti-inflammatory, antihypertensive, antitumoral, and psychiatric medications. Further to this, the same study found six out of 25 volunteer fecal samples to contain antibiotics ranging from 10 to 456 ng/g when they had reported not having taken a pharmaceutical compound in at least two months. Curiously none of the volunteers whose fecal sample contained antibiotics followed a vegan or vegetarian diet, supporting the argument that consuming animal products leads to exposure to pharmaceutical residues (Miguez-Suárez et al., 2022). In addition, it is important to consider the impact of pharmaceutics on the gut microbiota; mice exposed to low doses of antibiotics had increased (harmful) proteobacteria and decreased (beneficial) *Bifidobacterium* and *Lactobacillus* (Miguez-Suárez et al., 2022). Especially if this alteration of the microbiome is occurring without consumers' knowledge, they are unlikely to take steps to remediate the impact. This indicates that populations are exposed to pharmaceuticals, antibiotic or not, through various sources. To ensure HE is as food- and environmentally-safe as it can be, these other avenues of contamination need to be addressed.

1.3. Household Products and Environmental Pollutants

In a preliminary screening of HFC, Häfner et al. (2023) found a diverse presence of household products, including, but not limited to, flame retardants, UV filters, rubber additives, and insect repellents (Häfner et al., 2023). Similarly, McClellan and Halden (2010) found 38 different pharmaceuticals and personal care products in biosolids from 94 wastewater treatment plants

(WWTPs), with all of the samples containing at least 26 different compounds (McClellan & Halden, 2010). When considering WWTPs, it is important to consider that human excreta only contributes a fraction of the influent, with the rest stemming from greywater (whatever goes down the sink or shower), industrial runoff, rainwater from street drains, and more (European Environment Agency, 2023).

1.3.1. Household Compounds

Triclosan (See Figure 1) is a broadly used antimicrobial agent with applications in various household products, from toothpaste to kitchenware and furniture to cosmetics (Nie et al., 2020; U.S. Food and Drug Administration, 2020). Given its ubiquitous presence in water, there is reasonable concern for its potential to contaminate soil and crops grown therewith. Nie et al. (2020) conducted experiments using a radioactive isotope of carbon (C^{14}) to trace its movement in soil and the crop, in this case, a peanut plant, selected due to its early maturation time and high rank as a cash crop in the United States (Nie et al., 2020). They measured the bioconcentration factor to be, from highest to lowest concentration: roots > stems > leaves > fruits. This result, alongside the finding that uptake of triclosan into the plant was 1.02 ± 0.17% at the time of harvest (after 120 days), points to a low-risk assessment of compounds like triclosan. Given its wide use, triclosan has a well-researched ADI of 83 µg/day/kg body weight, yet calculations by Nie et al. (2020) give the estimated daily intake (EDI) from peanuts to be 0.082 µg/day/kg body weight. Although this is a positive outcome for the human health risk assessment, the fact that 99% of triclosan remains in the soil is a potential issue for bioaccumulation in a circular agricultural system and overall soil health. As most people, at least in high-income countries, are exposed to triclosan and drugs like it regularly, it is nearly certain that it will continue to be present in HE going forward. Considering the potential for HE to be employed as a fertiliser in a closed agricultural system, compounds that persist in the soil environment are likely problematic, despite the minimal risk they seem to pose to human health.

1.3.2. Microplastics

Microplastics are defined as “synthetic solid particles or polymeric matrices...ranging from 1 µm to 5 mm of either primary or secondary manufacturing origin [and] are insoluble in water” (Campanale et al., 2020). Fecal analyses by Pérez-Guevara show that microplastics are found in excretions after organisms ingest them. As microplastics travel through the digestive system, they undergo digestive fragmentation and microbial-facilitated plastic degradation, which can extend microplastics’ lifespan, make them bioavailable to other organisms, and perturb the soil environment (Pérez-Guevara et al. 2021).

Microplastics are a foreign addition/xenobiotic in the soil environment, and their migration within and beyond the soil depends on the characteristics of the plastic (size, shape, degradation status) and the properties of the soil such as cracks, macropores and biotic presence (Pérez-Guevara et al. 2021). Microplastics can interact with other compounds like minerals and silicates and absorb pollutants like pesticides or herbicides. Furthermore, chelation, a type of chemical bonding involving one or two coordinate bonds (Flora & Pachauri, 2010), can occur with (toxic heavy) metals, leading to an unpredictable environmental or health-related risk potential (Pérez-Guevara et al. 2021). The emission of microplastics or the conjugates they form can be highly contaminating if they reach water sources or lead to “growth inhibition, genotoxic and oxidative damage, and reduced germination” in plants (Pérez-Guevara et al., 2021).

Fecal matter containing microplastics can serve as a vector for further contamination of the environment and accumulation through trophic levels (Pérez-Guevara et al. 2021). Human feces were studied by Schwabl et al. (2019) and Zhang et al. (2021) to investigate the involuntary consumption of microplastics through food and other sources. Although Schwabl et al. (2019) have a small sample size of eight fecal donors, they found all samples to contain microplastics, with a median of 20 microplastics/10 g of HE, ranging from 50 to 500 µm in size. The threat of microplastics accumulating when HE is applied to soil limits the realisation of circular agriculture. If intakes of microplastics from other sources, like drinking water and animal products, is not eliminated, humans will continue to be regularly exposed to microplastics and thus produce microplastic-contaminated feces, which may be taken up in the plant and then consumed by humans, thus perpetuating the cycle of contamination.

1.3.3. Heavy Metals

Heavy metals are an umbrella term for metals and metalloids with high density and a tendency for toxicity (Ali & Khan, 2017). Some heavy metals (iron (Fe), zinc (Zn), and copper (Cu), for example) are essential in the body due to their function as catalytic enzymes for metabolic processes which regulate health and disease (National Research Council (US) Committee on Diet and Health, 1989). Essential heavy metals are non-toxic in trace amounts yet become harmful if exceeding a threshold (Slobodian et al., 2021). The rest of the heavy metals have no biological function and are toxic even in trace amounts, and include aluminium, cadmium (Cd), mercury (Hg), arsenic (As), and lead (Pb) (Slobodian et al., 2021; National Research Council (US) Committee on Diet and Health, 1989).

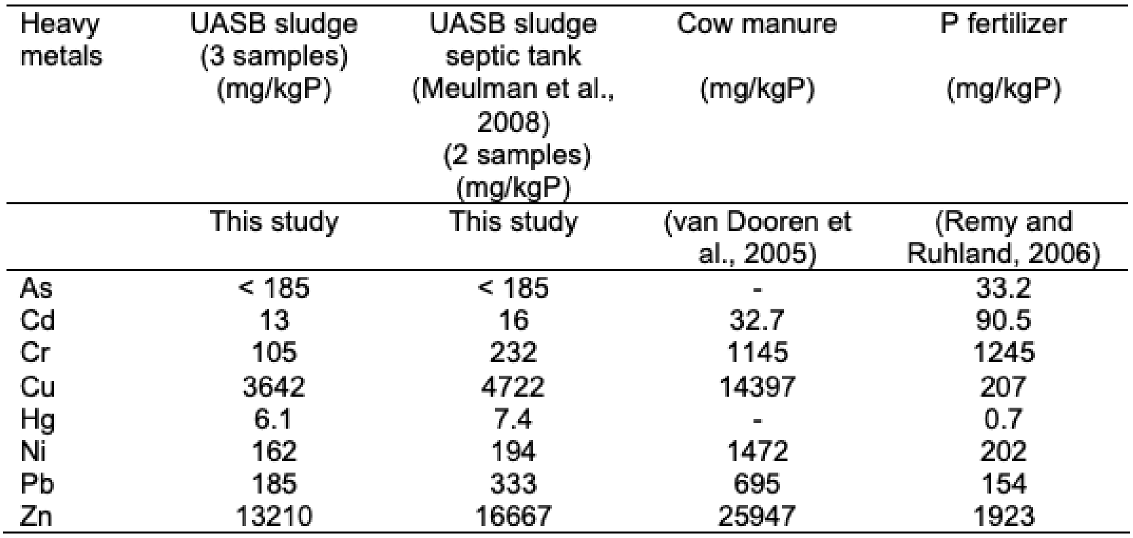
Concerns regarding heavy metal contamination must be overcome to ascertain the safety of HE for use as fertiliser for human-consumable crops. A key difference in the makeup of vacuum-collected blackwater (waste and water exclusively from toilets) and sewage sludge is the origin of the heavy metal content. In source-separated toilets (See Figure 4), HE contributed 52-84% of the heavy metal content, whereas, in sewage sludge, less than 10% originates from HE (Tervahauta et al., 2014). This points to HE being only a minor contributor to the heavy metal content in sewage. Koch and Rotard (2001) explain this phenomenon, stating that tap water is the greatest source of heavy metal loading in municipal sewage, particularly contributing to Cu and Zn concentrations (Koch and Rotard, 2021).

