Article:

Elder, F.C.T. orcid.org/0000-0003-4356-444X, Fajardo-Escoffié, J. orcid.org/0000-0003-4307-5005, Carter, L. orcid.org/0000-0002-1146-7920 et al. (5 more authors) (2025) An integrated social and natural sciences case study for the reuse of organic wastes as soil amendments. Plants, People, Planet. ISSN: 2572-2611

https://doi.org/10.1002/ppp3.70141

Received: 27 February 2025 | Revised: 29 August 2025 | Accepted: 22 October 2025

DOI: 10.1002/ppp3.70141

RESEARCH ARTICLE

Plants People Planet PPP Open Access

An integrated social and natural sciences case study for the reuse of organic wastes as soil amendments

Felicity C. T. Elder[1] | Jose-Luis Fajardo-Escoffié[2] | Laura Carter[1] | Emily K. Durant[3] | Katie J. Field[3] | John Nightingale[1] | Brett Sallach[4] | Andrea-Lorena Garduño-Jiménez[1]

[1]School of Geography, Faculty of Environment, University of Leeds, Leeds, UK

[2]School of Geography and Planning, University of Sheffield, Sheffield, UK

[3]Plants, Photosynthesis and Soil, School of Biosciences, University of Sheffield, Sheffield, UK

[4]Environment and Geography, University of York, York, UK

Correspondence
Andrea-Lorena Garduño-Jiménez, School of Geography, Faculty of Environment, University of Leeds, Leeds, UK.
Email: a.l.gardunojimenez@leeds.ac.uk

Funding information
White Rose University Consortium Collaboration Fund; Research England, Grant/Award Number: MR/S032126/1; Economic and Social Research Council, Grant/Award Number: ES/S007830/1; ERC, Grant/Award Number: 865225; Natural Environment Research Council, Grant/Award Numbers: NE/V013041/1, NEOF1561; de Laszlo Foundation

Societal Impact Statement

Reusing organic waste materials, such as animal manure, as soil amendments reduces water and fertiliser demand, contributing to achieving the Sustainable Development Goals. However, organic wastes may contain contaminants of emerging concern (CECs), posing potential ecosystem and human health risks. Despite the importance of this issue, there is a lack of open dialogue between researchers studying CECs and the farming community, limiting farmers' awareness of potential risks and researchers' understanding of realistic agricultural scenarios and constraints. Furthermore, farmers face financial, practical and policy challenges when deciding whether to use organic amendments; decisions are often made without a shared understanding of broader environmental concerns.

Summary

- The aim was to address the lack of communication between farmers and researchers from various disciplines by integrating research on contaminant of emerging concern (CEC) presence and their effects on arbuscular mycorrhizal (AM) colonisation, with insights from social anthropology.
- A UK farm using a combination of wastewater biosolids, farmyard manure and synthetic fertiliser as soil amendments on three fields served as a case study. CEC presence and impact on AM colonisation was evaluated for soil from each field. The farmer and farm manager were interviewed to understand financial, practical and policy challenges around organic amendment use. Finally, a UK-wide stakeholder workshop presenting the case study results to farmers, and other stakeholders was undertaken.
- The presence of 16 chemicals, including human and veterinary pharmaceuticals, pesticides and industrial chemicals across the three fields was confirmed. There was no significant effect on AM colonisation depending on which field the soil was from. A recorded interview of the farmer and farm manager demonstrated that their agricultural practices are motivated by both environmental

Disclaimer: The New Phytologist Foundation remains neutral with regard to jurisdictional claims in maps and in any institutional affiliations.

consciousness and economic pragmatism. During the workshop, seven research questions were identified. Topics included what information is or should be available for farmers to make decisions on waste reuse in agriculture, for example, CEC presence. In addition, concerns were raised on how specific farming practices affect CEC fate and effects and how adequate policy on waste reuse is.

- This work integrates chemical, biological and social considerations surrounding soil amendment choices, emphasising the need for interdisciplinary collaboration and informed decision-making in sustainable agriculture.

KEYWORDS

arbuscular mycorrhizal fungi, biosolids, contaminants of emerging concern, organic soil amendments, soil health, stakeholder engagement, sustainable agriculture

1 | INTRODUCTION

Pressures on the food system, such as an increasing population and climate change, call for a critical analysis of existing food systems and exploration of alternatives within frameworks such as the circular economy (Mosnier et al., 2022; Rodias et al., 2020). Alternative approaches to intensive agriculture, such as decreasing the use of synthetic fertilisers, are rooted in ancient practices and are now encompassed within the concept of regenerative agriculture (Beacham et al., 2023; Rebanks, 2021; Sands et al., 2023). This approach broadly refers to 'a suite of principles, practices, or outcomes which seek to improve soil health, biodiversity, climate, ecosystem function, and socioeconomic outcomes'. However, this is open to interpretation, resulting in varied agricultural approaches being employed under the regenerative agriculture banner (Sands et al., 2023). Despite this variability, there is a general consensus on the need to reduce synthetic fertilisers, driven largely by the potential for pollution through over-application and leaching, and the production costs associated with these products (Sud, 2020). An alternative to synthetic fertiliser usage is the reuse of organic 'wastes', including wastewater sludge, animal manures and slurries, as soil amendments. This practice has the potential to reduce carbon emissions associated with the production and application of fertilisers and landfill requirements (Urra et al., 2019).

The UK's Circular Economy Package, a legislative framework introduced in 2019 to reduce and improve the management of waste, aims to achieve a 65% reduction in municipal waste by 2035 (Department for Environment Food & Rural Affairs, 2022). As part of this initiative, wastewater treatment companies are incentivised to reuse wastewater biosolids, aligning with the principles of the circular economy. This approach seeks to reduce pressure on natural resources by reutilising and reducing waste, contributing towards Sustainable Development Goal (SDG) 11: *Sustainable Cities and Communities* and SDG 12: *Responsible Consumption and Production* (United Nations Environmental Assembly, 2019). However, wastewater biosolids may contain contaminants of emerging concern (CECs), such as human and veterinary pharmaceuticals, other chemicals, microplastics and bacteria harbouring antimicrobial resistance (AMR) genes (Carter et al., 2019; Urra et al., 2019).

The presence of CECs in agricultural soils poses a risk to ecosystem and human health. For example, research has demonstrated that CECs can contribute to AMR, a global health emergency that threatens the efficacy of antibiotics, potentially increasing disease transmission and contributing to an estimated five million deaths in 2019 (EFSA Panel on Biological Hazards [BIOHAZ] et al., 2021; UNEP, 2023). AMR occurs when bacteria, viruses, parasites or fungi develop resistance to antimicrobial treatments, either intrinsically or through mutations or the transfer of mobile genetic elements. Exposure to CECs at sublethal concentrations, including antimicrobials and other microbial stressors like other pharmaceuticals, heavy metals and biocides, creates conditions that favour the development of AMR (James et al., 2023; Murray et al., 2024; Stevenson et al., 2022; UNEP, 2023). If left unaddressed, AMR could significantly impact agricultural production due to antimicrobial use in crop and animal production and labour shortages due to the human health burden, threatening food security, particularly in the Global South, which is expected to bear the greatest burden (UNEP, 2023).

The negative consequences of CECs are not limited to AMR; it has been demonstrated that CECs can also negatively affect soil health (Mohapatra et al., 2016; Urra et al., 2019) and plant health (Garduño-Jiménez & Carter, 2024; Mansilla et al., 2021). Environmentally persistent human-use pharmaceuticals such as carbamazepine and verapamil have been found to alter plant hormone levels and nutrient content in zucchini (courgette—*Cucurbita pepo*) when present in soils at concentrations ranging from 0.005 to 10 mg kg^{-1} (Carter et al., 2015). Another study observed the expression of stress-related genes in lettuce (*Lactuca sativa*) grown in a hydroponic system containing diclofenac (20,000 ng L^{-1}) (Bigott et al., 2021). Recent research has also demonstrated that human-use azole antifungals (clotrimazole, miconazole nitrate and fluconazole), detected in wastewaters and biosolids and subsequently in agricultural soils, disrupt phosphorus transfer from arbuscular mycorrhizal (AM) fungal networks within the soil to *Triticum aestivum* (Sallach et al., 2021) and other food crop (Durant et al., 2025) host plants. AM fungi are symbiotic soil organisms that form mutualistic associations with the roots of most terrestrial plants. They can enhance nutrient and water uptake, particularly phosphorus, of their host plant while also improving plant resilience to stressors such as drought and disease (Smith & Read, 2010). In agroecosystems, AM fungi can play an important role in maintaining soil health, reducing the need for synthetic fertilisers and promoting sustainable crop production. However, intensive management can disrupt AM fungal communities (Helgason et al., 1998). In regenerative and low-input agricultural systems, where soil disturbance is lower and the application of synthetic fertilisers and pesticides is limited, AM fungi have a greater potential to play a crucial role in supporting biodiversity and contribute to long-term soil health and fertility. This is especially true in degraded soils, as AM-mediated benefits to crop yield are generally limited in healthy soils (high microbial carbon, high AM fungal richness, lower pathogen abundance and high organic carbon and plant-available phosphorus and nitrogen) (Rog et al., 2025). CEC-driven disruption of AM-mediated phosphorus transfer to crops highlights potential disruption to nutrient uptake by crops via microbial pathways, ultimately undermining the goals of circular and regenerative agriculture. Collectively, these studies demonstrate that CECs in organic wastes in agriculture can negatively impact both crop and soil microbiome health and function. Thus, a deeper understanding of these effects is essential to ensure that the reuse of organic waste enhances soil fertility and crop growth rather than inadvertently hindering them. In England, Wales and Northern Ireland, regulations set in 2018 state that biosolids must be tested for dry matter, organic matter, pH and nutrient content (phosphorus and nitrogen) and for seven potentially toxic elements (chromium, zinc, copper, nickel, cadmium, lead and mercury). In addition, there are limits for the concentration of molybdenum, selenium, fluoride and arsenic that may be present before application to land. Finally, there are restrictions on biosolids application to land in terms of treatment processes (pre-application), application method and timing depending on the crop to protect consumers. However, there are no required measurements or restrictions in terms of CECs or considerations on how these may impact the environment (Biosolids Assurance Scheme, 2019; DEFRA, 2018).

Advances across the chemical, biological and environmental science disciplines are key to building the deeper understanding required on the effects of using organic materials as soil amendments. This knowledge is crucial for broader adoption of such practices and for achieving the goals outlined in the UK's Circular Economy Package, as well as broader agricultural sustainability aims. However, this knowledge published in scientific papers rarely reaches those faced with implementing the use of organic soil amendments. There is a critical lack of dialogue between the researchers generating this knowledge and the farmers who are faced with the decision and practicalities of choosing the most appropriate soil amendment for their fields. For research to have a long-lasting impact on agricultural practices, farmers must be involved from the onset, their views, observations and knowledge being valued in equal measure to empirical chemical and biological data. Here, we present a case study involving chemical, biological and social expertise as well as stakeholder involvement to analyse the use of different soil amendments in a farm. The study site was a farm located in the south of England in which three fields have been amended with a combination of wastewater biosolid waste, farmyard manure slurry and synthetic fertiliser. Soil samples were analysed from each field for CEC presence, particularly pharmaceuticals, as well as their impact on AM fungal colonisation of crop roots. An interview of the farmer and farm manager outlining the drivers, barriers and practicalities of utilising different soil amendments in the participant farm was recorded. Results from the fieldwork were discussed in a workshop involving researchers, farmers and key policy stakeholders, leading to the identification of crucial research questions for the sustainable use of organic soil amendments.