Furthermore, high contributions of Pb and Cu to sewage sludge are from flush water, with concentrations 50-200 times greater than that of blackwater, which is attributable to the materials used in piping (Tervahauta et al., 2014).

For several reasons, blackwater sludge from vacuum-collected source-separated toilets is a better option for reducing heavy metal content in soils and plant matter than current fertilisers. It has significantly lower heavy metal content than cow manure and lower levels of As, Hg, Pb, Cd, and chromium (Cr) as compared to phosphate (P) fertilisers (de Graaff, 2010). These results can be seen in Table 2, showing cow manure to have higher levels of Cd, Cr, Cu, Zn, and nickel (Ni), and chemical (P) fertiliser to have higher levels of Cd, Cr, and Ni, being compared to both sludges anaerobically digested with an Upflow Anaerobic Sludge Blanket (UASB) from vacuum-toilets and UASB sludge from a septic tank (de Graaff, 2010). Cd and Cr levels in phosphate fertilisers threaten the environment to the extent that they stimulated the development of EU legislation to regulate these metals' contents in commercial fertilisers (Tervahauta et al., 2014). Table 3 compares the heavy metal content from the sources mentioned to Dutch and EU guidelines and makes it clear that Dutch regulations are considerably stricter than those of the EU and that the digested sludge only fails to meet requirements for Cu and Zn, thus, if these concentrations can be rectified, HE-derived BBF should be suitable (de Graaff, 2010).

Table 2

Comparison of Heavy Metal Content of UASB Sludge with Standard Fertiliser Types

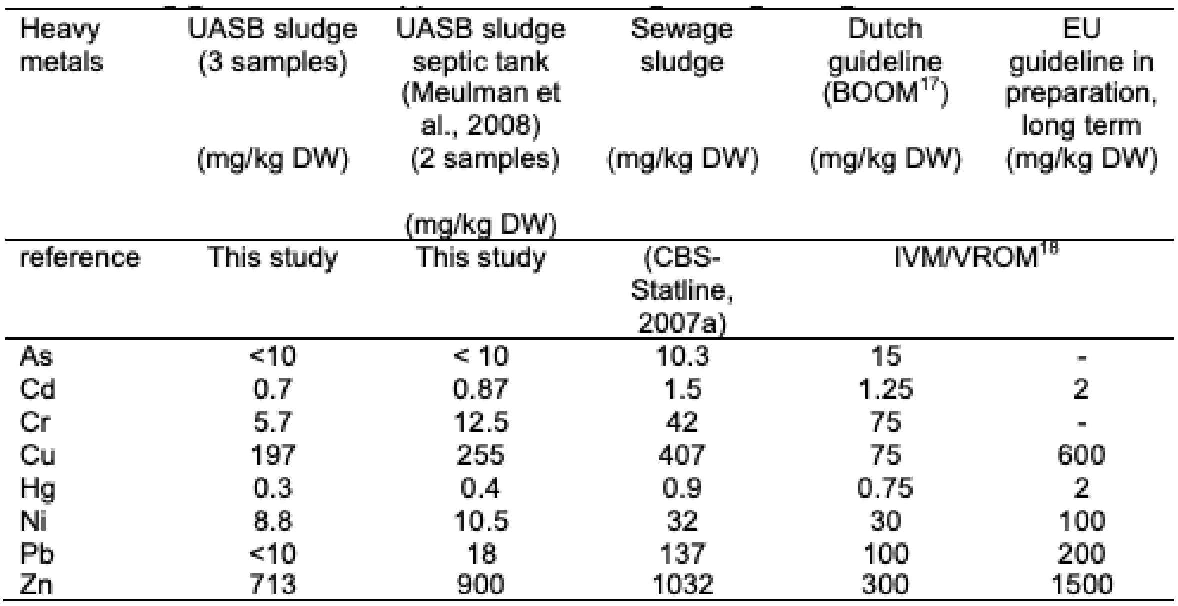


Heavy metals	UASB sludge (3 samples) (mg/kgP)	UASB sludge septic tank (Meulman et al., 2008) (2 samples) (mg/kgP)	Cow manure (mg/kgP)	P fertilizer (mg/kgP)
	This study	This study	(van Dooren et al., 2005)	(Remy and Ruhland, 2006)
As	< 185	< 185	-	33.2
Cd	13	16	32.7	90.5
Cr	105	232	1145	1245
Cu	3642	4722	14397	207
Hg	6.1	7.4	-	0.7
Ni	162	194	1472	202
Pb	185	333	695	154
Zn	13210	16667	25947	1923

Note. Adapted from de Graaff (2010).

Table 3

Comparison of Heavy Metal Content of UASB Sludge with Dutch & EU Regulations



Heavy metals	UASB sludge (3 samples) (mg/kg DW)	UASB sludge septic tank (Meulman et al., 2008) (2 samples) (mg/kg DW)	Sewage sludge (mg/kg DW)	Dutch guideline (BOOM^{17}) (mg/kg DW)	EU guideline in preparation, long term (mg/kg DW)
reference	This study	This study	(CBS-Statline, 2007a)	IVM/VROM^{18}	
As	<10	< 10	10.3	15	-
Cd	0.7	0.87	1.5	1.25	2
Cr	5.7	12.5	42	75	-
Cu	197	255	407	75	600
Hg	0.3	0.4	0.9	0.75	2
Ni	8.8	10.5	32	30	100
Pb	<10	18	137	100	200
Zn	713	900	1032	300	1500

Note. Adapted from de Graaff (2010).

An overarching pitfall of all fertiliser types is that regardless of the concentration of heavy metals found in whatever fertiliser is applied, in a circular agricultural system, there is always a risk of bioaccumulation that is likely to affect the soil microbiome. However, using a HE fertiliser rather than the aforementioned livestock- or P-based fertilisers is likely to reduce the concentrations of heavy metals that are applied to soils over time and that reach products intended for human consumption. This lessened input of heavy metals into the food production chain, on top of the circularization of the chain, would yield an overall decrease in heavy metal presence. This can be particularly helpful for bread, cereals, fruits, and vegetables, which are the most heavily contaminated crop types (Tervahauta et al., 2014).

1.4. Pathogens

Beyond the occurrence of antibiotics, other pharmaceuticals, microplastics, heavy metals, and more, pathogenic bacteria are also found in HE (Dollmann et al., 2020). The Dutch Q-fever epidemic of 2007 is a recent memory in the Netherlands of a manure-borne pathogen that infected over 4000 people and claimed the lives of over 100 (Schneeberger et al., 2014). Additionally, in light of the COVID-19 pandemic and growing dense populations, waste management, sanitation, and avoiding zoonotic diseases are more important than ever.

Most research in pathogen transmission by HE, whether from HFC or sewage sludge, is largely related to exposure to fecal parasites and their eggs, predominantly helminths. Soil-transmitted helminths (STHs) are a broad group of intestinal worms that contaminate soils, most commonly in tropical climates, particularly those lacking good hygiene (Tran-Thi et al., 2017). Infection occurs when helminth eggs are inadvertently ingested or when the skin comes into contact with larvae. For farmers using HE as a BBF, for example, in Northern Vietnam, along the Red River Delta, infection with STH was 1.24 times more likely if they handled fresh HE compared to those who did not handle it or only make contact after composting (to be discussed in Section 1.5.2) (Tran-Thi et al., 2017). Although no standard method exists to measure helminth eggs in fresh excreta, Chandana & Rao (2021) used microscopic inspection and various staining techniques to identify their prevalence in HE. They found 38 eggs/mL of fresh HE sample, of which 6-13 eggs/mL were viable (Chandana & Rao, 2021). They further identified bacterial colonies of both lactose- (*E. coli, Enterobacter, and Klebsiella*) and non-fermenting bacteria such as *Salmonella, Yersinia and Shigella* to be present in the fecal samples. Researchers measured the CFU of fecal coliforms and found 6 log CFU fecal coliforms/g (Chandana & Rao, 2021), which is high considering the U.S. Environmental Protection Agency (EPA) regulates bacterial presence at 3 log CFU fecal coliforms/g (US EPA, 2015).

Human urine, on the other hand, unless contaminated with feces, presents a low risk of carrying pathogens whilst carrying a significant nutrient load (Mihelcic et al. (2011). This is except for Schistosoma haematobium parasites, which cause schistosomiasis (a specific type of helminth infection). However, this risk can be minimised or eliminated via various treatment options, as will be discussed in Section 1.5.2. (Kramer et al., 2014).

Becoming ill from consuming food grown with HE fertilisation is a common hesitation that consumers have and is a key obstacle that circular agriculturists must overcome. Parasitic and other pathogenic infections can largely be avoided through the treatment of soil and the appropriate use of protective equipment (see Section 1.5.2). The transmission of pathogenic bacteria from plants to humans is a real threat, as made evident by the German *E. coli* outbreak of 2011 (Centers for Disease Control and Prevention, 2019), yet one that is also highly monitored, at least for the agricultural use of sewage sludge and reclaimed wastewater in high-income countries (Chandana & Rao, 2021).

1.5. Mitigating Food Safety Risk

Continued heavy prescription of pharmaceuticals as populations and rates of non-communicable diseases increase means their disappearance from HE seems unlikely, asserting the importance of their removal and management in HE. Composting and anaerobic digestion (AD) are ways to ensure pathogen and pharmaceutical-free products for use as fertiliser. The difference between these two processes is that composting is an aerobic process whereby microbes degrade OM, and AD is a technological method of microorganisms digesting OM in the absence of oxygen, yielding biogas (Fernandez-Bayo et al., 2018). Although AD effectively couples waste valorisation with energy production, which is an ideal configuration in a circular economy, it is under-researched for treating raw HE, hence why most upcoming studies focus on composting, typically in its thermophilic stage due to maximal efficiency in this period.

1.5.1. Attenuating the Threat of Pharmaceuticals and Pollutants

Zhou et al. (2020) studied animal manure and found that composting is a suitable method for removing antibiotics from fecal matter, supporting the method's transferability to HE. Of 32 antibiotics initially found in manure, 22 remained in “highly residual concentrations” after thermophilic composting, with these largely being tetracyclines (Zhou et al., 2020). They attribute this to the simple structure and high mobility of tetracyclines and nevertheless iterate their support for the efficacy of composting for the removal of most pharmaceutical compounds (Zhou et al., 2020). Häfner et al. (2023) further offer support for heat exposure and distillation for urine, and pasteurisation and thermophilic composting for feces, to be suitable methods of hygienisation. Their results agree with that of Dalahmeh et al. (2022) and Butkovskyi et al. (2016), whereby composting significantly reduces the presence of pharmaceutical compounds and allows the complete degradation of most other substances and hormones. Chen et al. (2018) found similarly that composted manure had a significantly lower antibiotic load (up to 3.1 mg/kg) compared to raw (uncomposted) manure (up to 19 mg/kg), and although antibiotic dissipation occurred significantly faster in the raw manure, overall, after 120 days levels were lower in the compost-amended condition. Despite the removal of most antibiotics is a positive result, complete removal does not seem to be possible, and it will be important to ascertain whether complete removal is indeed necessary to provide a ‘safe’ fertiliser.

An alternative solution besides composting and beyond AD is Fenton oxidation, a process usually used to treat polluted water in WWTP (Walling et al., 2021). Hydrogen peroxide and Fe^{2+} ions are used to create hydroxyl radicals that can decompose organic materials, which for example, can contribute to the removal of sulfonamides (Walling et al., 2021; Zhou et al., 2022). Additionally, to combat the accumulation of pollutants like heavy metals, Chojnacka et al. (2019) recommend an alternating cycling scheme for HE-based fertilisers of ‘three years on’ and ‘two years off’. Although this is not cost-effective or a suitable long-term solution for achieving a circular economy, it can be seen as a positive potential transition step.

1.5.2. Pathogen Stabilisation

Recycled, HE-derived fertilisers do pose a risk of transmissible human pathogens if left untreated (Häfner et al., 2023). Composting is a known method of killing STHs, and many studies recommend, with the authority of the World Health Organisation (WHO), that farmers compost HE for a minimum of six months prior to land application with the purpose of inactivating eggs and larvae (Tran-Thi et al., 2017). A systematic review reports that currently, only ⅓ of farmers in Northern Vietnam follow this recommendation (Tran-Thi et al., 2017). Further support of thermophilic composting is issued by Chandana & Rao (2021), who cite EPA regulations for pathogen stabilisation to be achievable via “composting, heat drying, heat treatment, thermophilic aerobic digestion, beta ray irradiation, or pasteurisation”. Bai and Wang (2010) describe a bio-toilet involving the addition of a bulk matrix such as sawdust to act as a site of microorganism growth and facilitator of porous space to aid in ventilation for aerobic composting. They recommend the maintenance of the bio-toilet at 50-60°C, as they have determined it to be optimal for removing *E. coli*, fecal coliforms, viruses, and ascarid (STH) eggs (Bai & Wang, 2010). Tervahauta et al. (2014), however, suggest pasteurisation at 70°C to make waste material appropriate for field application.

Several methodologies can be employed to improve the efficacy of composting, for example, the addition of 10% lime to accelerate the inactivation of STH and larva. *Ascardi lumbricoides* eggs are particularly resilient, yet lime successfully reduces their occurrence (Tran-Thi et al., 2017). Mixing feces with a bulk matrix (like sawdust) until a homogenous blend is reached, allows for quick evaporation of excess liquid (Bai & Wang, 2010). Chandana & Rao (2021) claim that moisture and pathogen content are the only shortcomings of fecal sludge as a BBF, thus increasing airflow through mixing will stimulate evaporation and contribute to the amelioration of the issue.

Finally, personal protective equipment such as proper boots and gloves for handling HE is likely helpful in the reduction of STH transmission in low- and middle-income countries where the practice of handling HE directly and navigating agricultural land without shoes is common (Tran-Thi et al., 2017). Regular and subsidised anthelmintic prophylaxis would also mitigate the risk that farmers face when handling HE (Tran-Thi et al., 2017).

2. Nutrient Recovery Potential from Human Excreta and Implications for Crop Yield

Gaps form in nutrient cycles involving the agricultural sector when more nutrients are taken out of the soil than are returned. The plants' largest nutrient demands are N, P, and K (Van Dijk et al., 2022). Chemical fertilisers (CFs) add an abundance of nutrients to the soil, and that not consumed by the plant roots is lost to the agricultural system, into groundwater, the atmosphere, or other parts of the soil (Bijay-Singh & Craswell, 2021). This leaching can pollute waterways and promote eutrophication, algal bloom, and decreased dissolved oxygen concentration (Park et al., 2019). Additionally, CFs do not replenish the OM depleted from the soil environment when crops are harvested (Chojnacka et al., 2022).

2.1. Nitrogen

The timely invention of the Haber-Bosch process in 1913 was critical in allowing for the agricultural industry to meet the demands of a growing population (Russel & Williams, 1977). The Haber-Bosch process uses the airborne unreactive form of nitrogen to generate plant-available nitrogen in the form of ammonia (Häfner et al., 2023), which, when added to the soil environment, helps plants produce proteins and nucleic acids (Chojnacka et al. 2022). The flaw in this system, however, is that rather than entering a closed (circular) system where these amino acids are recycled (for example, through digestion) and returned to the soil, crops (like corn, sorghum, barley, or oats) are fed to livestock, which encourages the production of nitrogen oxides (NO_x) and nitrogen dissipation (Chojnacka et al. 2022). Not to mention it requires high pressures and temperatures thus, factories use huge amounts of fossil-fuel-derived energy to create these conditions artificially (Darmawan & Aziz, 2021). The production of 1 kg of N fertiliser consumes almost 60 megajoules of energy, making it a highly energy-demanding process for the quantities the current agricultural system requires (Chojnacka et al., 2022).

2.1.1. Nitrogen Inputs

HE-based fertilisers, such as nitrified urine and human fecal compost (HFC), show promising effects as an N supply for agricultural systems. Häfner et al. (2023) report that due to nitrified urine's high mineral N content, it has a promising short-term fertilising effect. N in fecal compost, on the other hand, is predominantly bound to OM and thus has a long-term fertilising effect (Häfner et al., 2023). In fact, N from organic fertilisers has been found to show a reduced effect on crop growth in the year of application yet improved results thereafter due to the "slow-release characteristics of organically bound N" (Gutser et al., 2005). This is a challenge for organic fertilisers because they struggle to give farmers the immediate effect they often desire. The potential N supply from HE is stressed in the findings of Park et al. (2019), who report the influent of WWTP to contain 12-31% total nitrogen with HE origin (Park et al., 2019). There are differences between human and animal manure, for example, the daily volume produced (10 kg and 140 g, respectively (Kagohashi, 2012; Larsen et al., 2009)), however, the magnitude of N supply potential can be imagined through the estimation that the global annual production of N from animal manure is 100 tera-grams, equivalent to 10^{10} kg, making the urgency of recovering this nutrient loss clear (Chojnacka et al., 2019).

A study by Ogendo et al. (2018) investigating the effect of HE-based fertilisers on nutrient uptake in maize found no significant difference in N uptake between various fertilisers, including diammonium phosphate (CF), cow manure, struvite, and HFC. The main finding revealed that fertiliser treatments had better yield (≤3.73%) than the control (2.15%), allowing for the conclusion that HFC can achieve similar results compared to other dominant varieties in the field. The same study also notes that municipal sewage sludge, due to its C/N ratio of 5.68-16.75:1, may also be acceptable for field application due to its increased N accessibility to plants. Although N depletion does not threaten the Netherlands, in nutrient-scarce places worldwide, HE-based fertilisers can provide short- and long-term nitrogen inputs with comparable success to chemical fertilisers.