2 | METHOD

2.1 | Case study farm and agricultural soils sampled

The farm is a 100-ha arable operation in Gloucestershire, South West England, with a block system growing wheat, oilseed rape, barley and beans. Wastewater biosolids from a local wastewater treatment plant and farmyard manure are regularly used on this farm as soil amendments. Grab samples, a single sample from one location in the field collected by removing top vegetation and collecting approximately 4 kg of soil from the top 10 cm, were collected from three fields (Soils 1, 2 and 3) in May 2023. The most recent soil amendment for Soil 1 was biosolids from a local wastewater treatment plant in autumn 2022, and the most recent crop was winter barley (*Hordeum vulgare*). For Soil 2, these were farmyard manure in August 2021 and winter wheat (*T. aestivum*). For both Soil 1 and Soil 2, straw residues are regularly incorporated post-harvest from winter oil seed rape, bean and wheat, but winter barley straw is given to a neighbouring farm in exchange for farmyard manure. Both Soil 1 and Soil 2 also receive synthetic fertiliser (YaraBela SULFAN) but in a lower quantity when biosolids or farmyard manure are applied. Soil 3 was from a field that had been used historically for grazing, and since 2020, it was included in the cropping rotation. Since 2020, it had been fertilised using synthetic fertiliser (YaraBela SULFAN), and no organic amendments had been added for at least 5 years. Further details of the fertilising and crop history of each soil can be found in Table 1.

2.2 | Soil preparation and analysis

Soil samples were transported in a cool box (4°C) from the farm to the laboratory. One kilogram of soil per field was freeze-dried, ground and sieved through 2 mm prior to chemical analysis to determine soil characteristics (analysed in triplicate). The remaining soil was air-dried and sieved (2 mm) and used for assessment of AM colonisation bioassays using spring onion (described in Section 2.3). All soil property and CEC content analysis on the three soils was carried out on the soil before and after the AM colonisation trial and was conducted in triplicate.

TABLE 1 Amendment received and crops harvested in each soil (red for Soil 1, green for Soil 2 and yellow for Soil 3).

Harvest year	2015	2016	2017	2018	2019	2020	2021	2022
Soil 1								
Amendments received				First biosolid application in May 2018 (*ahead of w. OSR for harvest 2019*)		Farmyard manure in September 2020 (for harvest 2021)		Biosolids from a local wastewater treatment plant in August 2021, for gravest in 2022
Crops harvested	Winter barley (*Hordeum vulgare*)	Winter oil seed rape (*Brassica napus* subsp. *napus*)	Winter wheat (*Triticum aestivum*)	Cover crop	Winter oil seed rape (*B. napus* subsp. *napus*)	Summer wheat	Winter wheat (*T. aestivum*)	Winter barley (*H. vulgare*)
Soil 2								
Amendments received			First biosolid application in August	Farmyard manure in August		Biosolids in September	Farmyard manure in August 2021	
Crops harvested	Winter oil seed rape (*B. napus* subsp. *napus*)		Winter barley (*H. vulgare*)	Winter oil seed rape (*B. napus* subsp. *napus*)	Winter wheat (*T. aestivum*)	Summer barley	winter linseed	and winter wheat (*T. aestivum*)
Soil 3								
Amendments received						Synthetic fertiliser (YaraBela SULFAN) with total nitrogen content of 26% (19% ammoniacal nitrogen and 7% nitric nitrogen) and 35% sulfur trioxide		
Crops harvested	No crops (used for grazing)							

2.2.1 | Soil characteristics

pH was assessed in 0.01 M $CaCl_2$ using a Hanna Groline field pH probe. Cation exchange capacity for calcium, potassium, magnesium and sodium was measured using standard methods (Cappo et al., 1987). Briefly, 2.5 g of soil and 25 ml of 1 M ammonium chloride were mixed prior to shaking for 2 h at 150 rpm. Samples were centrifuged for 15 min at 4350 rpm, filtered through Whatman paper 42. Filtrate was diluted by 50% and analysed using inductively coupled plasma-optical emission spectrophotometer: iCAP 7600 Duo ICP-OES Analyser (Thermo Scientific). The ICP-OES was calibrated using commercially prepared stocks of cations and checked using certified reference material (CRM) ERM Ca011a. All samples, blanks and CRMs were spiked with 2 ppm gallium as an internal standard. A reference clay soil from AgroMAT (SPC Science, Canada) was used to confirm that values were within the tolerance intervals. Organic carbon was measured by finely grinding the soil using an agate pestle and mortar, followed by analysis using an Elementar vario MICRO cube and comparison against CRM. Soil type was determined after removing organic matter by slow addition of hydrogen peroxide to the soil samples in a hot plate. Soil was then dried in an oven at 60°C and analysed using a Beckman Coulter LS230 laser diffraction particle size analyser.

2.2.2 | Detection and quantification of CECs in soils

The method validated in Nightingale et al. (2025) was used. Briefly, 2.5 g of freeze-dried and ground (<2 mm) soil was weighed into 15-ml centrifuge tubes. Five millilitres of acetone was added; samples were vortexed for 30 s and sonicated for 10 min. Samples were then shaken at 250 rpm for 16 h, followed by centrifugation at 2500 rpm for 10 min, and then the supernatant was collected. The procedure was then repeated using methanol/McIlvaine buffer (50:50 v/v) and then 50 mM phosphoric acid in acetonitrile, with just a 30-min shake. Extractants were pooled and frozen at −20°C for 24 h prior to solid-phase extraction (SPE). Oasis HLB 500 mg, 6 cc (Waters, Elstree) cartridges were conditioned with 3 ml ethyl acetate, followed by 3 ml methanol and finally 3 ml of deionised water. Extractants were diluted in 285 ml of deionised water to achieve <10% solvent. Samples were loaded on to the cartridge at 5 ml min^{-1} and then dried under vacuum. Cartridges were stored at −20°C until analysis. Elution was done the day prior to liquid chromatography–mass spectrometry (LC-MS) analysis using consecutively 1.5 ml of methanol and 1.5 ml of 0.1% formic acid in methanol/acetone (50:50,v/v). Samples were dried using a Genevac Evaporator (Biopharma, UK) at 30°C and 500 rpm. Reconstitution was done by adding 100 μl of methanol, vortexing for 30 s and sonicating for 10 min at 25°C, followed by addition of 400 μl of deionised water and vortexing and sonicating under the same conditions.

Samples were analysed by LC-MS using targeted and non-targeted approaches (Nightingale et al., 2025). Targeted analysis is performed using a reference standard and provides a concentration in the sample, as well as level 1 confidence (Schymanski et al., 2014). Untargeted analysis provides a 'fingerprint' of the chemical presence within a predefined mass range; the mass spectrum obtained for each chemical is compared against a database, and so it is possible to ascertain with level 2a confidence (Schymanski et al., 2014) whether the chemical is present in the sample, but not to quantify its concentration. For both methods, the same chromatography column was used: Acquity HS T3 C_{18} ligand bonded column (1.8 μm particle size, 2.1 × 100 mm) (Waters, Elstree). For the targeted approach, quantification was achieved using a 10-level calibration curve in the range of 0.01–25.7 ng mL^{-1} and by calculating recoveries based on the addition of 3 ng g^{-1} in methanol of analytes of the highest purity available (≤98%) an hour prior to extraction in samples of all soils extracted. Selected analytes included lamotrigine, sulfamethoxazole, trimethoprim, ofloxacin, carbamazepine, metformin, oxytetracycline, tylosin (Sigma Aldrich), clotrimazole and diclofenac (Cayman Chemicals). Recoveries were 80%–110% for at least two of the three soils for all analytes, except clotrimazole, enrofloxacin, lamotrigine and ofloxacin (recoveries for all analytes for each soil are available in Table S1). Ageing the spiked soils for an hour was done to ensure methanol had evaporated and to obtain recoveries that better approximate field conditions, where the analytes would have had time to sorb to the soil. Therefore, it is expected that recoveries would be lower as compared to if they had been extracted immediately after spiking. Individual stock solutions were made up in methanol (LC–MS grade) and stored at −20°C for ≤3 months. Diluted mixed stock solutions were also made up in methanol. The chromatographic conditions used for the targeted method comprised mobile phase A: 1 mM ammonium formate, 0.1% formic acid in water and mobile phase B: 1 mM ammonium formate, 0.1% formic acid in methanol/acetonitrile. The reversed phase gradient was composed of the following organic percentages: 0%–80% (0.5–8 min), 80%–99% (8.5–9.5 min), 99% (9.5–11.5 min), 99%–1% (11.5–12 min), 1% (12–15 min). Source conditions were as follows: ionisation spray 5000 V, ion transfer tube 350°C and the inert gases were set to 50.7, 18 and 23 for sheath, aux and sweep, respectively. Blanks were run every three injections to ensure the absence of carryover, and a calibration curve was run at the start and end of the run. Thermo Scientific Vanquish and Quantiva software were used for peak integration. Limit of detection and quantification were calculated based on signal-to-noise ratio of 3 and 10, respectively. Limit of quantification was below 1 ng ml^{-1} for all analytes, except for ofloxacin, for which it was 4.7 ng ml^{-1} (details of all limits of instrumental quantification, detection and linearity can be found in Table S2).

For non-targeted screening chromatography composed of a mobile phase A: 0.1% formic acid in aqueous solution and mobile phase B: 0.1% formic acid in methanol. The gradient lasted for 15 min; it started at 99% mobile phase A and was decreased to 1% over 8 min, which was maintained for 2 min and then returned to initial conditions over 0.5 min and kept at these conditions for 3 min. Scans were run using the full scan mode with a resolution of 120,000, in the scan range (*m/z*) 200–1000. A 20 data-dependent product ion scan ($ddMS^2$) scan cycle was selected based on monoisotopic precursor selection, intensity exclusion, dynamic exclusion and apex detection. The RF lens was set to 70, and the polarity was positive at 3500 V. The ion transfer tube and vaporiser temperatures were 320°C and 350°C, respectively. To process spectra, Compound Discoverer (V 3.3.200) was used. The workflow consisted of the following criteria: retention time tolerance of 0.3 min, peak threshold of 10^4, signal-to-noise ratio >3 and a mass accuracy of 5 ppm. Presence was identified where the peak rating was above 5 and the confidence was higher than 70%. Comparisons were made to a blank control; presence at the specific soil was confirmed when 67% of the samples had confirmation and any signal in the controls was below 20% that of the samples. The workflow contained compared spectra against the mZCloud database. Results were further screened by removing any chemicals that are naturally occurring in soils, namely, ethyl oleate. The confidence level that was achieved using this methodology was level 2b (MS/MS) (Schymanski et al., 2014).

2.3 | Assessment of AM colonisation in plants frown from farm soils

Plant pots (1 L) were prepared with each of the three agricultural soils ($n = 6$). Three 'White Lisbon' spring onion seeds (*Allium fistulosum*) from Marshalls Garden were planted in each pot. Pots were maintained at 24°C, an 8-h dark cycle, and 40%–60% humidity for 6 weeks. During harvest, shoot and root tissues were separated, and a sub-sample of roots (roughly 50%) were taken for root staining to assess AM colonisation using the method of Vierheilig et al. (1998). Briefly, sub-samples were cleared in 10% KOH for 40 min at 80°C, stained in acidified ink (Pelikan brilliant black) for 1 h and then destained in 1% acetic acid overnight. After this, roots were mounted on glass slides using 1% acetic acid. One slide was made per pot with 10 root fragments each (roughly three root fragments from each plant per slide). Finally, the intensity of AM colonisation of plant roots was quantified under a light microscope using 20× magnification as per Trouvelot et al. (1986). Following AM fungal colonisation quantification, a one-way ANOVA was performed using R (R Core Team, 2024) and RStudio (Posit Team, 2024).