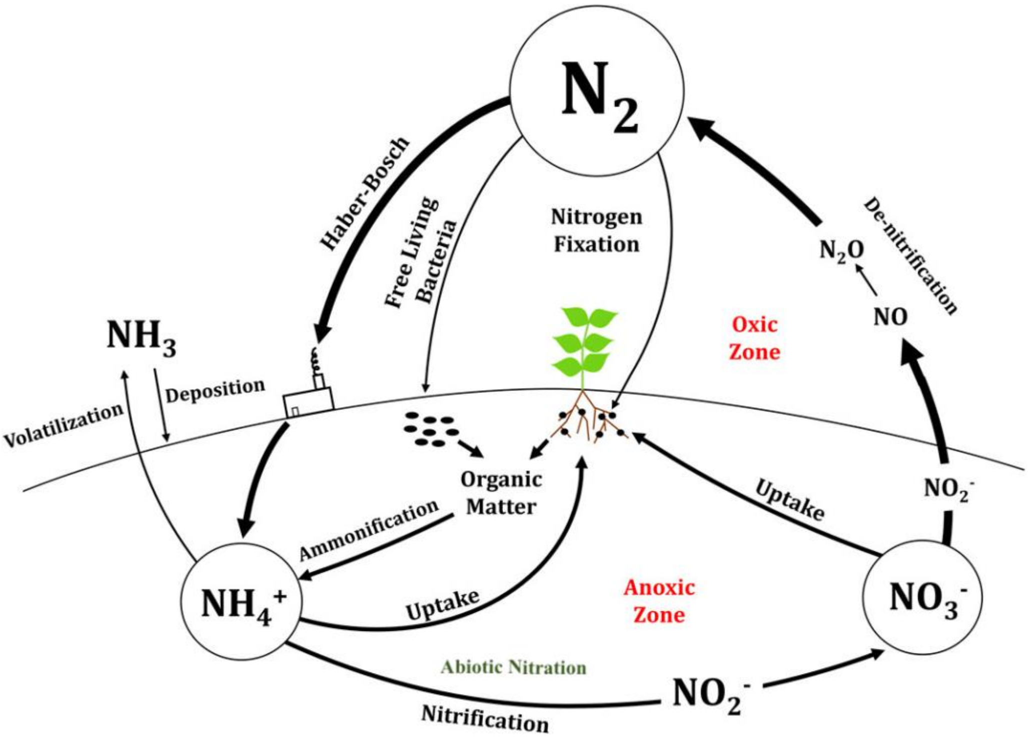
2.1.2. Nitrogen Emissions

Human activity accounts for over 40% of overall emissions of N compounds (Chojnacka et al., 2022), and the application of N fertilisers has a significant impact on the N cycle (See Figure 2).

Approximately 20-50% of applied N fertiliser is lost to the atmosphere as gaseous ammonia (NH_3) emissions, as nitric oxide (NO), and nitrous oxide (N_2O), or to water via N leaching and runoff (Yang et al., 2021). These nitrogen emissions can have serious consequences for human health, such as increasing the risk of cataracts and skin cancer (Yang et al., 2021). Yang et al. examined the effect of inorganic fertilisers and human manure at different concentrations and found that N_2O and NO emissions peaked after N fertiliser application and gradually decreased after one week, remaining low thereafter. The CHF2 treatment, which involved human excreta with a nitrogen ratio of 1:3, significantly increased gaseous reactive nitrogen emissions, leading to a 44.9% increase in N_2O emissions compared to a CF treatment. The researchers hypothesise this to be caused by the higher water content of HE and the role that soil moisture has in increasing gaseous reactive nitrogen emissions. They also mention the reduced moisture content of mineralised urine (found as bicarbonate (HCO_3^-) and ammonium (NH_4^+)) to be able to explain slower N_2O losses in urea-based fertilisers compared to HE-BBF (Yang et al., 2021).

Figure 2

Diagram of the Major Emission Sources and Deposition Locations in the Nitrogen Cycle



Note. Abiotic nitration is featured in dark green to mark the conversion of NH_4^+ to NO_2^-. Adapted from Langenfeld et al. (2021).

Composting processes have also been found to contribute to nitrogen losses, primarily through the discharge of gaseous productions like NH_4^+ and NO_x and leachate (the liquid byproduct that seeps through compost) (Chojnacka et al., 2019). To counteract a problem similar to this, Chen-fang et al. (2008) found that the addition of ducks and fish in rice cultivation was able to reduce nitrogen losses via ammonia volatilisation, NO_x emissions, and nitrate leaching (Cheng-fang et al., 2008).

2.1.3. Nitrogen Efficiency

One way to assess the efficacy of fertiliser is based on its N uptake and N use efficiency (NUE). In Yang et al. (2021), the chemical fertiliser treatment showed higher N uptake compared to the HE-supplemented conditions. Subsequently, CHF1 (nitrogen ratio of 1:7) and CHF2 (ratio of 1:3) were found to have reduced NUE of 17.2 and 5.4%, respectively. This unexpected outcome contradicted the expectation that additional organic matter usually increased N uptake and reduced gaseous losses (Yang et al., 2021). Moya et al. (2017) investigated the nutrient uptake efficiency of three HE-based fertilisers, namely digestate (from anaerobic digestion), compost, and vermicompost (further decomposition facilitated by earthworms). They found no significant difference in nutrient uptake between the fertilisers, which they attribute to already high levels of N being present in the soil. Thus, the lowest application rate of fertiliser (non-significantly) led to the greatest yield (Moya et al., 2017). Given the pre-existing nitrogen saturation of the soil, this scenario is foreseeable in the Netherlands. Therefore, the application of a phosphate-centred fertiliser would likely be most fruitful.

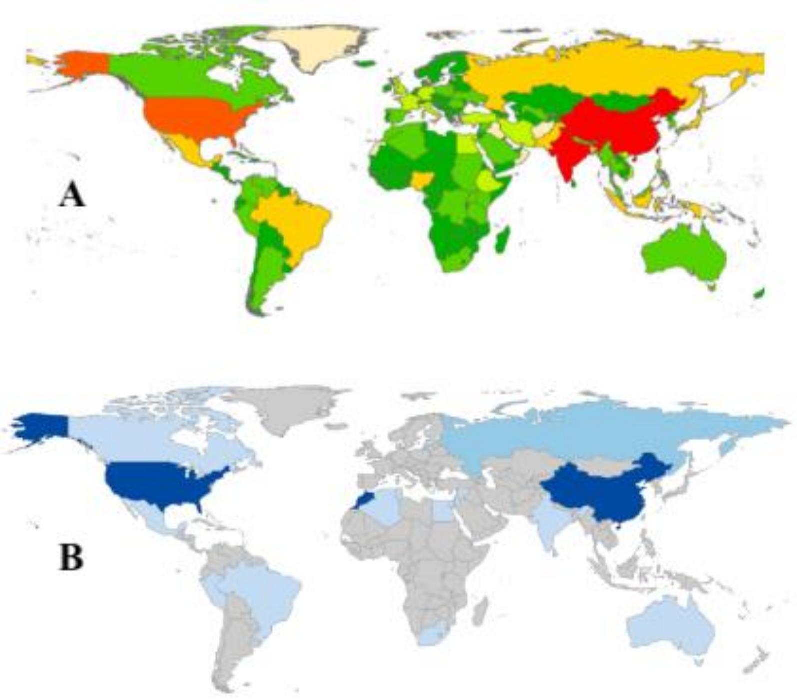
2.2. Phosphorus

2.2.1. Phosphorus Distribution and Recovery Potential

Phosphorus (P) is obtained from a finite and depleting resource of P rock, labelled as a “critical raw material” by the EU Commission in 2014 (Häfner et al., 2023; Chojnacka et al., 2022). By the mid-21st century, the demand for phosphate rock will be greater than its supply (Tran-Thi et al., 2017), making the establishment of circular P sources essential in achieving global food security (Häfner et al., 2023). In the EU, 25% of soils already have low availability of P (Chojnacka et al., 2022). Given Morocco holds more than 77% of world P resources, Europe uses imported mineral phosphates to meet its agricultural demand (Chojnacka et al., 2022). Creating independence from imported fertilisers is a way to safeguard food safety in Europe, although circular sanitation (See Section 3.1.1), is, of course, applicable in many contexts around the world. As non-renewable phosphate rock resources diminish, they not only become more expensive and polluting to extract, but also much of the P in the environment is not accessible to plants to use for growth, as it is adsorbed on clay, metal oxides, carbonates, and OM (Chojnacka et al., 2022).