2.4 | Interviews

We conducted a field visit consisting of a semi-structured interview walking in the fields with the farmer and farm manager at our case study site to understand the practicalities, drivers and barriers of using different soil amendments. The interview, conducted in the summer of 2023, was video recorded and edited into a short video. Discussion was initiated using the following guiding questions, aiming to elicit both general knowledge of the farm and their specific experiences using organic soil amendments:

1. Can you explain your farming system?
   (Size, type of farm, number of people working, machinery, crop rotation, animals, use of fertilisers and herbicides, market)
2. Do you use synthetic fertiliser?
3. Why did you choose to use synthetic fertilisers?
4. When did you start using synthetic fertiliser?
5. Why did you choose to use (or not) organic soil amendments as an alternative to synthetic fertiliser?
6. When did you start using organic amendments?
7. Have you noticed any change in your soil and/or elsewhere from using these organic amendments? Where and how?
8. Have you noticed any change in your yield from using organic amendments?
9. What do you think is a good way in which farmers can share among them their knowledge and concerns about soils?

2.5 | Workshop

A 1-day workshop was held at the University of Leeds research farm. Key stakeholders including farmers, non-profit organisations, government bodies and academics were invited, with a total of 15 attendees, in addition to seven researchers from our team. The final attendant composition was three non-profit environmental organisation members, five farmers, six academics and one person from the private waste management sector. The day consisted of research presentations, a farm tour, results discussions and break out groups to discuss concerns over the reuse of waste as fertiliser. The workshop started with four academic presentations: (1) *introduction to mycorrhizal fungi*, (2) *science behind chemical analysis of soil*, (3) *sustainable agriculture and greenhouse gas emissions* and (4) *the impact of pharmaceuticals in slurry and impact on mycorrhizas*. This was followed by a presentation on preliminary project results (obtained by the research authors), namely, initial contaminant of concern identification in the soils studied and mycorrhizal study results. Finally, the videoed interview was screened for all attendants to see. Four breakout groups, each led by a project member, were organised in advance to achieve a balance of disciplines and backgrounds, and three questions were used to initiate discussion: (1) What benefits do you see from the reuse of waste as fertiliser? (2) What challenges/fears do you see relating to the reuse of waste as fertiliser? (3) What research questions do you think still need to be addressed? Finally, there was time for general discussion on results presented.

3 | RESULTS

3.1 | Soil properties

As can be seen in Table 2, all three soils had a similar silty clay loam texture, with organic carbon content between 2.165% (Soil 1) and 2.876% (Soil 2). Soil pH was between 6.5 (Soil 1) and 6.7 (Soil 2). It increased for both Soils 1 and 2 following the AM colonisation study but decreased for Soil 3 (from 6.6 in field conditions to 5.9 following the AM study). Cation exchange capacity and nutrient content were similar across all soils; however, variability was observed for phosphate and nitrate. Phosphate content ranged from 35.8 mg kg^{-1} in Soil 1, followed by 15.3 mg kg^{-1} in Soil 3 and 6.6 mg kg^{-1} in Soil 2. Nitrate followed the same trend with Soil 1 > Soil 3 > Soil 2, with concentrations of 9.2, 6.8 and 2.5 mg kg^{-1}, respectively.

3.2 | CEC presence in case study farm soils

A total of 16 chemical pollutants were detected across the soils. Pharmaceuticals used exclusively by humans and both by humans and animals were the most prevalent chemicals present in all soils (Figure 1). They were followed by chemicals of agricultural use and, finally, by the plasticiser stearamide. Soil 3 had the greatest number of chemicals from agricultural use, followed by Soil 1 and then Soil 2 (three, two and one, respectively). All soil samples taken from the farm (i.e. ‘field conditions’) had the same number of chemicals from other categories (human-only = 4, human and animal = 4 and plasticiser = 1). In Soil 1, one less human-only pharmaceutical and one more human and veterinary pharmaceutical were detected after spring onion harvest. In Soil 2, after spring onion harvest, the human-use pharmaceuticals detected decreased by one, whereas they decreased by two in Soil 3, along with human- and veterinary-use pharmaceuticals.

3.2.1 | Targeted quantified CECs

Of the identified CECs, a total of six were quantified in the soils studied through targeted LC-MS using reference standards as can be seen in Table 3. Of these, diclofenac, the non-steroidal anti-inflammatory drug used to treat pain and swelling, and the anti-epileptic lamotrigine are of exclusive human use. The antibiotic used to treat bacterial infections, ofloxacin, is not licensed for veterinary use (although it can sometimes be used to treat eye infections in animals). Trimethoprim (an antibiotic used to treat bacterial infections) and clotrimazole (an antifungal used to treat yeast-caused infections) are used both for humans and animals. Finally, the broad-spectrum organophosphate insecticide diazinon is of agricultural use.

The presence of four CECs was outside the calibration range of the targeted method. Therefore, their presence was confirmed with analytical reference standards, giving the maximum confidence of level 1 (Schymanski et al., 2014), but quantification was not possible. Of these four identified chemicals (Table 4), two are exclusively of human use: the antiepileptic carbamazepine and the antidiabetic metformin. Oxytetracycline, the antibiotic of human and veterinary use, was also identified, as well as tylosin, a bacteriocyte and feed additive.

The antibiotics sulfamethoxazole and enrofloxacin were not detected in the soils studied. Enrofloxacin recoveries were low

TABLE 2 Characteristics of the three farm soils studied (Soil 1 [red]: most recent biosolid application, Soil 2 [green]: most recent farmyard manure application, Soil 3 [yellow]: no organic amendment in the last 5 years).

		Soil texture					Cation exchange capacity (meq 100 g^{-1})				
	Soil	Clay (%)	Silt (%)	Sand (%)	Organic carbon (%)	pH_{CaCl2} ($n = 3$)	Total (Ca^{2+}, K^{+}, Mg^{2+}, Na^{+})	Calcium (Ca^{2+})	Potassium (K^{+})	Magnesium (Mg^{2+})	Sodium (Na^{+})
Field conditions	1	30.80 ± 2.40	61.50 ± 4.80	7.74 ± 0.06	2.876	6.5 ± 0.0	16.29 ± 0.33	14.16 ± 0.26	0.58 ± 0.02	1.51 ± 0.04	0.05 ± 0.01
	2	29.48 ± 1.47	61.30 ± 3.07	9.25 ± 0.46	2.556	6.7 ± 0.0	15.82 ± 0.08	13.15 ± 0.05	0.53 ± 0.01	2.10 ± 0.02	0.04 ± 0.00
	3	32.33 ± 1.20	66.00 ± 2.44	1.67 ± 0.06	2.165	6.6 ± 0.1	14.21 ± 0.33	11.26 ± 0.21	0.50 ± 0.02	2.39 ± 0.06	0.06 ± 0.02
After spring onion harvest	1	—	—	—		7.0 ± 0.0	16.12 ± 0.38	12.83 ± 0.23	0.91 ± 0.03	2.18 ± 0.05	0.20 ± 0.06
	2	—	—	—	2.353	6.9 ± 0.0	15.56 ± 0.08	13.00 ± 0.05	0.62 ± 0.01	1.76 ± 0.02	0.20 ± 0.00
	3	—	—	—	1.971	5.9 ± 0.0	14.56 ± 0.27	9.29 ± 0.17	0.54 ± 0.02	1.73 ± 0.04	0.16 ± 0.04

TABLE 2 (Continued)

	Nutrients (mg kg^{-1})						
	Fluoride	Acetate	Chloride	Nitrite	Nitrate	Sulphate	Phosphate
Field conditions	1.73 ± 0.03	0.35	6.46 ± 1.38	3.03 ± 0.03	9.17 ± 2.08	23.10 ± 0.52	35.77 ± 2.14
	3.60 ± 0.05	<DL	5.13 ± 1.09	1.66 ± 0.01	2.54 ± 0.58	26.54 ± 0.60	6.58 ± 0.39
	2.86 ± 0.04	<DL	6.64 ± 1.42	3.78 ± 0.03	6.77 ± 1.54	24.18 ± 0.55	15.27 ± 0.92
After spring onion harvest	3.44 ± 0.05	0.25	62.15 ± 13.27	14.53 ± 0.12	162.14 ± 36.84	137.0 ± 3.10	24.66 ± 1.48
	3.07 ± 0.05	<DL	51.34 ± 10.96	71.18 ± 0.60	209.35 ± 47.57	177.89 ± 4.03	34.32 ± 2.06
	2.79 ± 0.04	<DL	16.24 ± 3.47	15.94 ± 0.14	50.31 ± 11.43	87.00 ± 1.96	20.31 ± 1.22

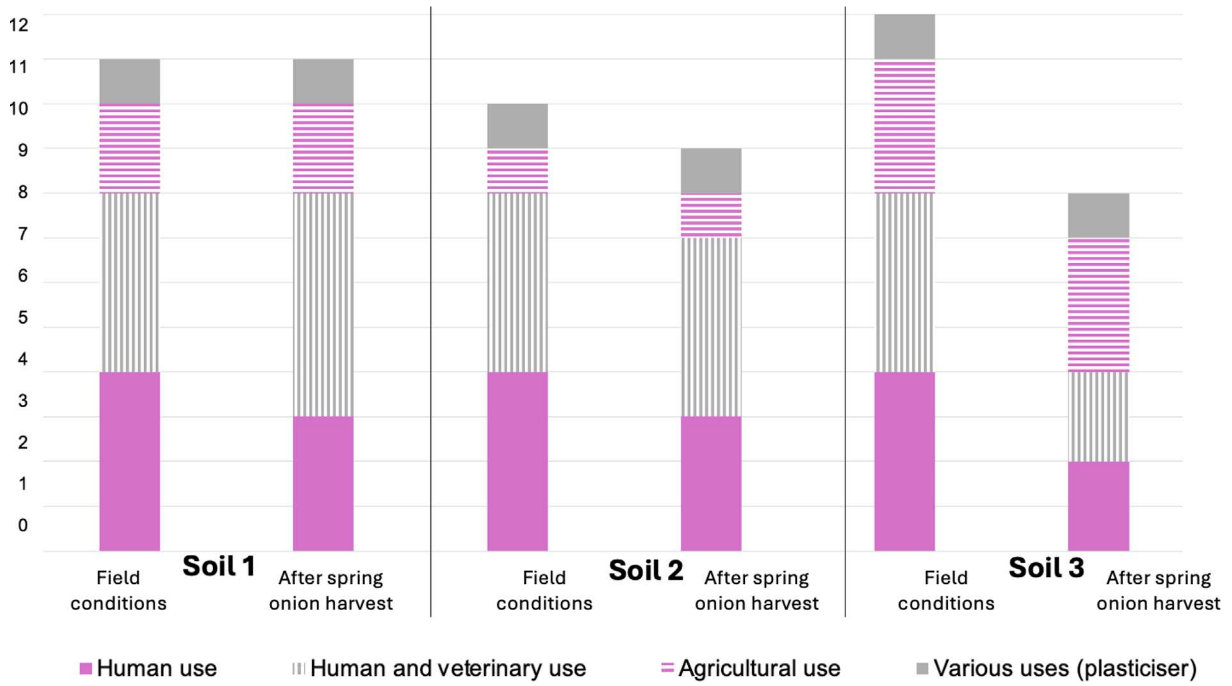

FIGURE 1 Number of contaminants of emerging concern categorised by chemical origin (exclusive human use; human and veterinary use; agricultural use and plasticiser) found in each soil (Soil 1: most recent biosolid application, Soil 2: most recent farmyard manure application, Soil 3: no organic amendment in the last 5 years).

TABLE 3 Results from the liquid chromatography–mass spectrometry targeted analysis, contaminants of emerging concern identified with level 1 confidence and quantified in the soils studied (Soil 1 [red]: most recent biosolid application, Soil 2 (Green): most recent farmyard manure application, Soil 3 (Yellow): no organic amendment in the last 5 years).

Chemical class	Soil	Diclofenac Human use non-steroidal anti-inflammatory drug	Lamotrigine Human use anti-epileptic	Ofloxacin Human antibacterial	Trimethoprim Human and veterinary antibiotic	Clotrimazole Human and veterinary antifungal	Diazinon Agricultural insecticide
Field conditions	1	0.2977 ± 0.0256	0.011 ± 0.002	11.919 ± 1.978	0.014 ± 0.004	0.419 ± 0.073	0.0019 ± 0.0001
	2	BLD	0.019 (0.013, BLQ,0.025)	7.935 ± 1.724	0.044 ± 0.027	1.053 ± 0.195	0.0031 ± 0.0002
	3	0.4325 ± 0.0850	BLD	8.205 ± 2.662	0.020 ± 0.003	1.594 ± 0.1000	0.0022 (0.0021, 0.0024)
After spring onion harvest	1	BLD	BLQ	52.532 (48.121, 56.943)	0.041 ± 0.005	0.261 ± 0.080	0.0016 ± 0.0006
	2	BLD	BLD	52.154 ± 3.783	0.063 ± 0.004	1.118 ± 0.250	0.0015 ± 0.0006
	3	BLD	BLD	BLD	0.294 ± 0.021	0.392 ± 0.019	0.0383 ± 0.0141

Abbreviations: BL, below limit of detection; BLQ, below limit of quantification.

(19.0%–25.1% across the three soils), which may be the reason this pollutant was not detected. However, sulfamethoxazole recoveries were 68.7%–107.5%.

3.2.2 | Untargeted CEC results

The untargeted screening of the chemicals found in the soils revealed the presence of six pollutants with confidence level 2a, meaning that they were identified by library spectrum match (Schymanski et al., 2014). Three of the chemicals identified were of agricultural use, one was a veterinary anthelmintic, and another was the digestion metabolite of liquorice, which is used widely as a sweetener and human and veterinary pharmaceutical ingredient (Zhang et al., 2020). Full details can be found in Table 4.

3.3 | AM colonisation evaluation across the three soils studied

All plant roots were well colonised by AM fungi, with >80% root length colonisation in some cases (Figure 2). The lowest values

TABLE 4 Results from the liquid chromatography–mass spectrometry targeted analysis, contaminants of emerging concern identified with level 1 confidence in the soils studied (Soil 1 [red]: most recent biosolid application, Soil 2 [green]: most recent farmyard manure application, Soil 3 [yellow]: no organic amendment in the last 5 years).

Chemical class	Soil number	Carbamazepine Human antiepileptic	Metformin Human antidiabetic	Oxytetracycline Human and veterinary antimicrobial	Tylosin Human and veterinary antibiotic and feed additive
Field conditions	1	Present	Present	Present	Present
	2	Present	Present	Present	Present
	3	Present	Present	Present	Not detected
After spring onion harvest	1	Present	Present	Present	Present
	2	Present	Present	Present	Present
	3	Present	Present	Not detected	Not detected

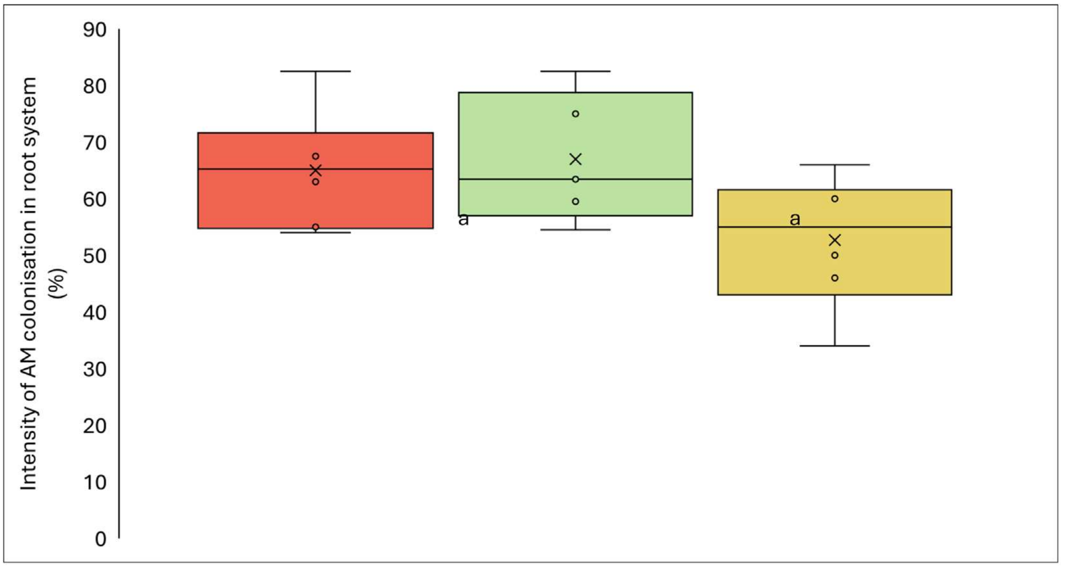

FIGURE 2 Arbuscular mycorrhizal fungi colonisation in spring onion roots. Red = Soil 1, green = Soil 2, yellow = Soil 3 (Soil 1: most recent biosolid application, Soil 2: most recent farmyard manure application, Soil 3: no organic amendment in the last 5 years, $n = 6$). Boxes extend from the 25th to 75th percentile, and whiskers extend to maximum and minimum data points. Lines in boxes indicate median values, and X's indicate mean values. Significant differences are represented by different letters (one-way ANOVA).

recorded were in plants grown in Soil 3 (synthetic amendments); however, differences between soils were not significant ($p = 0.09922$, df = 2, $F = 2.737$, one-way ANOVA; Figure 2).

3.4 | Interview with farmer and farm manager

The interview with the farmer and farm manager is available to watch in Video 1. Their decision to use organic amendments as alternatives to synthetic fertilisers stemmed from a combination of hope for improving soil fertility, soil structure and organic matter while also reducing fertiliser costs and enhancing production. To achieve this, they use different amendments on different fields across their farm, including organic (biosolids and farmyard manure) and inorganic (synthetic fertilisers), dependent on the crop: 'We're trying to use the combination of all the different sorts of fertiliser together to bring our crops to harvest', they explained. In their farm system, biosolids supply phosphates, farmyard manure provides potash and synthetic fertilisers add the main source of nitrogen.

In addition, they consider farmyard manure as the most effective for enhancing soil structure and organic matter, while biosolids offer less organic content. As part of their farm system, they also incorporate straw residues post-harvest for winter oil seed rape, bean and wheat, which returns organic matter and nutrients to the soil and promotes microbial populations (Ninkuu et al., 2025). Overall, this approach reduces fertiliser costs and gradually improves soil structure, also thanks to the adoption of reduced tilling methods such as minimum till and direct drilling. Although they say that yield improvements are challenging to measure due to variable weather patterns, they have perceived improvement in soil structure and machinery handling over time: 'Over the years we're not noticing huge differences in yield either way because of the weather patterns that we're getting are upsetting our averages … [The fields are] carrying the machinery better because the soil has not been cultivated so much. We are using min-tilling, so the soil is not slumping'.

When the field from Soil 3 was brought back into cropping after being used for grazing in 2020, synthetic fertiliser was used to bring the nitrogen content of the soil up for the requirements of the milling wheat crop, and no organic amendment had been used for over 5 years. However, since August 2023, they have applied biosolids (after our sampling took place) and hope to continue applying organic amendments (biosolids and manures) instead of synthetic fertilisers.

However, they are cautious about the environmental impact of biosolids and manure applications, as they desire to improve the soil without causing harm: 'There are always concerns [when applying organic amendments]. We apply it with the best of intentions, and it would be upsetting to learn that actually we are doing harm rather than good'. Considering the array of uncertainties farmers experience day by day, it is crucial that research into the fate and effects of CECs can provide certainty of how biosolids impact the fungi and soil health of the farm. In this way, farmers' intentions of using biosolids can at least be aligned to their expectations.

3.5 | Workshop with stakeholders

There was consensus that the reuse of organic waste as fertiliser has the potential to provide a vital resource within the farming community provided key research questions are answered to identify and prevent any risks posed by chemicals found in it. Benefits of the reuse of waste as fertiliser were identified as:

- Decreasing reliance on synthetic fertilisers and therefore depleting finite resources, thus increasing farm security.
- Improving soil health and stabilisation by returning nutrients, organic matter and carbon into the agri-food system.
- Offering an option for waste reuse aligning to the principles of circular economy.
- Reducing overhead costs for farmers by decreasing the need to buy synthetic fertiliser and instead either reusing their own or other's waste or through the exchange of resources, for example, straw for muck (farmyard manure) arrangements.

Alongside the benefits of the reuse of waste as fertiliser, concerns and challenges identified included:

- The risk of applying a material with unknown properties, for example, CEC content and concentration.
- The lack of guidance and regulation around waste reuse, particularly on requirements to assess and disclose content of chemicals of non-farm derived waste (e.g. sludge).
- There is increasing pressure on the agriculture sector to reduce its carbon emissions and the reuse of organic wastes as fertilisers enables alignment with the principles of a circular economy and reducing overall carbon emissions. While this currently is not a main driver of the reuse of waste as fertiliser, it is expected to play an increasing role as we tackle the challenges of climate change.
- Lack of long-term scientific monitoring and research of chemical environmental presence and effects leading to environmental issues being identified until it is too late and soil has been irreversibly contaminated.
- Social concerns around the use of wastes on soil including smell and sanitation concerns.
- The misalignment with the regenerative agriculture practice of no-till as it is not possible to use waste as fertiliser and use a no-till approach.
- Timing and logistical challenges in terms of waste location and time production not aligning to when or where it is needed in the crop cycle. For example, in the farm from this case study, the amendment choice depends the on crop calendar: Biosolids are used before planting oil seed rape and farmyard manure is applied prior to winter wheat and synthetic fertiliser and before beans and barley. Crop choice is also dependent on environmental conditions, for example, oil seed rape in 2021 was not possible so winter linseed was planted instead.