Figure 3

National Phosphate Distribution from Waste (A) Compared to Mineral Extraction Sites (B)



Note. (A) Colour transition from dark green (least) to red (most), represents the quantity of phosphate production from human urine and feces per nation in 2009. Adapted from Mihelcic et al. (2011). (B) Color transition from grey (least/none) to dark blue (most) represents the amount of production of phosphate rock per nation in 2011. Adapted from de Ridder et al. (2012)

Figure 3 (A) shows the regional sources of human-derived phosphorus via urine, composted feces, and biosolids as of 2009, compared to (B), which shows the current locations where P is extracted. This figure exemplifies the sheer quantity of P that could be recovered in various regions (Mihelcic et al., 2011) if resources and attention are invested relative to the current areas where mining occurs (de Ridder et al., 2012). It also demonstrates the current great disparity between P production potential from humans, and the limited locations where it can be mined. Zeeman (2012) calculates that recovery of P from blackwater and kitchen compost can replace up to 25% of the global demand for artificial P fertiliser (Zeeman, 2012). In Swedish diets, it was found that 67% of bodily P is excreted via urine, and 33% in feces, but countries with less ‘digestible’ (meaning lower nutrient to fibre fractions) diets, will see feces contain a greater portion of excreted nutrients (Mihelcic et al., 2011). With an estimated average of 50% P excreted in the urine, Mihelcic et al. (2011) propose that from urine alone, 11% of the global P demand could be met. Schröder et al. (2021) found that HFC treatment led to higher phosphorus availability than standard green waste compost (Schröder et al., 2021). Mihelcic et al. (2011) stress that human-derived phosphorus has immense potential, particularly in developing regions of Africa and Asia with large populations and underserved sanitation systems (Mihelcic et al., 2011). Implementing urine diversion toilets can facilitate biosolid recycling to recover essential nutrients like phosphorus.

2.2.2. Phosphorus Uptake

In the field study by Ogendo et al. (2018) investigating the uptake of various nutrients with fecal-based fertilisers, the only nutrient found to have a significant difference was phosphorus, and only on one of the three plots. The greatest to least uptake of P was as follows: chemical fertiliser (diammonium phosphate) (0.50%) > control > struvite > cow manure > fecal compost (0.15%). Struvite, known to have a higher P content than HE, performed better than the HFC yet worse than the control (Ogendo et al., 2018). Conversely, Schröder et al. (2021) found that fecal compost led to the highest uptake of P and K in plant shoots, compared to urban-waste-derived vermicompost, despite lower uptake of Ca and Mg. This points not only to soil quality and type being impactful in the uptake of nutrients, given soils were different on all three plots in the study by Ogendo et al. (2018), but also that different fertiliser types can be better or worse suited to treat nutritional deficiencies in soil. Ca and Mg deficiency often occurs in highly weathered, acidic, sandy soil. Thus, the application of the aforementioned vermicompost is likely more applicable in that situation. On the other hand, Schröder et al.'s results demonstrate HFC's high delivery rate of plant-available P and K, thus exemplifying its application potential to soils that lack these nutrients, much like those that will likely occur in the Netherlands as soils become overrun by nitrogen.

2.2.3. Alternative Avenues for Phosphorus Recovery

With the hope of achieving a circular economy, waste products of all kinds should be considered as means to recover nutrients. Bones, for example, from animal slaughterhouses, are valuable and concentrated sources of P. However, some technical problems may arise if they simply replace a portion of the phosphate rock (given the low mineralized content due to the presence of OM) (Chojnacka et al., 2022). The industry's hesitancy to make substantial changes is made evident. Since 1942 when the patent was developed for the wet process phosphoric acid, it has remained virtually untouched due to the lack of pressure of change. The fertiliser industry has focused on process (efficiency, higher yields, profitability etc.) rather than product innovation because it simply is not profitable for their business model (Chojnacka et al., 2022).

The prospect of bio-fertilisers employing microflora to solubilize non-plant-accessible P is a creative solution to use smaller quantities of P fertiliser effectively. One limitation of inoculating soil with microflora is their struggle to compete with the local soil microflora (Chojnacka et al., 2022). Chojnacka et al. (2022) suggest that a focus on stimulating the indigenous soil microflora to better solubilize nutrients like N, P, and K would be more effective (Chojnacka et al.. 2022). Another route for P recovery is through the incineration of sewage sludge, which already occurs in the Netherlands, and thus would require minimal infrastructural investments. However, the process directly loses organic carbon to the atmosphere rather than returning it to the soil. Although a direct stream of waste products to the soil would be ideal, sewage sludge is considered a valuable source of nutrients and have the ability to neutralise post-solubilization digestate (Chojnacka et al., 2022). However, given P has been removed from most detergents, its prevalence in sewage sludge may be decreased and the efficiency of this process may be limited and thus receive less support from local governments and stakeholders.

2.3. Organic Matter

Extending beyond its potential to provide the soil with nitrogen, phosphorus and potassium, HE contains organic matter (OM). OM has been found to improve soil health in several ways: by increasing its capacity to hold water, reducing erosion, and facilitating better soil structure (Moya et al., 2017). Dried fecal solids have a carbon content of 44-55%, compared to dried urine solids which contain 65-85%, with urea being the largest constituent of this fraction (Rose et al., 2015). Due to the relationship between OM content and soil water retention, the application of these solids, particularly urine, has the potential to reduce the effects of drought, a phenomenon which is becoming more common in the wake of climate change (Fisk, 2021). HE-BBF is also likely to be most applicable in warmer climates due to the tendency for those soils to contain less OM (European Communities, 2009).

The OM content of HE has been found to have implications for the persistence and uptake potential of pharmaceutical compounds in soil. Malchi et al. (2014) found that carbamazepine and lamotrigine (two anticonvulsants) were present at higher levels in high-OM soils and thus were taken up less into the plants due to their capture in the OM-matrices. Pharmaceutical compounds have higher mobility in soils with low OM; thus, these soils present the greatest risk of uptake and exposure to humans through the food chain (Häfner et al., 2023). Although this is a positive result for food safety, pharmaceutical accumulation in high-OM soils is a threat to the soil environment and would likely not function well in a closed system. An added element is that the mobility of pharmaceuticals is not solely determined by the soil's composition but also by its structure (Drillia et al., 2005). As mentioned, HE has been found to improve soil structure, thus reinforcing its potential to be a suitable addition (Moya et al., 2017).

2.4. Crop Growth and Yield

Historically, organic manure has been essential in plant cultivation, yet intense demand for higher agricultural yields have driven chemical fertilisers to be the most important source of plant nutrients in the 20th and 21st centuries (Chojnacka et al., 2022). Unlike non-organic fertilisers, organic fertilisers increase microbial activity in the soil. This increases nutrient mineralisation, making them more accessible to crops (Montgomery & Biklé, 2021). The stimulation of microbes (like (an)aerobic bacteria and fungi) by organic fertilisers allow for roots to penetrate the soil more deeply and provide more nutrients to the crop, which in turn, promotes growth (Badu Brempong & Addo-Danso, 2022).

Park et al. (2019) aimed to show the positive effects of manure on the soil environment for plant growth. They compared several types: human manure (HM), HM from organic eaters (HMO), cow manure (CM), and poultry manure (PM) to analyse their organic and inorganic nutrient contents. They found PM and HMO to contain the highest levels of K and sulphate and higher C/N ratios than HM and CM. Furthermore, they found PM and HMO to contain “humic- and fulvic-acid-like substances”, which are molecules that provide optimal plant growth environments by transferring essential nutrients through plant cell membranes. HMO was found to have the highest chlorophyll-ɑ and -β concentrations, which indicates high nutritional benefits for the barley grown with this BBF (Park et al., 2019). Furthermore, these results from Park et al. (2019) indicate the potential for a combination fertiliser (HMO/PM) to be an effective way to transition from livestock to human manure use, given poultry’s lower carbon and nitrogen footprints and a higher protein yield to resource input ratio compared to other livestock.

In terms of crop yields, Ogendo et al. (2018) found that struvite and fecal compost treatments produced the highest grain yield and 1000-seed weight at two of the three plot locations, compared to cow manure, chemical fertilizer, and a control. Somewhat contrasting results to Ogendo et al. (2018) were found by Yang et al. (2021), who found that CHF1 (nitrogen ratio 1:7) and CHF2 (ratio 1:3) decreased vegetable yields by 6.7% and 7.4%, respectively, as compared to the yield with chemical fertilisation. These results do not make a strong claim towards the efficacy of fecal compost as being superior to CF, yet Ogendo et al. (2018) conclude that fecal compost is effective at increasing maize yield by up to 45% in comparison to the control (no fertiliser) condition. More research to understanding the limitations of BBFs, especially HE-derived BBFs, will be essential in ensuring they can meet the same standards that chemical fertilisers have accustomed our societies to, in terms of growth and yield.

A long-term study at Colorado State University found that although there was no difference in crop yield between organic and inorganic fertiliser use, organic manure increased “soil health, soil mineral availability, nutrient uptake, and thus grain quality” (Miner et al., 2020). Another comparative study between organic and chemical fertilisers found that “organic and integrated” fertilisation enhanced plant growth and yields, and organic fertilisers on their own increased soil health in terms of carbon content and micronutrient availability (Noor et al., 2020). Further to this, another study found that long-term application of organic manure significantly increases maize yield, by 7.4% over a four-year period (Wang et al., 2017). As stated, organic fertilisers cause greater permeation of roots into the soil and allow more nutrients to be transported to the plant, thus resulting, on average, in higher yields (Badu Brempong & Addo-Danso, 2022).