Key research questions identified for further research in the intersection between farmer needs and constraints around soil amendments, waste regulation and the unknowns around the risks posed by CECs found in organic wastes with the potential to be used as soil amendments are detailed below:

1. Which waste parameters should be measured and reported to inform on-the-ground farmer decisions as well as inform (or meet future) policy and reporting regulations? Should CECs be routinely monitored before a waste is used as fertiliser? If so, which CECs?
2. How can farmers decide which waste, with a given CEC profile, would present a higher risk depending on their soil type and crop? How would this link to other factors considered when choosing a waste such as nutrient content, cost, availability, crop needs and carbon footprint?
3. What are the impacts of different organic waste storage methods on CEC presence and fate?
4. What are the long-term effects to soil health of using a variety of wastes with a varying CEC profile? And what are the impacts on differing soil types on this?
5. What are the multi-stressor effects on crops or soil health, for example, of CECs and drought?
6. Are incentives for the reuse of waste as fertiliser appropriate at the regulatory level?
7. How does CEC presence and fate vary depending on waste management and application practices, in particular:
   a. Solid (organic fertilisers such as farmyard manure, anaerobic digestate or sludge) versus liquid (farmyard slurry or compost tea).
   b. Dewatering of solid organic fertilisers. Dewatering is the process in which the liquid is removed from the solid organic fertiliser to produce a dry fibre compost. This process has the

benefits of enabling water reuse, increasing the nutrient concentration within the fertiliser and decreasing the bulk of the fertiliser, making transport and storage easier. However, there is little research on how CECs are partitioned within this process and how this effects their fate within the agri-environment.

Organic fertiliser can be applied to the soil via broadcasting (with or without incorporation into soil), which is where the manure is spread onto the surface of a field, then mixed into the soil if incorporated or if liquid manure, it can be injected directly below the surface of the soil. Each process is known to have different impacts on nutrient availability, but there is limited research into the impact on the fate of CECs within the soil.

4 | DISCUSSION

4.1 | Identified benefits of the use of organic soil amendments

The benefits of the reuse of waste as fertiliser were acknowledged by the workshop participants, from an academic, environmental and farming point of view. It was agreed that the reuse of waste as fertiliser has the potential to play an important role in improving soil health, increasing farm financial security, reducing pressure on finite nutrient resources and reducing synthetic fertiliser production. Farmers in our study (interview and workshop) demonstrated genuine interest in understanding the composition and effects of the biosolid fertilisers they use, actively welcoming further research in this area. Their attentiveness to soil conditions and eagerness to learn reflect a deep engagement with soil stewardship.

The soil property results demonstrate an alignment between the nutrients measured and the farmer's expectations on nutrient contribution depending on the soil amendment history of each field. The significantly higher ($p < .001$) phosphate concentration found in Soil 1 (35.77 ± 2.14 mg kg^{-1}), over double that in Soil 3 and over five times that of Soil 2, is in line with the farmers' description of using biosolids to supply phosphates, as Soil 1 had been the one most recently amended with this material. Potassium content was described by the farmer to be obtained from farmyard manure, and it was significantly lower ($p < .05$) in Soil 3 (0.50 ± 0.02), which had not received farmyard manure in recent farming history (Table 1). The other two soils, which had received farmyard manure in recent farming history, had significantly higher potassium, with 0.58 ± 0.02 and 0.53 ± 0.01 mg kg^{-1} in Soil 1 and Soil 2, respectively. Finally, the farmer indicated that synthetic fertilisers are the main source of nitrogen, and this trend was observed for nitrite, where the significantly higher ($p < .001$) concentration was found in Soil 3 (3.78 ± 0.03 mg kg^{-1}), which had received synthetic fertiliser most recently, followed by Soil 1 (3.03 ± 0.03 mg kg^{-1}) and Soil 2 (1.66 ± 0.01 mg kg^{-1}). However, nitrate was not significantly different between Soil 1 (9.17 ± 2.08) and Soil 3 (6.77 ± 1.54) but was significantly ($p < .05$) lower for Soil 2 (2.54 ± 0.58). The balance in nutrient contribution arising from the different types of soil amendments used speaks to the farmer's and farm manager's knowledge and understanding of these organic waste resources.

4.2 | Identified drawbacks of the use of organic soil amendments

The main drawback we identified from this case study was the uncertainty around the use of organic amendments. This uncertainty was identified in two senses: firstly as expressed by the farmers and workshop attendants in terms of uncertainty about the effects on soil and the wider environment and secondly by the lack of conclusive information about the presence and effects of CECs in these materials. The positive engagement observed from the farmers and wider environmental community in this study is potentially undermined by the aforementioned uncertainties. The implications are significant: While farmers' intentions to adopt more sustainable practices are strong, the success of soil care initiatives depends on complete transparency around the effects on the soil and wider environmental systems of the materials introduced into agricultural systems. Without clear information about the composition (including CEC content) and effects of organic soil amendments, farmers' efforts to care for soil and the wider environment may be compromised. This suggests that the transition to circular economy practices requires not just farmer buy-in but also robust systems for research, information sharing and quality assurance of alternative fertiliser products. CEC soil presence in this study was intended as a snapshot and discussion point with the farmers and workshop attendants. It consisted of a single grab sample per field and, as such, is not comprehensive of physical or temporal variability in terms of field topography and the history of varied soil organic amendments used in each field.

The only chemical recognised as being used in the farm by the farmer and farm manager was clothianidin as being used for 'seed treatment only and in small quantities prior to the substance being banned in 2018'. Clothianidin has a half-life in soil ranging from 144 to 7000 days, which means it is possible its presence is from the use prior to 2018 (Vickneswaran et al., 2023). The farmer and farm manager stated that the other identified chemicals of exclusive agricultural use had not been used recently (at least not since 2015). These were the insecticide diazinon, the anthelmintic veterinary pharmaceutical fenbendazole sulfoxide, the derivative of difenzoquat herbicide difenzoquat metilsulfate (Kim et al., 2019) and the toxic fungicide flusilazole (Šudoma et al., 2019). Diazinon has been banned in the EU since 2007 (European Food Safety Authority [EFSA] et al., 2023). However, diazinon is the most commonly used active ingredient in the United Kingdom to treat and prevent sheep scab (Smith et al., 2023), and the farmer has stated the farmyard manure obtained from the farm next door is from sheep, so it would likely come from this source. However, this does not explain why higher concentrations were found in Soil 2 where farmyard manure had not been used in the past >10 years prior to sampling; this may be due to runoff from the neighbouring farm but would necessitate further investigation. Fenbendazole sulfoxide may be present for a similar reason in Soil 3, as it has not been used in the farm since the 1970s when they last had livestock. Difenzoquat has been banned in the EU since 2002, so its presence must be from historic use, which is possible given its high soil half-life of 6810 days (Pateiro-Moure et al., 2010).

However, the reported presence of five chemicals of exclusive human use (Figure 1 and Tables 3 and 4), ubiquitous in wastewater-derived biosolids (Gottschall et al., 2012; Mejías et al., 2021; Sellier et al., 2022), is indicative of them entering the environment via biosolids application. These included the anti-epileptics lamotrigine and carbamazepine, the non-steroidal anti-inflammatory drug diclofenac, the antidiabetic metformin and the antibiotic ofloxacin. Despite the relatively low recoveries of ofloxacin (Table S1), it was quantified at the highest concentration across all soils (7.9–52.5 ng g^{-1}, as can be seen in Table 3). This is in line with previous research acknowledging it as persistent and prevalent in sludges (as other quinolones) (Sellier et al., 2022), as well as its particularly high DT_{50} of 1.10–2.01 years (Yang et al., 2018). It is important to note that diclofenac, carbamazepine and metformin were also detected in Soil 3 (Tables 3, 4 and 5), which is unexpected given that this soil has not had biosolids application in recent years (<5 years). All three of these pollutants have been reported to be persistent in the environment (Ambrosio-Albuquerque et al., 2021; Baldasso et al., 2024; Mejías et al., 2021; Thelusmond et al., 2018), the DT_{50} in soil for carbamazepine of 533.2 days (Lautz et al., 2017). Despite their reported soil persistence, the reported DT_{50} values for diclofenac and metformin are <5 (Al-Rajab et al., 2010) and 5 days (Mrozik & Stefańska, 2014), respectively. Their presence in Soil 3 may be due to surface runoff from fields where biosolids were applied. Diclofenac and lamotrigine were not found in soils following spring onion harvest, possibly due to plant uptake (Bigott et al., 2021; Siemieniuk et al., 2021), soil sorption or microbial degradation (Mosharaf et al., 2024). In addition to chemicals of exclusive human use, six chemicals of human and veterinary use were identified across all soils. These included three antibiotics (trimethoprim, oxytetracycline and tylosin), two antifungals (clotrimazole and flusilazole) and one metabolite of a food additive (18-β-glycyrrhetinic acid). The presence of these pharmaceuticals can be explained by the application of biosolids and farmyard manure. In particular, tylosin has been reported by the farmer to be likely present due to use in sheep (therefore presence in farmyard manure) or from slurry from livestock (also exposed to this chemical), as confirmed by wide UK usage figures of these chemicals (Davies et al., 2023).

The concentrations of human and veterinary pharmaceuticals measured are comparable to those reported in the literature (Baldasso et al., 2024; Martin & Hart, 2023; Mejías et al., 2021; Wu et al., 2023), accounting for expected differences based on many factors such as initial sludge content (which may depend on population consumption and wastewater treatment method), method of application and potential agricultural runoff, soil type, crop grown and other environmental factors (such as catchment-specific characteristics), all of which mean a wide variety is not unexpected. For example, lamotrigine has been quantified in other agricultural soils ranging from 1500 to 9000 ng g^{-1} (Baldasso et al., 2024), concentrations higher than those found in this study (>0.01 ng g^{-1}, as can be seen in Table 3), and trimethoprim concentrations found in this study (0.014–0.294 ng g^{-1}; Table 3) are at least an order of magnitude lower than those reported in other sludge amended soils (0.64–2.15 ng g^{-1}) (Mejías et al., 2021). Previous research indicates that antimicrobials are found to be at higher concentrations in soils receiving cattle, chicken and swine manure, compared to biosolids (Wu et al., 2023). The presence of trimethoprim seems to follow this trend, with higher concentrations found in Soil 2 (most recently having received manure) than Soil 1 (most recently having received biosolids). It is important to quantify and understand the variability in CEC concentrations in agricultural environments as this will directly link to the local environmental risk posed by these chemicals.

One of our results for the spring onion trial speaks to the importance of the link between chemical pollution concentration and other environmental and agricultural factors, such as crop affecting soil pH. The concentration of trimethoprim increased following the harvest of spring onion, potentially due to the increased pH in all three soils following harvest (Table 2). Trimethoprim has a pK_a of 7.2, which means that it is found in a greater proportion in its ionised state at higher soil pH, meaning it has less affinity for solid matter, making it more available for extraction of soil and analysis. For both Soil 1 and 2, the concentration of ofloxacin, like trimethoprim, was greater following the harvest of spring onion. Again, this may be due to the pH of the soil being more acidic pre-harvest, meaning ofloxacin would be found in its protonated form, in which it is known to have strong electrostatic interactions with the clay and organic matter in the soil (Parente et al., 2019), making it less available for extraction (and less bioavailable in the environment).

The presence of four antibiotics, namely, trimethoprim, ofloxacin, oxytetracycline and tylosin, evidences the need for further research in terms of potential AMR threats. Further studies to determine the presence of AMR genes in this farm would elucidate the extent to which current agricultural practices are leading to potential AMR. Previous research has already demonstrated oxytetracycline (and other antimicrobials) presence alongside antibiotic-resistant genes including *tetA* and *tetB*, related to tetracycline resistance, following manure application in soils (Wei et al., 2019). Previous research indicates that compared to single manure applications, mixed manure/biosolids application may cause more severe enrichment of AMR genes (Wu et al., 2023), which could be of concern in an agricultural scenario such as the one studied here.

In addition to AMR, antifungal resistance is of growing concern, including the role of environmental selection (Environment Agency, 2022). In this study, the human and veterinary antifungal clotrimazole was quantified in all soils, in line with its reported environmental persistence (Mejías et al., 2021) and a recent UK study which quantified it in wastewater biosolids from seven sites, with a median concentration of 1.32 mg kg^{-1} (dw) (Martin & Hart, 2023). In the present study, the highest concentration was found in Soil 3, as the farmer reports no recent (since at least 2015) use of this chemical; this indicates likely presence from farmyard manure from a neighbouring farm. Clotrimazole, alongside other azole antifungals, was also added to the 3rd EU Water Watch List in 2020, which includes the top 10 priority substances or groups of substances that are potentially detrimental to the aquatic environment and require better monitoring, including their potential to select for resistance.

Finally, the untargeted approach highlighted the need to understand the presence of previously understudied chemicals in soils, such as streamide, which was detected in all soils (Table 4). Streamide is used in the manufacture of plastics such as polyvinyl chloride (PVC) and has been previously detected as a pollutant in aquatic environments (Selwe et al., 2024); however, little is known about its presence in agricultural soils.

4.3 | Unknowns to be addressed for a safe use of organic wastes as soil amendments

In addition to the specific research questions identified by the workshop participants (detailed in Section 3.3), we outline below areas identified from the analysis of the results of this case study.

4.3.1 | What do the measured CEC concentrations mean in terms of environmental risk?

It is difficult to assess the potential environmental impacts of the CECs detected in the farm soils, as our current understanding of CEC-induced toxicity is limited by a focus on understanding their impacts in aquatic species (Carter et al., 2025; Maddela et al., 2022; Masinga et al., 2024; Wang et al., 2024). A more comprehensive evaluation of potential risks in the agricultural environment necessitates assessing toxicity at environmentally relevant concentrations, considering long-term effects and considering the soil compartment (as opposed to hydroponic assessment). In addition, chemical toxicity must be evaluated as a mixture (as this work shows there are a wide variety of chemicals present, from human, veterinary, industrial and agricultural sources, which may act synergistically or antagonistically) (Carter et al., 2025; Garduño-Jiménez & Carter, 2024). In addition, it is necessary to study sublethal endpoints that can compound to affect whole ecosystems (Straub et al., 2020).

There is also the added risk of the spread and development of antibiotic resistance, which has led to the development of predicted no effect concentration of resistance for a range of antibiotics (PNEC-R). These to date have been developed mainly through three different mechanisms: isogenic single species competition assays (Gullberg et al., 2014) and estimation of selective endpoints using minimum inhibitory concentration data (Bengtsson & Larsson, 2016) and through in vitro models utilising the wastewater microbiome (Murray et al., 2024). For both antibiotics quantified, the measured concentrations were below the lowest published PNEC-R of 0.5 μg L^{-1} for ofloxacin (Bengstsson-Plam & Larsson, 2016) or 1.56 μg L^{-1} for trimethoprim (Murray et al., 2024), indicating no direct risk. However, published PNEC-Rs have not been developed for soil microorganisms, which will differ from water and clinical microorganisms, and currently, there is no accepted standard for the calculation of PNEC-Rs. In addition, it would be necessary to consider the effect of co-exposure to other non-antimicrobial pollutants like pharmaceuticals, heavy metals and biocides, which create conditions that favour the development of AMR (James et al., 2023; Murray et al., 2024; Stevenson et al., 2022; UNEP, 2023).

4.3.2 | What are the effects to mycorrhizal colonisation depending on organic soil amendment and crop?

Under the agricultural conditions of the farm studied, and for the spring onion variety assessed (albeit over a relatively short time frame), there is little discernible impact of the amendments used on mycorrhizal colonisation of plant roots, despite the differing soil amendment histories of Soils 1, 2 and 3 (see Table 1 for amendment histories). However, it is important to contextualise these results against the prevailing specific agricultural and environmental conditions, such as the type of crops grown, the organic amendment/s used, and soil type. Additionally, the pots used in this experiment limited the volume of soil the AM fungi could extend into, thus allowing the AM fungi and plant roots to interact closely, perhaps more closely than they would in the field if fungal propagules are present in low abundance, as is often the case in agricultural soils (Verbruggen et al., 2013). Interestingly, AM fungal colonisation of roots of the plants in our study was not impacted by the presence of clotrimazole, an azole antifungal drug, at higher concentrations in Soils 2 and 3 compared to Soil 1 (Table 2). This aligns with previous research showing that the ability of AM fungi to colonise and form associations within wheat roots is not affected by the presence of azole antifungals (Sallach et al., 2021). However, it contrasts with results from Durant et al. (2025) who showed the same antifungals reduced AM colonisation in spring onion and lettuce systems at 100 ng g^{-1}. Therefore, it is likely that the concentrations present in the soil tested were too low (0.419 ng g^{-1} in Soil 1 to 1.594 ng g^{-1} in Soil 3) to affect the ability of AM fungi to colonise host plant roots. However, we did not test the functionality of the associations formed, and so, it remains unknown whether the treatments impacted any potential AM-associated benefits such as plant nutrition or stress tolerance. As in all mycorrhizal research, some caution should be taken when interpreting microscopical root colonisation data as AM fungal colonisation was assessed in only a relatively small subset of roots. Given the patchy nature of colonisation by AM fungi, this may not be fully representative of the whole root system of each plant and is further evidence of the need for studies assessing sublethal endpoints which may have cascading effects in the ecosystem. The degree of colonisation of roots by AM fungi observed here may not accurately reflect the overall benefits of AM associations derived by the host plants, especially those not nutrient-related, or the fungal acquisition of plant-fixed carbon.

4.3.3 | What is the farmer's role in implementing best agricultural practice in the context of organic soil amendments?

Adoption of regenerative practices 'is driven both by a desire to make environmentally beneficial changes as well as a logic of economic pragmatism, either in terms of increasing productivity or, more presciently in the circumstances, reducing costs' (Beacham et al., 2023). Consequently, the drive to move away from synthetic fertilisers faces the challenge of finding a balance between the profitability of the farm and the risks involved in changing an agricultural system reliant on synthetic fertilisers, a heritage of the green revolution. The risks and uncertainties of this process of change in farming practices are generally absorbed by the farmer, just as 'caring for soils is currently configured primarily as the obligation of the individual farmer, whose power to act is constrained' (Krzywoszynska, 2019). This means that various degrees of support, including knowledge exchange and financial subsidies, are key to encourage appropriate practices from the soil microbiology perspective to help the transition to new production methods. Our research aligns with previous observations that the farmers' adoption of regenerative practices is motivated by both environmental consciousness and economic pragmatism, particularly regarding productivity and cost reduction (Beacham et al., 2023). This was demonstrated in our interview with the farmer and land manager, as we discussed above.

The benefits of biosolids perceived by research participants could be neutralised and diminish their use if the uncertainties are not clarified. The farmer's interest in this matter, in the context of a climate change emergency, creates significant momentum. This, combined with the need for more research to achieve more conclusive results, creates the social conditions to produce a generative route of action for research collaborations. This can effectively reduce uncertainty about the soil effects of biosolids and include by-case farm studies to enrich the depth of knowledge about biosolids for the farming and scientific communities.

4.3.4 | The need for transdisciplinary approaches

If properly implemented, transdisciplinary approaches have been shown to be very effective for successful social change for positive environmental impact (Kiatkoski Kim et al., 2022). The research questions identified need to be answered by a wide variety of disciplines and stakeholders; it is not possible to provide farmers with the information they need to make the choice of which soil amendment to use based on environmental, profitability and practicality issues from within single discipline silos. This demonstrates the importance of building multidisciplinary research networks with stakeholder involvement to develop research that can inform practical and environmentally sustainable agricultural practices.

5 | CONCLUSION

This work united social, chemical and biological expertise alongside stakeholder engagement for a holistic appreciation of the effects of CECs entering the agricultural environment following organic waste reuse as soil amendments. The presence of 17 CECs, with a high proportion of human-use chemicals, was confirmed in the farm case study where wastewater-derived biosolids and farmyard manure are used as soil amendments. The assessment of the effect of soils with differing amendment history on AM colonisation revealed no significant effect on AM colonisation of plant roots depending on soils but provided an important discussion topic with key stakeholders on the different endpoints that CECs in soils may affect. Farmers and policy stakeholders demonstrated a keen interest in understanding the effect of organic soil amendments in their soils and the wider environment, reflecting a growing engagement with soil stewardship. Their involvement in discussing the chemical, biological and social findings of this case study led to the identification of five key research questions that span elucidating unknown chemical presence and effects, policy around waste reuse and chemical presence transparency and integrating environmental concerns with farming practicalities such as crops' nutrient demands, costs and soil organic waste availability. Further research is still needed to answer many questions around the sustainable reuse of organic amendments in soils, but the integration of disciplines and stakeholders in the process can aid in ensuring efforts remain focused on providing practical and relevant answers for more sustainable agricultural practices.

AUTHOR CONTRIBUTIONS

Felicity C. T. Elder, Jose-Luis Fajardo-Escoffié, Laura Carter, Katie J. Field, Brett Sallach and Andrea-Lorena Garduño-Jiménez designed the research. Felicity C. T. Elder, Jose-Luis Fajardo-Escoffié John Nightingale and Andrea-Lorena Garduño-Jiménez conducted fieldwork, interviews and carried out laboratory experiments. Felicity C. T. Elder, Jose-Luis Fajardo-Escoffié, Emily K. Durant, Laura Carter, Katie J. Field, John Nightingale and Andrea-Lorena Garduño-Jiménez analysed and interpreted the data. Felicity C. T. Elder, Jose-Luis Fajardo-Escoffié, Laura Carter, Emily K. Durant, Katie J. Field, John Nightingale and Andrea-Lorena Garduño-Jiménez wrote the manuscript.

ACKNOWLEDGEMENTS

All authors would like to thank the White Rose University Consortium Collaboration Fund, which made this work possible. Felicity C. T. Elder, John Nightingale, Laura Carter and Andrea-Lorena Garduño-Jiménez would like to thank Research England (UKRI) for the funding from a Future Leaders Fellowship (grant no. MR/S032126/1). Jose-Luis Fajardo-Escoffié would like to thank Economic and Social Research Council (ESRC) for the funding from 'Agri-Environmental Governance Post-Brexit: Coproduction of policy frameworks' (ES/S007830/1). Katie J. Field is supported by ERC CoG 'MYCOREV' (865225). Emily K. Durant is supported by the Natural Environment

Research Council (NERC) ECORISC CDT (NE/V013041/1). We are grateful for support for mycorrhizal research via NERC-NEOF (NEOF1561) and the de Laszlo Foundation for supporting PhD research in Katie J. Field lab.

CONFLICT OF INTEREST STATEMENT

We declare that we have no conflicts of interest.

DATA AVAILABILITY STATEMENT

The data that support the findings of this study are available from the corresponding author upon reasonable request.