3. Application and Barriers to Implementing Circular Sanitation Practices

3.1. Establishing Circular Economy

Circular economy is a strategic framework implemented in some laws and policies (Häfner et al., 2023), usually in response to environmental and social issues (Chojnacka et al., 2019). At its core, circular economy repurposes and valorises ‘by-products’ or ‘waste products’ to mitigate loss from systems, whether that loss is nutrients, energy, money, or anything else which can be reimplemented. In fact, ‘by-product-use’ is nothing but an implementation of the circular economy theory (Chojnacka et al., 2019).

Funding initiatives and policy actions contributing to nutrient recovery are essential steps towards establishing a circular economy (Chojnacka et al., 2019). It is projected that major policy changes regarding food systems will occur in ten to thirty years as the need for sustainable agriculture becomes more dire (Kronberg et al., 2021). In nations with already established linear sanitation systems, the next challenge will be determining how to retrofit existing sanitation technology to recover nutrients that are quickly becoming depleted. This will also require a change in human behaviour and mindset related to reusing preconceived ‘waste’ products (Mihelcic et al., 2011). The EU has set the ambition of reducing non-renewable resources by 30% in fertiliser production (Chojnacka et al. 2019), and incentivising waste valorisation will be paramount in achieving this goal.

3.1.1. Circular Sanitation

Modern-day linear sanitation systems were developed to prevent exposure of humans to pathogens that exist in HE and minimise the incidence of eutrophication that occurs when aquatic ecosystems are exposed to additional nutrients (and pollutants) (Häfner et al., 2023). Closed loop sanitation technology addresses these objectives by facilitating decomposition of pathogens whilst recovering nutrients for direct crop use (Mihelcic et al., 2011)

Current pilot studies use portable and temporary toilets, for example those used at festivals (Häfner et al., 2023). These are not source-separated toilets (as seen in Figure 4) thus feces and urine are collected together, yet any liquid runs through the solid matrix of HE, sawdust, and toilet paper, making this urine-nutrified fecal product (Häfner et al., 2023). The benefits of source-separation is that the moisture content of HFC is kept low, and oxygenation is promoted to enhance evaporation and encourage pathogen stabilisation (Mihelcic et al., 2011).

Figure 4

Source-separated Toilet

Note. Taken from Larsen et al. (2009)

Special toilets, like the aforementioned, as well as vacuum toilets, have been trialled in several European projects. In the German settlement of Flintenbreite in Lübeck, a pilot project of 350 inhabitants aims to demonstrate sustainable sanitation in an urban setting, using vacuum toilets and blackwater sanitation (Winblad, n.d.). Alternatively, a building in Sweden has implemented source-separated toilets and found that the households use 44% less water than standard toilet users (Winblad, n.d.). These examples serve as encouragement for what the future could look like with investments in decentralised sanitation.

3.2. Barriers to Implementation

3.2.1. Legal Frameworks and Regulations

A lack of regulation of HE collected separately from wastewater threatens the implementation potential of this waste valorisation practice. Europe’s implementation of centralised sanitation systems in the 1870s was propelled by their affliction with unpleasant smells and a rampant spread of disease (Abbelán, 2017; Zeldovich, 2019). Since then, perceptions of HE have remained overwhelming unpleasant, thus reinforcing a lack of perceived need to engage with HE to regulate its content and use for agricultural purposes (Zeldovich, 2019). However, in 2019, the highest Dutch court found the government guilty of breaking EU law due to their failure to act in reducing nitrogen levels in “vulnerable natural areas” (Levitt, 2021).

The European Union already regulates maximum residue limits of pharmacologically active substances in food, particularly those of animal origin (Miguez-Suarez et al., 2022), as well as enforcing content and applications of other source materials that are used as fertiliser (wastewater sludge, animal manure, and biowaste) (Häfner et al., 2023). Yet HE does not fit neatly into these categories (Moya et al., 2019). Updated fertiliser regulation that extends and adapts existing regulations to HE and approves of using this quality-controlled BBF will be a key step in safeguarding an uncontaminated fertiliser that can aid in nutrient recovery.

Further, pathogen reduction is undoubtedly a key consideration in using HE as a BBF. Situations where there is a lack of regulation, or HE is used regardless of regulation, pose a threat for improperly treated HE(-derived fertiliser) to be applied to fields and enter the food chain. This stresses the importance of monitoring and regulating fertiliser content and quality to ensure long-term agricultural success in all parts of the world. Some governments do not have the capacity to implement the regulation, yet enterprises in locations such as Haiti and Kenya, where circular sanitation practices are novel, welcome the adaptation and implementation of local legislation (Moya et al., 2019). Regulation of content and use not only gives independent companies in the aforementioned countries the potential to legitimise their businesses but contributes to more widespread acceptance and commercialization of HE-derived BBF.

In the Netherlands, the Environmental Management Act (2004) subjects toilet wastewater to the same regulation as any other garbage, placing it under the jurisdiction of the National Waste Management Plan and requiring strict adherence to rules pertaining to separating, storing, and mixing (Stichting Toegepast Onderzoek Waterbeheer & Saniwijzer, n.d.). Sewage sludge and compost are recognized fertilisers, thus suggesting some leeway for HE to be used. On a positive note, the Municipal Water Tasks Act of 2008 allows municipalities to use source-separated toilets or systems if they achieve they can meet the same level of environmental protection (Stichting Toegepast Onderzoek Waterbeheer & Saniwijzer, n.d.). The clarification and harmonisation of existing legislation, as well as the generation of new regulations to safeguard the integrity of the HE-derived BBF, is an urgent matter that, if resolved, will make great strides towards a circular economy (Chojnacka et al., 2019)

3.2.2. Economic Feasibility

Profitability is a cardinal determinant in farmers' willingness to modify their agricultural practice (Yang et al., 2021). The concepts of net economic income (NEI) and net ecosystem economic income (NEEI) are metrics used to measure the efficacy of HE-based fertilisers to provide a sufficient economic incentive to farmers to alter their fertilisation practices and improve N management. Researchers found that using CHF2 (fertiliser with highest proportion of human manure) yielded the highest values of NEI and NEEI, substantiating that HE use can be an economically viable option (Yang et al., 2021).

Tran-Thi et al. (2017) found in their study focusing on the Red River Delta region of Northern Vietnam that farmers using fresh HE experienced the most cost savings, followed by those who composted it for six months, as recommended by the WHO, followed by those who used lime supplementation but composted for a shorter duration (Tran-Thi et al., 2017). Although this study did not include health care costs that accompanied treating acute or chronic STH infection due to contaminated HE, overall findings suggest that farmers in this region of Vietnam can profitably use HE as a renewable and local product whilst composting for five or six months, depending on the addition of lime (Tran-Thi et al., 2017). An interesting element to consider is farmers' willingness to risk their health for a higher profit margin. This points to the need for governments to support farmers in their endeavours to use a renewable, local, and nutrient-dense fertiliser option, for example, through providing PPE and anthelmintic prophylaxis medications.

Kronberg et al. (2021) make the argument that the "true cost" is not evident from the price of foodstuffs, and many costs are externalised, for example, through taxes for WWTPs or management of eutrophication (Kronberg et al., 2021). These costs are less visible to the consumer than the price of vegetables at the (super)market, yet would largely be mitigated through CS practices, but also less noticed. This raises an essential point about community and population-level education on the relevance and financial benefits that CS can have, particularly on crop production and prices.

An interesting phenomenon accompanying the valorisation of waste is commodification. Interviews with employees of *Sanergy*, a social enterprise that provides dry toilets to the urban slums of Nairobi, reveal that when people have waste to get rid of, they will pay to do so, but when the script is flipped, and companies like Sanergy make clear that they want people's waste, they will say "Okay, but we want you to pay [for it]" (Moya et al., 2019). The realisation of HE's worth is positive in the sense that it changes public perception, yet also negative because cost is already an issue that companies like Sanergy face, for example, for purchase and transport of toilet contents and additional composting materials from urban to rural areas (Moya et al., 2019). However, overcoming challenges to profitability is possible, even more so with government-funded assistance. A Sri Lankan town of 35,000 people relies on a fecal slude composting facility for safe sanitation, which is operated and maintained through profits from compost sales, as well as waste tax, and collection fees (Moya et al., 2019).