ETHICS STATEMENT

We knew the farmer from a previous project in which we had sampled soil at several of his fields. This had led to a relationship being formed as he was very interested in our work around contaminants of emerging concern given that he had recently been evaluating the benefits and drawbacks of using wastewater-derived biosolids as soil amendments. This meant that the idea of the interview developed in a very organic way, which allowed for openness and ongoing communication. During our whole research process we were mindful of acting in an ethical manner, following the relevant sections of The University of Leeds guidelines on:

1. Research Ethics Policy
2. Informed Consent Protocol | Data protection at the University

INFORMED CONSENT

We, the authors, confirm that we followed the principles of Free Prior and Informed Consent when interviewing the farmer and farm manager for this project. We obtained verbal and written consent prior to conducting the interviews, and following the production of the video, we obtained written consent for its publication along with the paper. The farmer and farm manager were made aware that they were able to withdraw at any moment during the interview and were under no obligation to respond to any of the questions. We also obtained written confirmation regarding the details to be published about the farm in the manuscript.

ORCID

Felicity C. T. Elder https://orcid.org/0000-0003-4356-444X
Jose-Luis Fajardo-Escoffié https://orcid.org/0000-0003-4307-5005
Laura Carter https://orcid.org/0000-0002-1146-7920
Emily K. Durant https://orcid.org/0009-0004-6696-204X
Katie J. Field https://orcid.org/0000-0002-5196-2360
John Nightingale https://orcid.org/0000-0002-8690-0303
Brett Sallach https://orcid.org/0000-0003-4588-3364
Andrea-Lorena Garduño-Jiménez https://orcid.org/0000-0001-8441-8444

REFERENCES

Al-Rajab, A. J., Sabourin, L., Lapen, D. R., & Topp, E. (2010). The non-steroidal anti-inflammatory drug diclofenac is readily biodegradable in agricultural soils. *Science of the Total Environment*, *409*, 78–82. https://doi.org/10.1016/j.scitotenv.2010.09.020

Ambrosio-Albuquerque, E. P., Cusioli, L. F., Bergamasco, R., Sinópolis Gigliolli, A. A., Lupepsa, L., Paupitz, B. R., Barbieri, P. A., Borin-Carvalho, L. A., & De Brito Portela-Castro, A. L. (2021). Metformin environmental exposure: A systematic review. *Environmental Toxicology and Pharmacology*, *83*, 103588. https://doi.org/10.1016/j.etap.2021.103588

Baldasso, V., Sayen, S., Gomes, C. A. R., Frunzo, L., Almeida, C. M. R., & Guillon, E. (2024). Metformin and lamotrigine sorption on a digestate amended soil in presence of trace metal contamination. *Journal of Hazardous Materials*, *466*, 133635. https://doi.org/10.1016/j.jhazmat.2024.133635

Beacham, J. D., Jackson, P., Jaworski, C. C., Krzywoszynska, A., & Dicks, L. V. (2023). Contextualising farmer perspectives on regenerative agriculture: A post-productivist future? *Journal of Rural Studies*, *102*, 103100. https://doi.org/10.1016/j.jrurstud.2023.103100

Bengtsson-Palme, J., & Larsson, D. G. (2016). Concentrations of antibiotics predicted to select for resistant bacteria: Proposed limits for environmental regulation. *Environment international*, *86*, 140–149. https://doi.org/10.1016/j.envint.2015.10.015

Bigott, Y., Chowdhury, S. P., Pérez, S., Montemurro, N., Manasfi, R., & Schröder, P. (2021). Effect of the pharmaceuticals diclofenac and lamotrigine on stress responses and stress gene expression in lettuce (*Lactuca sativa*) at environmentally relevant concentrations. *Journal of Hazardous Materials*, *403*, 123881. https://doi.org/10.1016/j.jhazmat.2020.123881

Biosolids Assurance Scheme. (2019). Biosolids agricultural good practice guidance leaflet. Biosolids Assurance Scheme.

Cappo, K. A., Blume, L., Raab, G. A., Bartz, J. K., & Engles, J. L. (1987). Analytical methods manual for direct/delayed response project soil survey (EPA/600/8-87/020). US Environmental Protection Agency, Research Triangle Park, NV, USA.

Carter, L. J., Adams, B., Berman, T., Cohen, N., Cytryn, E., Elder, F. C. T., Garduño-Jiménez, A.-L., Greenwald, D., Kasprzyk-Hordern, B., Korach-Rechtman, H., Lahive, E., Martin, I., Ben Mordechay, E., Murray, A. K., Murray, L. M., Nightingale, J., Radian, A., Rubin, A. E., Sallach, B., … Chefetz, B. (2025). Co-contaminant risks in water reuse and biosolids application for agriculture. *Environmental Pollution*, *375*, 126219. https://doi.org/10.1016/j.envpol.2025.126219

Carter, L. J., Chefetz, B., Abdeen, Z., & Boxall, A. B. A. (2019). Emerging investigator series: Towards a framework for establishing the impacts of pharmaceuticals in wastewater irrigation systems on agro-ecosystems and human health. *Environmental Science. Processes & Impacts*, *21*, 605–622. https://doi.org/10.1039/c9em00020h

Carter, L. J., Williams, M., Böttcher, C., & Kookana, R. S. (2015). Uptake of pharmaceuticals influences plant development and affects nutrient and hormone homeostases. *Environmental Science & Technology*, *49*, 12509–12518. https://doi.org/10.1021/acs.est.5b03468

Davies, P., Hyde, R., & Corbishley, A. (2023). Comparison of multiple international metrics for benchmarking antibiotic usage (ABU) using UK beef and sheep data. *The Journal of Antimicrobial Chemotherapy*, *78*, 2496–2504. https://doi.org/10.1093/jac/dkad259

DEFRA. (2018). Sewage sludge in agriculture: Code of practice for England, Wales and Northern Ireland.

Department for Environment Food & Rural Affairs. (2022). Circular economy package policy statement.

Durant, E. K., Field, K. J., Sallach, J. B., Moeskjær, S., Williams, A., & Carter, L. J. (2025). Azole antifungal contaminants disrupt mycorrhizal function and risk agricultural sustainability. *Plants, People, Planet*. https://doi.org/10.1002/ppp3.70068

EFSA Panel on Biological Hazards (BIOHAZ), Koutsoumanis, K., Allende, A., Álvarez-Ordóñez, A., Bolton, D., Bover-Cid, S., Chemaly, M., Davies, R., De Cesare, A., Herman, L., Hilbert, F., Lindqvist, R., Nauta, M., Ru, G., Simmons, M., Skandamis, P., Suffredini, E., Argüello, H., Berendonk, T., … Peixe, L. (2021). Role played by the environment in the emergence and spread of antimicrobial resistance (AMR) through the food chain. *EFSA Journal*, *19*, e06651. https://doi.org/10.2903/j.efsa.2021.6651

Environment Agency. (2022). Scoping review into environmental selection for antifungal resistance and testing methodology (no. SC200011). Environment Agency, Bristol, UK.

European Food Safety Authority (EFSA), Bellisai, G., Bernasconi, G., Binaglia, M., Carrasco Cabrera, L., Castellan, I., Castoldi, A. F., Chiusolo, A., Chukwubike, K., Crivellente, F., Del Aguila, M., Ferreira, L., Giner Santonja, G., Greco, L., Istace, F., Jarrah, S., Lanzoni, A., Leuschner, R., Mangas, I., … Verani, A. (2023). Targeted review of maximum residue levels (MRLs) for diazinon. *EFSA Journal*, *21*, e08426. https://doi.org/10.2903/j.efsa.2023.8426

Garduño-Jiménez, A.-L., & Carter, L. J. (2024). Insights into mode of action mediated responses following pharmaceutical uptake and accumulation in plants. *Frontiers in Agronomy*, *5*, 1293555. https://doi.org/10.3389/fagro.2023.1293555

Gottschall, N., Topp, E., Metcalfe, C., Edwards, M., Payne, M., Kleywegt, S., Russell, P., & Lapen, D. R. (2012). Pharmaceutical and personal care products in groundwater, subsurface drainage, soil, and wheat grain, following a high single application of municipal biosolids to a field. *Chemosphere*, *87*, 194–203. https://doi.org/10.1016/j.chemosphere.2011.12.018

Gullberg, E., Albrecht, L. M., Karlsson, C., Sandegren, L., & Andersson, D. I. (2014). Selection of a multidrug resistance plasmid by sublethal levels of antibiotics and heavy metals. *mBio*, *5*(4), e01918–14. https://doi.org/10.1128/mbio.01918-14

Helgason, T., Daniell, T. J., Husband, R., Fitter, A. H., & Young, J. P. W. (1998). Ploughing up the wood-wide web? *Nature*, *394*, 431. https://doi.org/10.1038/28764

James, C., James, S. J., Onarinde, B. A., Dixon, R. A., & Williams, N. (2023). A critical review of AMR risks arising as a consequence of using biocides and certain metals in food animal production. *Antibiotics*, *12*, 1569. https://doi.org/10.3390/antibiotics12111569

Kiatkoski Kim, M., Douglas, M. M., Pannell, D., Setterfield, S. A., Hill, R., Laborde, S., Perrott, L., Álvarez-Romero, J. G., Beesley, L., Canham, C., & Brecknell, A. (2022). When to use transdisciplinary approaches for environmental research. *Frontiers in Environmental Science*, *10*, 840569. https://doi.org/10.3389/fenvs.2022.840569

Kim, S., Chen, J., Cheng, T., Gindulyte, A., He, J., He, S., & Bolton, E. E. (2019). PubChem 2019 update: Improved access to chemical data. *Nucleic Acids Research*, *47*(D1), D1102–D1109. https://doi.org/10.1093/nar/gky1033

Krzywoszynska, A. (2019). Caring for soil life in the Anthropocene: The role of attentiveness in more-than-human ethics. *Transactions of the Institute of British Geographers*, *44*, 661–675. https://doi.org/10.1111/tran.12293

Lautz, L. S., Struijs, J., Nolte, T. M., Breure, A. M., van der Grinten, E., van de Meent, D., & van Zelm, R. (2017). Evaluation of SimpleTreat 4.0: Simulations of pharmaceutical removal in wastewater treatment plant facilities. *Chemosphere*, *168*, 870–876. https://doi.org/10.1016/j.chemosphere.2016.10.123

Maddela, N. R., Ramakrishnan, B., Kakarla, D., Venkateswarlu, K., & Megharaj, M. (2022). Major contaminants of emerging concern in soils: A perspective on potential health risks. *RSC Advances*, *12*, 12396–12415. https://doi.org/10.1039/d1ra09072k

Mansilla, S., Portugal, J., Bayona, J. M., Matamoros, V., Leiva, A. M., Vidal, G., & Piña, B. (2021). Compounds of emerging concern as new plant stressors linked to water reuse and biosolid application in agriculture. *Journal of Environmental Chemical Engineering*, *9*, 105198. https://doi.org/10.1016/j.jece.2021.105198

Martin, I., & Hart, A. (2023). Antifungal medicines in the terrestrial environment: Levels in biosolids from England and Wales. *Science of the Total Environment*, *870*, 161999. https://doi.org/10.1016/j.scitotenv.2023.161999

Masinga, P., Simbanegavi, T. T., Makuvara, Z., Marumure, J., Chaukura, N., & Gwenzi, W. (2024). Emerging organic contaminants in the soil–plant-receptor continuum: Transport, fate, health risks, and removal mechanisms. *Environmental Monitoring and Assessment*, *196*, 367. https://doi.org/10.1007/s10661-023-12282-7

Mejías, C., Martín, J., Santos, J. L., Aparicio, I., & Alonso, E. (2021). Occurrence of pharmaceuticals and their metabolites in sewage sludge and soil: A review on their distribution and environmental risk assessment. *Trends in Environmental Analytical Chemistry*, *30*, e00125. https://doi.org/10.1016/j.teac.2021.e00125

Mohapatra, D. P., Cledón, M., Brar, S. K., & Surampalli, R. Y. (2016). Application of wastewater and biosolids in soil: Occurrence and fate of emerging contaminants. *Water, Air, and Soil Pollution*, *227*, 77. https://doi.org/10.1007/s11270-016-2768-4

Mosharaf, M. K., Gomes, R. L., Cook, S., Alam, M. S., & Rasmusssen, A. (2024). Wastewater reuse and pharmaceutical pollution in agriculture: Uptake, transport, accumulation and metabolism of pharmaceutical pollutants within plants. *Chemosphere*, *364*, 143055. https://doi.org/10.1016/j.chemosphere.2024.143055

Mosnier, A., Springmann, M., & Fan, S. (2022). Chapter 6. Transforming food systems – Emissions gap report 2022: The closing window—Climate crisis calls for rapid transformation of societies.

Mrozik, W., & Stefańska, J. (2014). Adsorption and biodegradation of antidiabetic pharmaceuticals in soils. *Chemosphere*, *95*, 281–288. https://doi.org/10.1016/j.chemosphere.2013.09.012

Murray, A. K., Stanton, I. C., Tipper, H. J., Wilkinson, H., Schmidt, W., Hart, A., Singer, A. C., & Gaze, W. H. (2024). A critical meta-analysis of predicted no effect concentrations for antimicrobial resistance selection in the environment. *Water Research*, *266*, 122310. https://doi.org/10.1016/j.watres.2024.122310

Nightingale, J., Elder, F. C. T., Garduño-Jiménez, A.-L., & Carter, L. J. (2025). Understanding the extent of emerging contaminants in English soils: Environmental implications of differing organic waste applications. *Journal of Hazardous Materials*, *500*, 140433. https://doi.org/10.1016/j.jhazmat.2025.140433

Ninkuu, V., Liu, Z., Qin, A., Xie, Y., Song, X., & Sun, X. (2025). Impact of straw returning on soil ecology and crop yield: A review. *Heliyon*, *11*, e41651. https://doi.org/10.1016/j.heliyon.2025.e41651

Parente, C. E. T., Brito, E. M. S., Azeredo, A., Meire, R. O., & Malm, O. (2019). Fluoroquinolone antibiotics and their interactions in agricultural soils – A review. *Orbital Electron. J. Chem*, *11*, 42–52. https://doi.org/10.17807/orbital.v11i1.1352

Pateiro-Moure, M., Arias-Estévez, M., & Simal-Gándara, J. (2010). Competitive and non-competitive adsorption/desorption of paraquat, diquat and difenzoquat in vineyard-devoted soils. *Journal of Hazardous Materials*, *178*, 194–201. https://doi.org/10.1016/j.jhazmat.2010.01.063

Posit Team. (2024). *RStudio: Integrated Development Environment for R*. Posit Software, PBC. https://posit.co/

R Core Team. (2024). *R: A Language and Environment for Statistical Computing*. R Foundation for Statistical Computing.

Rebanks, J. (2021). *English Pastoral- An Inheritance*. Penguin.

Rodias, E., Aivazidou, E., Achillas, C., Aidonis, D., & Bochtis, D. (2020). Water-energy-nutrients synergies in the agrifood sector: A circular economy framework. *Energies*, *14*, 159. https://doi.org/10.3390/en14010159

Rog, I., Van Der Heijden, M. G. A., Bender, S. F., Boussageon, R., Lambach, A., Schlaeppi, K., Bodenhausen, N., & Lutz, S. (2025). Mycorrhizal inoculation success depends on soil health and crop productivity. *FEMS Microbiology Letters*, *372*, fnaf031. https://doi.org/10.1093/femsle/fnaf031

Sallach, J. B., Thirkell, T. J., Field, K. J., & Carter, L. J. (2021). The emerging threat of human-use antifungals in sustainable and circular agriculture schemes. *Plants, People, Planet*, *3*, 685–693. https://doi.org/10.1002/ppp3.10222

Sands, B., Machado, M. R., White, A., Zent, E., & Gould, R. (2023). Moving towards an anti-colonial definition for regenerative agriculture. *Agriculture and Human Values*, *40*, 1697–1716. https://doi.org/10.1007/s10460-023-10429-3

Schymanski, E. L., Jeon, J., Gulde, R., Fenner, K., Ruff, M., Singer, H. P., & Hollender, J. (2014). Identifying small molecules via high resolution mass spectrometry: Communicating confidence. *Environmental Science & Technology*, *48*, 2097–2098. https://doi.org/10.1021/es5002105

Sellier, A., Khaska, S., & Le Gal La Salle, C. (2022). Assessment of the occurrence of 455 pharmaceutical compounds in sludge according to their physical and chemical properties: A review. *Journal of Hazardous Materials*, *426*, 128104. https://doi.org/10.1016/j.jhazmat.2021.128104

Selwe, K. P., Head, C. R., Phokedi, G. N., Andersen, J. E. T., Sallach, J. B., & Dessent, C. E. H. (2024). Suspect and non-targeted screening of chemical pollutants in Botswana's aquatic environments. *Emerging Contaminants*, *10*, 100377. https://doi.org/10.1016/j.emcon.2024.100377

Siemieniuk, A., Ludynia, M., & Rudnicka, M. (2021). Response of two crop plants, *Zea mays* L. and *Solanum lycopersicum* L., to diclofenac and naproxen. *International Journal of Molecular Sciences*, *22*, 8856. https://doi.org/10.3390/ijms22168856

Smith, A. E. O., Doidge, C., Lovatt, F., & Kaler, J. (2023). A survey of British sheep farmers: Practices, opinions and knowledge surrounding the management of sheep scab. *Preventive Veterinary Medicine*, *214*, 105898. https://doi.org/10.1016/j.prevetmed.2023.105898

Smith, S. E., & Read, D. J. (2010). *Mycorrhizal symbiosis*. Academic press.

Stevenson, E. M., Gaze, W. H., Gow, N. A. R., Hart, A., Schmidt, W., Usher, J., Warris, A., Wilkinson, H., & Murray, A. K. (2022). Antifungal exposure and resistance development: Defining minimal selective antifungal concentrations and testing methodologies. *Frontiers in Fungal Biology*, *3*, 918717. https://doi.org/10.3389/ffunb.2022.918717

Straub, L., Strobl, V., & Neumann, P. (2020). The need for an evolutionary approach to ecotoxicology. *Nature Ecology & Evolution*, *4*, 895. https://doi.org/10.1038/s41559-020-1194-6

Sud, M. (2020). Managing the biodiversity impacts of fertiliser and pesticide use. https://doi.org/10.1787/63942249-en

Šudoma, M., Neuwirthová, N., Hvězdová, M., Svobodová, M., Bílková, Z., Scherr, K. E., & Hofman, J. (2019). Fate and bioavailability of four conazole fungicides in twelve different arable soils – Effects of soil and pesticide properties. *Chemosphere*, *230*, 347–359. https://doi.org/10.1016/j.chemosphere.2019.04.227

Thelusmond, J. R., Kawka, E., Strathmann, T. J., & Cupples, A. M. (2018). Diclofenac, carbamazepine and triclocarban biodegradation in agricultural soils and the microorganisms and metabolic pathways affected. *Science of the Total Environment*, *640*, 1393–1410. https://doi.org/10.1016/j.scitotenv.2018.05.403

Trouvelot, A., Kough, J. L., & Gianinazzi-Pearson, V. (1986). Mesure du taux de mycorrhization VA d'un systeme radiculaire. Recherche des methodes d'estimation ayant une signification fonctionnelle. *The Mycorrhizae: Physiology and Genetic, INRA Press, Paris*, 217–221.

UNEP. (2023). Bracing for superbugs: Strengthening environmental action in the one health response to antimicrobial resistance. United Nations. https://doi.org/10.18356/9789210025799

United Nations Environmental Assembly. (2019). Innovative pathways to achieve sustainable consumption and production (no. UNEP/EA.4/Res.1).

Urra, J., Alkorta, I., & Garbisu, C. (2019). Potential benefits and risks for soil health derived from the use of organic amendments in agriculture. *Agronomy*, *9*, 542. https://doi.org/10.3390/agronomy9090542

Verbruggen, E., Van Der Heijden, M. G. A., Rillig, M. C., & Kiers, E. T. (2013). Mycorrhizal fungal establishment in agricultural soils: factors determining inoculation success. *The New Phytologist*, *197*, 1104–1109. https://doi.org/10.1111/j.1469-8137.2012.04348.x

Vickneswaran, M., Carolan, J. C., Saunders, M., & White, B. (2023). Establishing the extent of pesticide contamination in Irish agricultural soils. *Heliyon*, *9*, e19416. https://doi.org/10.1016/j.heliyon.2023.e19416

Vierheilig, H., Coughlan, A. P., Wyss, U. R. S., & Piché, Y. (1998). Ink and vinegar, a simple staining technique for arbuscular-mycorrhizal fungi. *Applied and Environmental Microbiology*, *64*, 5004–5007.

Wang, F., Xiang, L., Sze-Yin Leung, K., Elsner, M., Zhang, Y., Guo, Y., Pan, B., Sun, H., An, T., Ying, G., Brooks, B. W., Hou, D., Helbling, D. E., Sun, J., Qiu, H., Vogel, T. M., Zhang, W., Gao, Y., Simpson, M. J., … Tiedje, J. M. (2024). Emerging contaminants: A one health perspective. *The Innovation*, *5*, 100612. https://doi.org/10.1016/j.xinn.2024.100612

Wei, R., He, T., Zhang, S., Zhu, L., Shang, B., Li, Z., & Wang, R. (2019). Occurrence of seventeen veterinary antibiotics and resistant bacterias in manure-fertilized vegetable farm soil in four provinces of China. *Chemosphere*, *215*, 234–240. https://doi.org/10.1016/j.chemosphere.2018.09.152

Wu, J., Wang, J., Li, Z., Guo, S., Li, K., Xu, P., Ok, Y. S., Jones, D. L., & Zou, J. (2023). Antibiotics and antibiotic resistance genes in agricultural soils: A systematic analysis. *Critical Reviews in Environmental Science and Technology*, *53*, 847–864. https://doi.org/10.1080/10643389.2022.2094693

Yang, L., Wu, L., Liu, W., Huang, Y., Luo, Y., & Christie, P. (2018). Dissipation of antibiotics in three different agricultural soils after repeated application of biosolids. *Environmental Science and Pollution Research*, *25*, 104–114. https://doi.org/10.1007/s11356-016-8062-6

Zhang, Q., Gao, B., Xiao, Y., Yang, H., Wang, Y., Du, L., & Zhu, D. (2020). Purification and characterization of a novel β-glucuronidase precisely converts glycyrrhizin to glycyrrhetinic acid 3-O-mono-β-D-glucuronide from plant endophytic *Chaetomium* globosum DX-THS3. *International Journal of Biological Macromolecules*, *159*, 782–792. https://doi.org/10.1016/j.ijbiomac.2020.05.047

SUPPORTING INFORMATION

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

How to cite this article: Elder, F. C. T., Fajardo-Escoffié, J.-L., Carter, L., Durant, E. K., Field, K. J., Nightingale, J., Sallach, B., & Garduño-Jiménez, A.-L. (2025). An integrated social and natural sciences case study for the reuse of organic wastes as soil amendments. *Plants, People, Planet*, 1–17. https://doi.org/10.1002/ppp3.70141