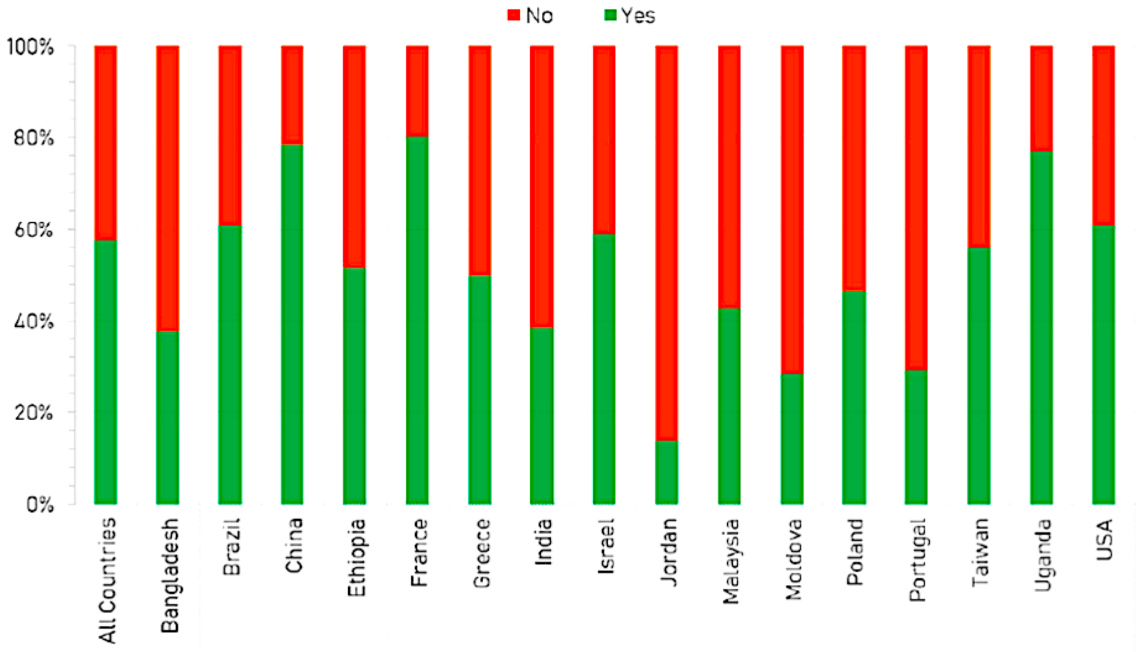
3.2.3. Sociocultural Resistance

Acceptance of this topic is two-fold: consumer acceptance to changes in their sanitation system or a new sanitation system coming into place, and consumers and farmers alike, accepting (growing) crops and foodstuffs fertilised with a HE-derived product.

Perception of HE and psychological resolution with the valuable contribution it can make in terms of agricultural success and independence from non-renewable resources (like phosphate rock and fossil fuels used to power the Haber-Bosch process) will likely take time and concerted effort, as every major change does (Häfner et al., 2023). Some cultures, for example in Ghana, associated HE with moral badness due to its taboo nature, yet Buit & Jansen (2016) found that changing its appearance (through drying) makes it less evocative and changes the moral symbology, giving HE a new meaning in this cultural context (Buit & Jansen, 2016). Familiarity (through family or neighbours) working with HE(-derived) fertiliser and a focus on what it achieves, for example, "[brightening] the green colour of leaves and… increasing long-term soil fertility," also improves acceptance (Buit & Jansen, 2016). Around the world, there is varying levels of acceptance of HE-fertilised foods. (See Figure 5). Simha et al. (2021) conducted a multi-national survey to determine willingness to consume foods cultivated with a urine-derived fertiliser, with results ranging from 14-80% 'Yes'. Notably enthusiastic countries include China, France, Uganda, and the United States. Most sceptical countries were found to be Jordan, Moldova, and Portugal, indicating HE-fertilised foods would find most resistance there. Across all countries, an average of 59% of surveyed people were willing to consumer food fertilised in this way. Although acceptance has a long way to go, this is a promising initial result (Simha et al., 2021).

Figure 5

Willingness to Eat Human Urine-Fertilised Food Across Several Countries



Note. Taken from Simha et al. (2021)

Farmer acceptance is also highly relevant as these are the people who must actively choose (hopefully with incentives from (local) government) to change their practice. HE reuse has remained popular in low-income countries as centralised sanitation never reached many rural areas. These communities perceive HE to be more valuable than animal manure because of the higher dietary protein content in HE, which they believe sustainably improves soil structure, which is highly prioritised, often over the risks to human health (like STH infection) (Tran-Thi et al., 2017). Tur-Cardona et al. (2018) also found that farmers accept replacing CF with BBF if their preferences are considered and the price reduction is 65% or more. Traits of the BBF which were found to be essential for farmers are high levels of bioavailable nutrients, organic carbon content, and hygiene (Yang et al., 2021). Additionally to this, fertiliser texture can impact farmer choice, whereby a majority prefer dry and grainy fertiliser due to ease of application, compared, for example, to liquid digestate (Moya et al. 2017)

A key roadblock in this agricultural transition is urbanisation. The challenge is to spatially connect urban sources of HE-derived BBF in urban areas to the rural areas where agricultural activity occurs (Mihelcic et al., 2011). In 2011, 50% of the global population lived in an urban centre (Mihelcic et al. 2011); however, the United Nations projected that by 2050, 2 in 3 people will live in urban centres (United Nations, 2018). These statistics, unfortunately, juxtapose and contradict the rates of HE reuse in urban compared to rural areas. Liu et al. (2008) suggest that at the time of writing, only 20% of urban HE is reused, compared to 70% in rural areas (Liu et al., 2008).

3.3. Evaluating Application Potential

3.3.1. Outside the Netherlands

Circular sanitation (CS), also called ecological sanitation, can provide hygienic, sustainable, and decentralised sanitation options to previously underserved areas and people. Trimmer and Guest (2018) analysed 56 of the largest cities in the world and evaluated their potential for nutrient loops to be closed in these locations using the metric of nutrient transport distance as an indicator of the success of waste recovery schemes (Trimmer & Guest, 2018). Their study reveals that CS could greatly benefit countries and continents with high cropland density, nutrient-intensive crops, and compact urban areas, for example, Bogotá, Colombia, or Dhaka, Bangladesh.

Water security is also a relevant factor to consider in implementing CS. CS practices such as bio-toilets (Bai & Wang, 2010) that do not flush may be more appropriate than sewers or centralised sanitation, in general, in water-stressed areas (Mihelcic et al., 2011). Ogendo et al. (2018) cite drought and water scarcity as a factor that reduces smallholder farmers' productivity in Kenya; thus, employing HE, which has naturally higher water content, could optimise their yield. Moya et al. (2019) investigated the social enterprise *Sanergy*. Their work providing closed sanitation facilities to impoverished and densely populated areas is impactful for hygiene and preventing the spread of pathogenic bacteria from feces. Additionally, the company stores, mixes, dries, sieves, and bags the HE-based fertiliser to sell to farmers, thus closing the cycle. The new fertiliser's content is measured along the way for moisture, pH, carbon dioxide (CO_2), pathogen concentration, and germination capacity, as regulated by the WHO standards for wastewater, excreta, and greywater (World Health Organization, 2013). The benefits provided by the implementation of CS are two-fold: providing accessible and cheap (0.05 USD per use) sanitation (Moya et al., 2019) and providing a sustainable and effective fertiliser to local farmers struggling with soil quality and declining land size (Ogendo et al., 2018).

The way in which HE application to soils is regulated in other countries beyond the Netherlands and Europe impacts the implementation of this process. In India, for example, there are no standard guidelines for the land application of fecal sludge (Chandana & Rao, 2021), and although current policies prohibit HE use altogether in Vietnam, limited surveillance and needs-based circumvention of legal regulations mean that soil application does indeed occur (Tran-Thi et al., 2017).

3.3.2. Within the Netherlands

The Netherlands is a small European nation with a high population and high livestock density, given agricultural products are a predominant export. As mentioned in the introductory section of this paper, the Netherlands has a unique agricultural landscape, characterised by nitrogen-rich soils due to the retention of large volumes of animal manure that accompany the dense livestock populations (with 70% being applied to local fields) (Dollmann et al., 2021). Given the intense supply of nitrogen (N) to the soil, phosphorus (P) recovery would be most beneficial in the Netherlands. Section 2.1.2. elaborates on the importance of P for plant growth and food security, its current retrieval from limited rock resources and its high potential to be recovered from HE, urine in particular.

Regarding legislation, the Netherlands is one of the most environmentally cautious states and sets limits below that of general EU standards (See Table 3), which largely prohibits the application of sewage sludge on agricultural soils and prompts incineration, which is undeniably polluting and energy-intensive. A further consideration is that Dutch culture is very orderly and, above all, law-abiding, meaning a change in policy regarding HE application to agricultural land would inevitably have a run-on effect on the population's perception of HE-grown vegetables, for example.

The Netherlands has the infrastructure and the financial capacity to implement circular sanitation, at least on a small scale, as is evident by the projects described in 3.1.1. Yet the government focuses on biomass options such as food waste and manufacturing residues (The Ministry of Infrastructure and the Environment et al., 2016). Although these are valuable resource streams, valorizing human waste will be integral in achieving the nation's target of reaching a fully circular economy by 2050. The lack of explicit inclusion of human excreta is a missed opportunity to recover nutrients and make HE use a reasonable possibility (The Ministry of Infrastructure and the Environment et al., 2016). A The factors contributing to the application potential of HE as a BBF have been laid out in a criteria-based framework, found in the Appendix.

Conclusion

The application of human excreta (HE) as a bio-based fertiliser (BBF) represents a crucial step towards achieving a circular economy in sanitation practices. Nutrient-rich HE can be harnessed and transformed into a valuable product with wide-reaching social and environmental consequences through the emphasis on repurposing and valorising products previously considered to be waste. This transition will unarguably require policy change on a national and international level that adapts existing regulations to approve of quality-controlled HE-derived BBF. This thesis has substantiated many claims for why this can and should be accomplished, which will now be summarised.

A key finding of this literature review is that pharmaceuticals (antibiotic or not), household compounds, heavy metals, and microplastics can be transferred from soil to crop. The transmission of antibiotics is particularly alarming because of their recalcitrancy in soil and incomplete removal by composting (Piña et al., 2018). Antibiotics taken by humans can infiltrate the gut microbiome and cause intestinal bacteria to carry antibiotic-resistance genes (ARGs), which can transfer to plants and re-enter the food chain (Boehme et al. 2004). It may be necessary as well to consider the type of crop grown with HE-derived BBF as some are particularly prone to taking up ARG-carrying bacteria (Boehme et al., 2004) or pharmaceuticals into their edible components (Häfner et al., 2023).

The co-occurrence and chelation of pharmaceuticals, heavy metals, and microplastics and the significance of compounds’ metabolites or transformation products (TPs) cannot be understated (Boxall et al., 2006). Heavy metals in HE are several magnitudes lower than that found in wastewater sludge and animal manure (Häfner et al., 2023) and can be further reduced through the use of source-separated toilets because they do not include the most polluting avenues: tap water and industrial effluents (European Environment Agency, 2023). On the other hand, TPs can be more genotoxic than the original, and compound-metabolite or other xenobiotic interactions are often unknown. Using frameworks like the threshold of toxicological concern (TTC) that consider exposure to a mixture of compounds will be important in ascertaining more accurate risk assessments (Malchi et al., 2014).

Another threat posed by using HE as a BBF is pathogens, like helminths, that can infect farmers if feces remain untreated before use. The adherence to not only using personal protective equipment to handle HE, but to the length of time that HE should be composted before application can largely mitigate this risk. However, profitability is crucial for farmers, and not composting is the most financially rewarding decision (Tran-Thi et al., 2017). This reaffirms the impact that government subsidies and incentives can have to ensure proper composting is observed in the name of farmer health. Furthermore, composting has broad support with many studies (Häfner et al., 2023; Dalahmeh et al., 2022; Tran-Thi et al., 2017; Butkovskyi et al., 2016; Chen et al., 2018) agreeing that composting, particularly in its thermophilic stage is a suitable method of pathogen stabilisation, ensuring hygiene, and reduction of xenobiotics.

In contrast to the Haber-Bosch process, HE-derived fertiliser does not depend on fossil-fuel-derived energy to generate plant-available nitrogen (N) (Darmawan & Aziz, 2021). N fertilisers made in this way are highly polluting, with severe health risks (Yang et al., 2021). HE-derived fertilisers, depending on whether urine or fecal-based, and thus on their composition, have been found to have short- or long-term fertilising effects, respectively (Häfner et al., 2023). Moreover, HE-derived fertilisers were found to be equally as effective in promoting crop yield as compared to chemical fertilisers, allowing for the conclusion that there is sufficient N provided to the soil and plant by human fecal compost (HFC) and struvite (Ogendo et al., 2018). Results in terms of nitrogen emissions from HE-derived BBF application and the preparatory composting processes show high N_2O and NH_4^+ emissions, yet these may be attributable to high water content (Yang et al., 2021) and are a general burden of fertiliser application.

Phosphorus (P) shows great potential to be recovered from HE from various sources such as green-, kitchen- and HE-compost. Struvite (from urine) and HFC have both been found to lead to successful P uptake in crops (Ogendo et al., 2018; Schröder et al., 2021). Fertilisers that can initiate high levels of P uptake will be essential in the Netherlands as soils and systems become P-limited due to being overburdened by nitrogen. Innovation in the extraction and management of P processes has remained stagnant since their conception (Chojnacka et al., 2022), a trend unfortunately seen across the chemical fertiliser industry. This must change if renewable sources of P are to be relied upon as mineral resources deplete from natural reserves (Chojnacka et al., 2022).

HE can improve soil structure and increase soil water retention, thus reducing the mobility of pharmaceuticals and reducing the effects of drought through its contribution of organic matter (OM) (Moya et al., 2017; Häfner et al., 2023, Fisk, 2021). Organic manure, in general, is highly beneficial to the soil environment, beyond what can be measured in crop yields, for example, better soil health, mineral availability, and nutrient uptake. It also increases the stimulation of microbes, allowing more nutrients to reach the plant and contribute to growth (Montgomery & Biklé, 2021). This corresponds to the evidence of humic- and fulvic-acid-like substances being found in the HE of organic eaters, given they are microbial byproducts (Park et al., 2019). A holistic view of the plant and soil environment exemplifies how HE can improve soil health, with particular benefits possible in areas with nutrient-depleted soils.

To successfully implement HE as a BBF, several barriers must be overcome. As populations become more urban and less rural, the challenge of spatially connecting the locations of HE production and use becomes more uneven (Mihelcic et al., 2011). Increased transport distances decrease the success of nutrient recovery from waste (Trimmer & Guest, 2018), and although this is not a threat in the Netherlands, due to high population density relative to agricultural land, in other more rural areas, this could be pivotal for success. Another barrier is the social acceptance of HE as a fertilising product, especially in cultures with a strong ‘fecophobic’ narrative that ties HE with a negative connotation and may deter it from being a favourable choice for farmers. If farmers' preferences in terms of nutrient levels (nitrogen, phosphorus, and carbon, for example) (Yang et al., 2021), visual appearance (distinct from raw feces) (Buit & Jansen, 2016), and ease of application (pellets are less bulky and easier to distribute) (Moya et al., 2017), are taken into account, and the price is within their acceptable range, this uptake of this product is highly likely.

The utilisation of human excreta as a valuable resource bridges the gap between sanitation and agriculture and allows for a significant stride towards a circular economy to be made. By embracing this paradigm shift, we are able to address critical environmental challenges and cultivate a holistic and sustainable approach to protecting our planet and feeding its inhabitants for generations to come.

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Appendix

Overview of Remaining Barriers in the Application of Human Excreta as a Bio-based Fertiliser in the Netherlands

		Composting	Education & Awareness	Government Action	Unresolved	**Notes**
Pharmaceuticals	Antibiotics ☆ ▵ • Resistant Genes	✓	✓		✓	Prescription should be limited to necessity and reduced in agriculture. Composting is successful but not 100% effective. ARG remain a threat.
	Non-antibiotic Pharmaceuticals ☆ ▵ • Poorly Metabolized Drugs • Metabolites with ↑ Toxicity • Endocrine Disruptors	✓	✓		✓	Some pharmaceuticals (and their metabolites) are particularly recalcitrant. Caution should be exercised alongside rigorous monitoring. TTC framework appears effective for assessing risks posed. Endocrine-disrupting pharmaceuticals appear to be removable with composting. Involuntary exposure via water and food remains a threat. Fenton Oxidation & AD are viable alternatives to composting.
Contaminants	Household compounds ☆ • Metabolites with ↑ Toxicity	✓				Food safety does not appear to be threatened by contamination of household products. Involuntary exposure remains concerning.
	Microplastics ☆ ▵				✓	Contamination via food and water should be explored. Bioaccumulation risk.
	Heavy Metals ☆ ▵	✓		✓		Cu and Zn are main limiters: their reduction is critical. Bioaccumulation risk.
Pathogens	Parasites • Soil-transmitted Helminths • Schistosoma	✓	✓	✓		Composting for 5-6 months reduced threat. The addition of lime and mixing accelerates the process. In combination with PPE and prophylactic medication, the threat is largely attenuated.

Nutrients	Nitrogen • Emissions & Efficacy • Variable N soil statuses		✓	✓	✓	HE seems to provide sufficient N to crops and be equally effective as CF in yield. Reactive N emissions are concerning. Reducing moisture content may help. The current agro-climate makes N additions to soils illogical in NL but logical elsewhere. Reducing livestock may make application appropriate.
	Phosphorus • Depleting P Rock Resources • Low P soils		✓	✓		P recovery is very applicable in NL, largely through urine. Soils in NL will become P depleted far before becoming N-deficient. Transition to recovered P is urgent due to polluting mining from reducing natural stores. Alternative methods should also be explored (Bones, microflora).
	Organic Matter ▵				✓	High OM can reduce contaminants from reaching the crop. ↑ soil bioaccumulation risk. OM has holistic benefits for soil.
Legislative & Sociocultural Barriers	Legal Frameworks & Regulation		✓	✓	✓	Dutch legislation is strict. NL would benefit from ↑ regulated BBF use.
	Economic Feasibility		✓	✓	✓	Appears to be feasible in the NL, yet investment in CS is not prioritized.
	Sociocultural Resistance		✓	✓	✓	Neighbouring countries appear accepting. Farmer acceptance will be key.

Note. ☆ = Threat of Involuntary Exposure, ▵ = Threat of Bioaccumulation